The Development of a Methodology to Determine the Maintenance Strategy for High Voltage Circuit Breakers

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BEng (Hons)

Submitted for the Degree
of
Doctor of Philosophy

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June 2010

Signed:

Date:

Abstract

In the power systems domain, utilities are under ever increasing pressure and constraints to improve plant reliability and availability whilst minimising capital and operating expenditure. Against this background, traditional methods of carrying out maintenance at fixed intervals are being challenged by alternative techniques such as Condition Based Maintenance, Reliability Centred Maintenance and mathematical modelling. In addition, with the advent of on-line condition monitoring systems and as the reliability of items of plant like circuit breakers improve through advancements in technology, asset managers are faced with a challenge in their own right as to how to evaluate these methods to ensure the optimum maintenance strategy is adopted.

This thesis evaluates these different maintenance methods and in particular develops an economic model that takes cognisance of the reliability of an on-line condition monitoring system to demonstrate that due to the unreliability of these systems, careful consideration needs to given as to how they are applied and the parameters that they monitor.

The evaluation of the different maintenance strategies prompts a major area of research in this thesis, which is to understand the critical failure modes of a high voltage circuit breaker. Using the technique of Fault Tree Analysis and applying it to a gas insulated circuit breaker, the contribution of each component to the overall circuit breaker availability is quantified. This allows the failure modes that have the highest impact on the availability of a circuit breaker to be identified thereby allowing the selection of cost-effective maintenance procedures.

The thesis concludes with examining the role of mathematical modelling, and explains that combining Markov models with Reliability Centred Maintenance and

Fault Tree Analysis provides a powerful methodology for a utility or operator to develop the optimum maintenance strategy, from both a technical and economical perspective, for a high voltage circuit breaker.

Glossary of Terms

ABCB	Air-Blast Circuit Breaker
AC	Alternating Current
AI	Artificial Intelligence
AIS	Air Insulated Switchgear
AMP	Asset Management Planner
ARM	Asset Risk Management
ASSP	Asset Sustainable Strategy Platform
ATA	US Air Transport Association
BCM	Breaker Condition Monitoring
CB	Circuit Breaker
CBM	Condition Based Maintenance
CBR	Case Based Reasoning
CIGRÉ	International Council on Large Electric Systems
CLK SYNC	Clock Synchronisation
CT	Current Transformer
CTC	Circuit Termination Cubicle
DC	Direct Current
DCRM	Dynamic Control Resistance Measurement
DTI	Department of Trade and Industry
EHV	Extra High Voltage
EPRI	Electric Power Research Institute
FMECA	Failure Mode Effects and Criticality Analysis
FTA	Fault Tree Analysis
FTD	Fault Tree Diagram
GCB	Gas Circuit Breaker
GCC	Grid Control Centre

GIS	Gas Insulted Switchgear
GNP	Gross National Product
GPS	Global Positioning System
HV	High Voltage
IEC	International Standard
KBS	Knowledge Based System
KPI	Key Performance Indicator
LCC	Local Control Cubicle
MBR	Model Based Reasoning
MPM	Major Preventive Maintenance
MPS	Maintenance Priority System
MSG	Maintenance Steering Group
MTBF	Mean Time Between Failures
MTTF	Mean Time To Failure
NME	Non-Metal Enclosed
NPRD	Non-Electronic Parts Reliability Data
NPV	Net Present Value
NSC	Non-System Critical
OLMS	On-Line Monitoring System
OREDA	Offshore Reliability Database
PC	Personal Computer
PD	Partial Discharge
PDM	Partial Discharge Monitoring
P-F	Point-Failure
PM	Preventive Maintenance
PRA	Probability Risk Assessment
PRD	Pressure Relief Device
PSU	Power Supply Unit
RBM	Risk Based Maintenance
RCAM	Reliability Centred Asset Manager
RCM	Reliability Centred Maintenance
RM	Routine Maintenance

ROM	Reliability Optimised Maintenance
RTU	Remote Terminal Unit
SAE	Society of Automotive Engineers
TPM	Transition Probability Matrix
UHF	Ultra High Frequency

Contents

Acknowledgements

I would like to offer my sincere thanks to Professor Jim McDonald, Principal of the University of Strathclyde, for giving me the opportunity to conduct this research and supporting me throughout it. In particular I would also like to thank Professor Graham Ault for his guidance and encouragement throughout the duration of my research. His enthusiasm and input towards my work is greatly appreciated. When balancing working life with the demands of postgraduate research, Graham's continual support not only motivated me, but also made my research an enjoyable and rewarding experience.

I would like to thank ScottishPower, my Employer, for financing this project and allowing me to undertake this research. In addition, I am extremely grateful to my colleagues, Stephen Olson and Tom Cumming, whose experience and technical knowledge were invaluable to the research detailed in this thesis. Both Stephen and Tom gave up a considerable amount of their time to review my research and provide me with feedback and advice. Their knowledge is derived from many years of operational experience, which unfortunately cannot be obtained from a textbook.

Appreciation and acknowledgment is also due to Robert Brinzer and John Pearson for sharing their experience with me on the failure mechanisms of circuit breakers. Without this guidance, it would have proved extremely difficult to develop the fault trees presented in Chapter 6.

Finally, and most importantly, I would like to thank my family for their patience and understanding in carrying out this research. Their support and encouragement gave me the motivation to keep going and although they had ample reason to complain, not once did they do so.

Chapter 1

1 Introduction

1.1 Introduction to Research

In many countries, there are ongoing efforts to improve the lifetime availability of transmission systems by minimising the number and duration of circuit outages, whether they are planned or unplanned. For some utilities there is an even greater incentive, as the financial penalties or loss of income from an outage can far exceed the maintenance or repair costs. Consequently, there is great interest in the factors that influence the reliability and associated availability of items of power plant, such as circuit breakers.

Traditionally, circuit breaker maintenance has been carried out at fixed time intervals [Cigré, 83, 1994]. However, intrusive maintenance is not only costly in terms of manpower, but also reduces plant availability and subsequent system security. Furthermore, it has been shown that it has little effect in detecting the defects that can cause future failures and it can introduce failures [Cigré, 83, 1994]. Therefore, with improving circuit breaker reliability, many utilities have been examining and applying alternative maintenance strategies, such as Condition Based Maintenance (CBM) and Reliability Centred Maintenance (RCM) [Cigré, 165, 2000]. The former means carrying out preventive actions depending on the condition of the equipment, whereas the latter is more a structured process that determines what is the most appropriate maintenance action for each individual item of plant or system.

A key question in applying a CBM or RCM strategy is the role of on-line diagnostics or condition monitoring. The use of on-line condition monitoring for circuit breakers is not new. Various systems are in use today and there has been extensive research on methods to assess the economic viability of such systems, the parameters that need to be monitored and how the data should be interpreted [Cigré, 167, 2000]. However, it is essential that On-Line Monitoring Systems (OLMSs) do not themselves affect the reliability of a circuit breaker and therefore negate any potential economic or system usage benefits.

Against this background, the research reported in this thesis examines the practicalities of moving towards a CBM or RCM strategy. In particular, it compares the economic and technical merits of one maintenance strategy versus another. To assist in this assessment, an economic model is developed to assess the role of on-line condition monitoring, which unlike other models examines the reliability of a condition monitoring system and its affect on the availability of a circuit breaker. Through case studies, the research highlights that careful consideration needs to be given to how the transducers of condition monitoring systems are applied to a circuit breaker, as in Non-System Critical (NSC) applications[1] the initial perceived economic benefits can be undermined.

[1] Refer to section 4.8 for a definition of a NSC circuit breaker application.

Despite the reliability issues surrounding on-line condition monitoring systems, the research highlights the benefits of moving towards a condition based regime. However, compared to either a pure off-line or on-line CBM strategy, the RCM case studies demonstrate that, depending on the failure mode, it is sometimes more advantageous from a technical and economical perspective to select a scheduled refurbishment task.

A major aspect of the research concentrates on identifying the critical failure modes of a circuit breaker. Although RCM uses the qualitative evaluation tool of Failure Mode Effects and Criticality Analysis (FMECA) to identify the failure modes, another method called Fault Tree Analysis (FTA) exists, which allows a user to understand how each component part quantifiably contributes towards the overall circuit breaker availability. It is a far more complicated process, compared to FMECA, but through applying it to a 145 kilovolt (kV) gas insulated circuit breaker, the research reveals failures modes that were previously thought to be less important to others when using the FMECA technique. Furthermore, it allows a user to rationalise the parameters being monitored and compare the benefits of comparing one parameter versus another.

The final area of the research examines the role of mathematical modelling, and in particular Markov models, as a tool for selecting and comparing one maintenance strategy against another. The research demonstrates that rather than replace heuristic techniques, such as CBM and RCM, Markov modelling complements them, as they can be used to examine the effect of a maintenance task on the overall life of a circuit breaker. Furthermore, when used with the economic model developed to assess the viability of an on-line condition monitoring system, they allow a complete economic and technical evaluation of each maintenance strategy to be undertaken.

In summary, when Markov modelling is combined with RCM and FTA, a powerful methodology is presented that allows a utility or operator to develop a maintenance strategy for an asset, such as a circuit breaker, that is the optimum from both a technical and economical perspective. Although a utility or operator may have different plant failure rates and operating drivers, such as regulatory constraints, the principles and techniques that have been developed in this thesis to arrive at this optimum maintenance strategy should be valid for each individual user.

1.2 Main Research Contributions

In terms of the novelty of the research undertaken, five main contributions can be identified:

- **The development of an economic model to assess the viability of on-line condition monitoring**

  Current evaluation methods make the assumption that the reliability of OLMSs can be ignored when assessing the viability of applying them to circuit breakers [Cigré, 167, 2000]. However, the research takes a novel approach and develops a model that takes account of the reliability of an OLMS. Through sensitivity studies it proves that this assumption is incorrect, and could lead to a utility being ill-advised when determining when and where to apply on-line condition monitoring.

  By carrying out further research it is shown that this model can easily be adapted to assess monitoring systems for other assets, such as Partial Discharge Monitoring systems (PDMs) for Gas Insulated Switchgear (GIS).

- **The role of on-line condition monitoring systems in moving to a CBM or RCM strategy**

  The research builds upon previous experience with off-line diagnostics and examines, both economically and technically, how on-line condition monitoring could be used as part of a CBM or RCM policy for single pressure SF_6 high voltage circuit breakers.

  Through case studies, the merits of each maintenance strategy are examined and potential application issues are identified.

- **Development of a circuit breaker model to identify the critical failure modes**

  Using FTA an extensive model is developed, which quantitatively links the basic component parts of a circuit breaker to its overall availability. Compared to techniques such as FMECA, as currently used in RCM, the FTA model is more accurate in identifying the critical failures modes. It is also shown that the model allows a utility to understand how a failure develops and thereby select the most appropriate maintenance task to detect its early inception.

  A further benefit of FTA is that it will prove invaluable in the development of a future ‘Expert System’ as its top down structure and logic system approach lends itself well to developing rules to assist a utility in fault finding.

- **The development of Markov models to compare the effect of different maintenance strategies on the life of a circuit breaker**

  Markov models for different maintenance strategies are developed to allow a comparison to be made between the different approaches and to assess the merits of mathematical modelling versus heuristic approaches such as CBM and RCM.

  Unlike existing research, the modelling also examines the effect of on-line monitoring on the life of a circuit breaker.

- **Development of a methodology to determine the optimum maintenance strategy for high voltage circuit breakers**

  Using RCM, complemented with FTA, and where appropriate Markov modelling, a methodology is developed that allows a utility to determine the optimum maintenance strategy for a high voltage SF_6 circuit breaker.

The methodology considers the use of a number of maintenance techniques, such as on-line monitoring, and leads a utility to develop a strategy that is the optimum from both an economical and technical perspective. Although the principles and techniques are focused towards an SF_6 high voltage circuit breaker, they are valid for other types of circuit breakers and indeed could be extended to other assets, such as cables and transformers.

1.3 Justification for Research

Until 1995, ScottishPower used a Time Based Maintenance (TBM) philosophy for all types of switchgear. The actual frequency and content of the maintenance was very much dependent on the manufacturers' recommendations. However, some relatively modest extensions of the time intervals had taken place previous to that date.

With the increasing availability of diagnostic monitoring techniques, a decision was made to fully review the maintenance practices for transmission circuit breakers. The investigation considered the current philosophy of maintenance at that time and examined the changes that could be implemented to reduce the incidence of routine intrusive maintenance, whilst maintaining the reliability of the system. In particular, it was tasked with producing detailed proposals for the content and frequency of the maintenance, taking account of the availability of off-line diagnostic techniques, plant type, climatic conditions, operating regime, performance history and known types of defects. Unfortunately, the study could not be extended to on-line condition monitoring, as the commercial availability of these systems was extremely limited at that time.

Now that on-line monitoring is commercially available and with the ever-increasing pressure to maximise the availability of assets at the minimum cost, utilities like ScottishPower need to answer questions such as:

- Considering the changes in technology, are existing maintenance practices addressing the potential failure modes of high voltage circuit breakers?

- What are the parameters that influence the reliability and service life of high voltage circuit breakers?
- Are these failure modes better addressed by alternative maintenance practices, such as CBM and RCM?
- What is the role of mathematical modelling in determining future maintenance strategies for circuit breakers?
- How does mathematical modelling compare with better known techniques such as CBM and RCM?
- With increasing circuit breaker reliability, what is the optimum maintenance strategy and is there a role for on-line condition monitoring?
- What parameters should be monitored and how should an OLMS be applied to a circuit breaker as opposed to the parameters that can be monitored?
- Should utilities purchase commercially available systems or is it more beneficial for utilities to adapt existing systems?
- What is the true cost of on-line condition monitoring?

Against this background and in an effort to ever improve system reliability and availability, ScottishPower has sponsored the research contained in this thesis.

1.4 Thesis Outline

This thesis is arranged into eight chapters. This section outlines the content of the chapters, which follow.

Chapter 2 covers the history and purpose of maintenance. It explains how TBM evolved and the challenges it now faces from techniques such as CBM and RCM.

Case studies are presented and the potential benefits of moving from a TBM to off-line CBM strategy are highlighted.

A description of various types of high voltage circuit breakers follows, as a basic understanding of the general principles of how a circuit breaker operates is essential to understanding future chapters in the thesis. Moreover, it is important to understand how circuit breaker technology has developed from oil and air blast to modern SF_6 single pressure types.

In Chapter 3 the concept of condition monitoring is introduced. Apart from reviewing the various types of monitoring that exist, the chapter examines the current experience with circuit breaker condition monitoring and identifies the future challenges that need to be addressed if there is to be a role for high voltage circuit breaker on-line condition monitoring. In particular, guidelines are provided on how on-line condition monitoring should be applied to minimise its impact on the reliability of a circuit breaker.

Chapter 4 reviews the existing economic models that are available to assess the viability of on-line condition monitoring and highlights their shortcomings. A model is then developed, which takes cognisance of these issues and through case studies it is demonstrated how a utility could be led to making the wrong decision regarding the use of on-line condition monitoring if factors such as the reliability of an OLMS are not considered in the analysis. The chapter concludes with showing how this model can easily be adapted to other monitoring systems for other types of assets.

In Chapter 5, RCM is introduced to explore the practicalities of applying it to a circuit breaker and whether it changes the view on the role of on-line condition that is formed in the previous chapter when using it as part of an on-line CBM strategy. The chapter compares RCM with CBM and through case studies demonstrates that through RCM's structured approach to identify a circuit breaker's failure modes it can be used to optimise the use of on-line condition monitoring both technically and economically.

Chapter 6 uses the technique of FTA to develop a model for a 145kV gas insulated circuit breaker to ascertain the accuracy of RCM in identifying failure modes and whether current thinking is correct in addressing the maintenance needs of modern, SF_6 single pressure high voltage circuit breakers. The analysis reveals that some failures modes that were previously thought less important, compared to others, actually contribute significantly to the reliability of a circuit breaker. As the model also quantifiably links each component part to the overall circuit breaker availability, it allows the effect of monitoring one parameter versus another to be better understood, thereby allowing a utility to further optimise the type and number of monitored parameters.

In Chapter 7 the concept of mathematical modelling is introduced. After reviewing the current utility experience, Markov models are developed to compare the effect of different maintenance strategies on the life of a circuit breaker and whether heuristic maintenance methods can be replaced by mathematical modelling. In particular the models include the effects of on-line condition monitoring and whether the economic case for OLMSs is weakened or strengthened.

Chapter 8 completes the thesis by presenting the conclusions, which have resulted from the research. In addition, future work is suggested, which will allow the concepts within the thesis to be developed further.

1.5 Associated Publications

The following publications have arisen from the research detailed in this thesis:

1. Camps G.D., Cumming T.A., Gibson D., Olson S., Walker D., Ault G.W., McDonald J.R., *An Economic & Technical Evaluation of Condition Monitoring for New SF_6 Circuit Breakers*, 39th International University Power Engineering Conference, Bristol, pp. 85-88, September 2004.

2. Camps G.D., Cumming T.A., Olson S., Ault G.W., McDonald J.R., *Economic Viability of CBM Strategies for Circuit Breakers*, 2004 EuroDoble Colloquium on Condition Based Maintenance for Power Equipment, 5.5, October 2004.

3. Camps G.D., Cumming T.A., Gibson D., Olson S., Ault G.W., McDonald J.R., *The development of a model to assess the economic viability of on-line condition monitoring and its effect on the reliability of an EHV SF_6 circuit breaker*, *CIGRÉ* SC A3 & B3 Joint Colloquium on Present and Future of High Voltage Equipment and Substation Technologies, 124, September 2005.

4. Camps G.D., Cumming T.A., Olson S., Ault G.W., McDonald J.R., *Economic and Technical Feasibility of Applying RCM to an EHV SF_6 Circuit Breaker*, CMD 2006, International Conference on condition Monitoring and Diagnosis, Changwon, Korea, 2.3, April 2006.

5. Camps G.D., Cumming T.A., Olson S., Ault G.W., McDonald J.R., *Determining the Cost Benefit and Payback of PDM systems*, Diagnostics Monitoring Systems Conference, U.K., June 2006.

Chapter 2

2 Maintenance Practices

This chapter introduces the concept of maintenance and describes how it has evolved from the days when it was carried out in reaction to a failure to the present day where the focus is on using a variety of methods, such as CBM and RCM, to meet the challenges of increasing the availability, reliability and safety of an asset. The chapter concentrates on the development of maintenance within the Transmission and Distribution utility industry, and in particular examines typical maintenance strategies for different types of high voltage circuit breakers. Case studies are presented to demonstrate the potential benefits of moving from a TBM approach to an off-line CBM method for high voltage circuit breakers and this point is further reinforced by examining the experience of different utilities when applying either CBM or RCM to high voltage circuit breakers.

2.1 The Changing World of Maintenance

In the last sixty years there has been dramatic change in the approach to maintenance of plant and equipment. Pre World War 2, when there was not the same reliance on plant as there is now, the tendency was to carry out repairs when the equipment failed. However, during World War 2 when the demand for plant and equipment increased, downtime became more important. Consequently, this led to the idea that failures should and could be prevented by carrying out scheduled maintenance at pre-defined intervals, otherwise known as TBM. In the last twenty years the focus has changed again. With rising maintenance costs and the emphasis now on greater availability, reliability and safety, new methods have had to be developed and adopted [Moubray, 1997].

The first industry to face these new challenges was the commercial aviation industry. In the nineteen sixties, with the introduction of more complex aircraft systems, it became apparent that the traditional maintenance practice, with its emphasis on rigidly scheduled inspection, servicing and removal, was not impacting on reliability as expected. Against this background the airline operators and manufacturers, through the US Air Transport Association (ATA), set up a group called the Maintenance Steering Group (MSG) to develop a new maintenance process to be used with the Boeing 747. The new approach was called MSG-1 and was later updated to include other wide-bodied aircraft, such as the DC-10 and L-1011. This version of the handbook was called MSG-2.

In 1980, the decision logic was further updated to develop maintenance programs for the Boeing 757 and 767. The new document is now known as MSG-3 and like its predecessors is a planning document, which uses decision logic to yield a maintenance programme that preserves the designed-in levels of safety and reliability at the lowest possible cost. Outside the commercial aviation industry, MSG-3 is known as Reliability Centred Maintenance or RCM [Anderson, 1990].

RCM has now been adopted by a number of other industry sectors, such as the US Department of Defence where it has been applied to naval aircraft and surface vessels [Bowler et al, 1994]. Other applications include the nuclear industry where [Ochoa et al, 1995] reports that pilot studies have been conducted on twelve US nuclear plants and in Europe, Electricité de France are incorporating RCM as the standard method for designing maintenance programmes in all of their nuclear power stations [Smith et al, 2004]. Within Europe, there are other users of RCM, which include the oil industry and the food sector such as Nestle (UK) Ltd [Bowler et al, 1994]. However, a significant user of RCM, and increasing more, is the utility sector and in particular the transmission and distribution industry. As detailed later in this section, most of this experience resides within the US, but experience is now being gained within Europe [Bowler et al, 1995; Renforth, 1998; and Cigré, 165, 2000] and Asia [Cigré, 165, 2000 and Chan et al, 2005].

2.2 Maintenance Strategies

Moubray [Moubray, 1997] describes maintenance as "Ensuring that physical assets continue to do what their users want them to do." In essence this means maintaining an item or plant towards a state of failure free operation. For most cases it does not mean at any cost, but as Figure 2.1 depicts, it is rather the optimum point between the cost of the failure and the cost of carrying out the maintenance.

There are many maintenance strategies that can be adopted to try and achieve this objective. In fact in the last twenty years literally hundreds have appeared and new techniques are emerging practically every week. Examples include Risk Based Maintenance (RBM) [Guo et al, 2009], Probabilistic Risk Assessment (PRA) [Dunn, 2010], Reliability Optimised Maintenance (ROM) [Tomic, 1993] and Total Productive Maintenance [Nakajima, 1998]. To cover all these strategies would be impracticable, so the following discussion has been limited to the main concepts that are used in the electrical power industry [Cigré, 152, 2000].

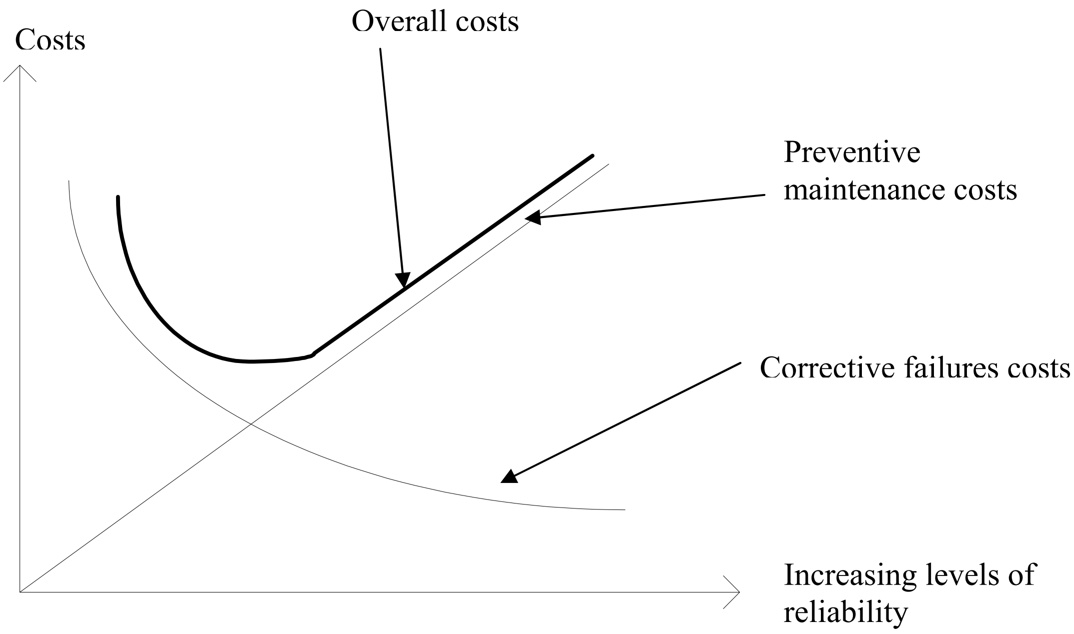


Figure 2.1: Maintenance and failure costs versus investment cost to improve reliability

2.2.1 Corrective Maintenance

Corrective maintenance means fixing things either when they are found to be failing or when they have failed. It does not necessarily mean that there is not any prior knowledge of the failure. The advantages of a failure based maintenance strategy include:

- Relatively low perceived costs;
- Requires low staff levels - although staff problems and/or resource problems could be experienced if several items of equipment fail at or around the same time;
- Allows equipment to run until breakdown – maximum life of equipment is always utilised; and
- Simple approach – very effective where consequences and costs are low.

The disadvantages of a failure based maintenance strategy include:

- Increased costs due to the unpredictable nature of activities – unplanned outages;
- Increased labour costs – overtime working hours may be required;
- Inefficient use of maintenance staff resource – peaks and troughs;
- Inventory problems – difficult to plan requirements;
- Consequential damage; and
- Safety considerations.

2.2.2 Time Based Maintenance

TBM is a sub-class of preventive maintenance, which means carrying out maintenance or overhaul activities at pre-determined time intervals. If specified components are to be replaced, they will usually be replaced regardless of the requirement. The time intervals are usually based on the manufacturers' recommendations or a company's own operating experience. The advantages of a TBM strategy include:

- Effective when the condition of the equipment is closely related to the age or the duty that the equipment has sustained;
- Easy to justify when the impact of a failure is high;
- Simple to organise as the resource requirements are known in advance; and
- Opportunity to co-ordinate activities in such a way that the duration of an outage is minimised and the efficiency of the maintenance staff is optimised.

The disadvantages of a TBM strategy include:

- There is a risk that intrusive maintenance may introduce failures;

- Ineffective when the failure rate of the equipment is independent of the age or the duty that the equipment has sustained;
- Equipment may be maintained unnecessarily; and
- Inefficient use of operating budget.

2.2.3 Condition Based Maintenance

CBM is sometimes known as predictive maintenance. It means carrying out preventive actions depending on the condition of the equipment; the condition can be determined through on-line monitoring, visual inspections, carrying out off-line diagnostics at fixed intervals or it can be derived from previous inspection results. The advantages of a CBM strategy include:

- Failures can be predicted in advance thereby avoiding unexpected events and consequential costs;
- Avoidance of damage to public or customer goodwill;
- Potential for reduced maintenance costs;
- Reduction in plant downtime;
- Efficient maintenance regimes can be adopted – just in time philosophy – therefore reducing costs and spares holding;
- Improved personnel and environmental safety through avoidance of leakages and explosions;
- Explanation of failure mechanism;
- Potential legal benefits from improved environmental and safety performance;

- Deferred plant refurbishment/upgrade costs due to more information on failure probabilities, defects and weaknesses; and

- Increased component life/availability.

The disadvantages of a CBM strategy include:

- Lack of operational data;

- Potentially difficult to develop due to lack of operational knowledge;

- May be difficult to justify both technically and economically;

- Possibly expensive due to cost of diagnostics equipment, communications infrastructure and training; and

- Any required on-line monitoring may have an adverse effect on the reliability of the plant.

2.2.4 Reliability Centred Maintenance

The earliest view of failure was that it was linked to the age of the equipment. With a growing awareness of infant mortality, the view was modified with the belief being that the failure mechanism of an item of plant now followed the so called bath tub effect. However, with more research and as shown in Figure 2.2, it became apparent this view was still incorrect and that there are actually six failure mechanisms [Moubray, 1997].

Pattern A is the well known bath tub curve, where, as stated previously, the failure rate is high initially due to infant mortality, before it settles down to a constant or slowly increasing rate, before then starting to increase due to wear.

Pattern B starts with a constant or slowly increasing failure rate, before increasing due to wear.

Pattern C shows a slowly increasing failure rate, but does not have a marked increased failure rate due to wear.

Pattern D shows a low failure rate when the equipment is new before rapidly increasing to a constant level.

Pattern E shows a constant failure rate throughout the life of the equipment.

Pattern F shows a high failure rate when the item of plant is new before decreasing to a constant or slowly increasing failure rate.

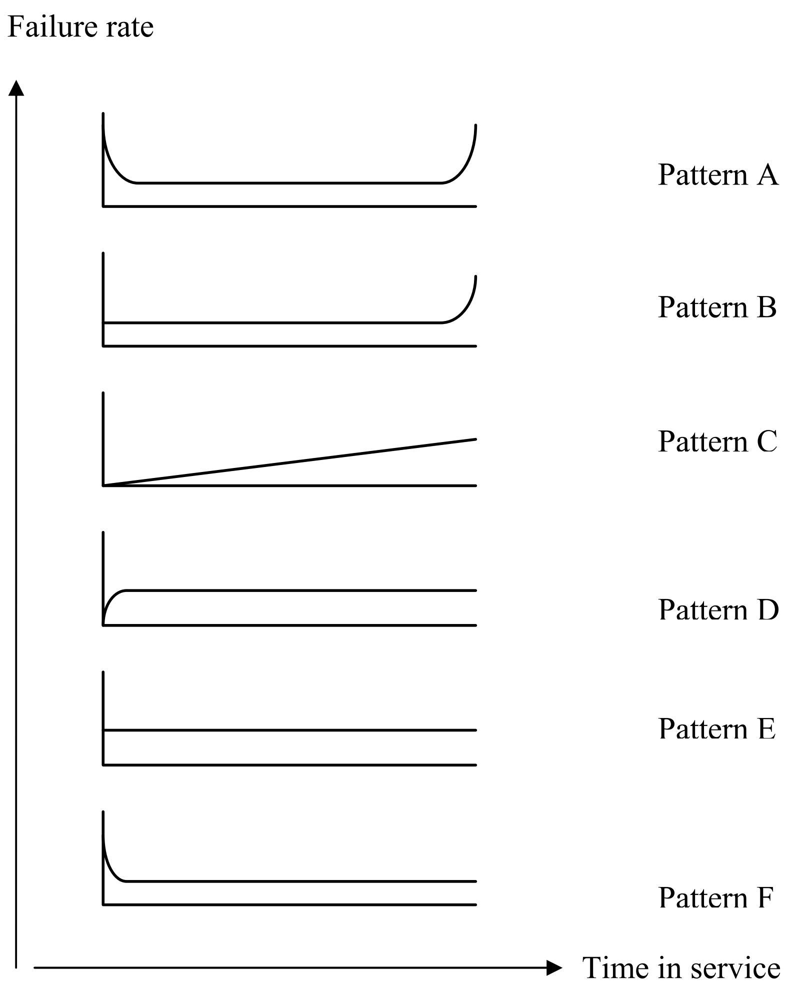


Figure 2.2: Diagram showing different types of equipment failure patterns[2]

2 [Derived from Moubray, 1997].

Research has shown [Moubray, 1997] that for civil aircraft, 4% of components follow pattern A, 2% follow B, 5% follow C, 7% follow D, 14% follow E and 68% follow pattern F. Apart from showing that as plant becomes more complex patterns E and F tend to dominate, the findings also indicate that a great many traditionally-derived maintenance tasks achieve nothing, while some are actually detrimental to the performance of the plant by introducing failures [Cigré, 83, 1994]. On the other hand there are potentially other techniques, such as on-line condition monitoring, which are not currently being employed that may be more effective in reducing failure rates.

As explained previously, these finding led the civil aviation authority to develop MSG-3, or as known outside the industry, RCM. Rather than adopting a common maintenance approach to all components, RCM is more a process that determines what is the most appropriate maintenance policy for each individual component taking into account its operating environment and regime. As [Moubray, 1997] describes it, it is “a process used to determine what must be done to ensure that any physical asset continues to do what its users want it to do in its present operating context”.

Many texts have been written on the subject of RCM [Nowlan et al, 1978; Smith, 1993; and Moubray, 1997] where its principles and procedures have been expressed in different ways. Therefore to ensure RCM is applied correctly and to ensure the overall objective of optimizing maintenance achievements in a systematic way remains the same, it led the American Society of Automotive Engineers (SAE) to publish SAE standard JA1011: “Evaluation Criteria for Reliability-Centered Maintenance (RCM) Processes” [SAE, 1999].

A widely accepted RCM methodology is RCM2 [Moubray, 1997]. Compared to the original version of RCM [Nowlan et al, 1978], the environmental aspects of failures are treated separately when determining the most appropriate maintenance task to reduce the failure probability to within tolerable limits. In Chapter 5, the application of RCM2 will be considered in detail, where it is applied to a modern SF_6 circuit breaker. However, in summary the RCM2 principles and objectives are achieved by addressing seven key questions:

- What are the functions and associated performance standards of the asset in its present operating context?
- In what ways does it fail to fulfil its functions?
- What causes each functional failure?
- What happens when each failure occurs?
- In what way does each failure matter?
- What can be done to predict or prevent each failure?
- What should be done if a suitable proactive task cannot be found?

By answering each of the seven questions, it is possible to identify the failure modes of the equipment, the causes of the failure, the criticality of each failure mode and the corresponding action to prevent the failure modes.

2.3 Maintenance Strategies in the Transmission and Distribution Utility Industry

Traditionally, maintenance of Transmission and Distribution system plant has been carried out at fixed time intervals. An international survey undertaken by Cigré on maintenance policies and trends [Cigré, 152, 2000] reported that 82% of utilities use TBM as a major strategy. Many of the utilities use more than one strategy, but as Figure 2.3 shows, the dominant strategy in use is time based.

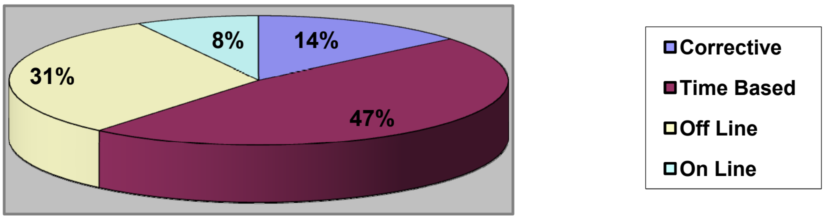


Figure 2.3: Results of a survey showing the maintenance strategies used by transmission and distribution utilities[3]

When the results are split into components, [Cigré, 152, 2000] reports that the maintenance strategy is dependent on the type of equipment. For example, for substation plant (switchgear and transformers), after TBM the second most used strategy is CBM. However, for overhead lines and cables, the second most used strategy is corrective maintenance.

With regard to geographical regions the analysis produces some revealing results and shows that TBM is not the dominant strategy in all areas. In South America, the main strategy is off-line CBM where 60% of utilities record using it compared to 20% for TBM. It is also interesting to note that in Australasia, corrective maintenance is not used and compared to the other regions they have the highest use of on-line CBM, where 25% of the utilities report employing this strategy.

As has been explained previously, TBM is not only costly in terms of manpower, but also reduces plant availability and subsequent system security. In addition, it has been shown that it has little effect in detecting the defects that may cause future failures and it has also been shown that it can introduce failures [Cigré, 83, 1994]. Consequently, it is not surprising that [Cigré, 152, 2000] reports that there is now a trend by utilities to move towards a strategy of using more off-line and on-line diagnostic techniques. Furthermore, the use of these maintenance strategies is reinforced when the most important Key Performance Indicators (KPIs) in determining maintenance strategy are identified by [Cigré, 152, 2000].

[3] Derived from [Cigré, 152, 2000].

More specifically, there is a strong relationship between utilities which use off-line CBM and finance as the most important KPI. Namely, they are only incurring maintenance expenditure when necessary. Similarly, there is a strong relationship between utilities where availability is the most important KPI and utilities that use on-line CBM, as on-line condition monitoring has the perceived advantage of improving availability. However, as shown in Chapter 4, utilities must be cautious when making this assumption.

2.4 Transmission Circuit Breaker Maintenance

Circuit breakers are commonplace in a modern power system, where they are used to make and break current from a few amps to many thousands of amps. They are vital components and their high reliability is essential to the successful generation, transmission and distribution of power. At voltages greater than 72.5kV, circuit breakers can be broadly classified into four types [Cigré, 165, 2000]; Air Blast, minimum oil, Bulk Oil and SF_6. Each type of circuit breaker includes one or a series of interrupting chambers that contain fixed and moving contacts to make and break the current. The moving contacts in turn are operated by a mechanism, which as described in section 2.4.5 can be powered pneumatically, hydraulically or by a spring. To initiate the operating mechanism, a control circuit is employed to energise an opening (trip) coil or closing coil, which depending on the type of mechanism either channels air or hydraulic fluid into a piston or in the case of a spring type mechanism de-latches it.

As described previously, the majority of utilities still employ a TBM strategy for substation plant and when circuit breakers are considered in isolation, another survey undertaken by [Cigré, 165, 2000] and as outlined in Figure 2.4 came to the same conclusion, where half the utilities involved in the survey reported that they use a TBM strategy. However, encouragingly, the use of CBM was a close second.

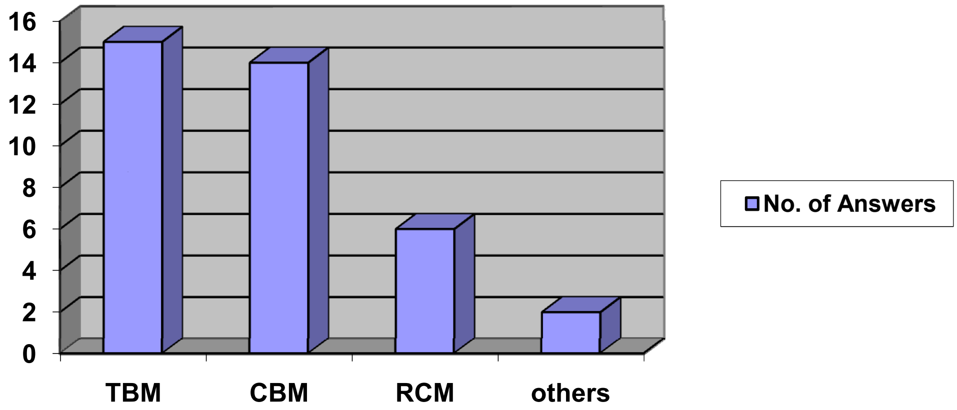


Figure 2.4: Results of a survey showing maintenance methods currently employed for circuit breakers[4]

Before examining what is involved in a typical TBM strategy for a circuit breaker and the experience so far in moving to a condition based or RCM regime, it is essential to first understand the design features of each type of circuit breaker along with the various types of operating mechanisms and control circuits.

2.4.1 Bulk Oil Circuit Breakers

Oil circuit breakers are one of the oldest types of circuit breakers, where the term “bulk oil” signifies that the interruption process takes place in a large tank of oil. In addition to acting as an interruption medium, the oil also acts as an insulating medium.

Most bulk oil circuit breakers consist of two breaks (interrupters) per phase, although at 275kV it is not unusual to employ four breaks per phase. A schematic of a 132kV bulk oil circuit breaker is shown in Figure 2.5 and a more detailed description can be found in [Flurscheim, 1982 and Lythall, 1972]. In summary, there are two sets of contacts per phase, where the lower and moving contacts are usually cylindrical copper rods that make contact with the upper fixed contacts. The fixed contacts consist of spring loaded copper segments, which exert pressure on the lower contact rod when closed to form a good electrical contact. On opening, the lower

[4] Derived from [Cigré, 165, 2000].

contacts move rapidly downwards and draw an arc. When the circuit breaker opens under fault conditions many thousands of amps pass through the contacts. Effective opening is only possible as the instantaneous voltage and current per phase reduces to zero during each alternating current cycle. The arc heat causes the evolution of a hydrogen bubble in the oil and this high pressure gas pushes the arc against special vents in a device surrounding the contacts called a turbulator. As the lowest contact moves downwards, the arc stretches, and is cooled and distorted by the gas causing it to eventually break. The gas also sweeps the arc products from the gap so that the arc does not re-ignite when the voltage rises to its full open circuit value.

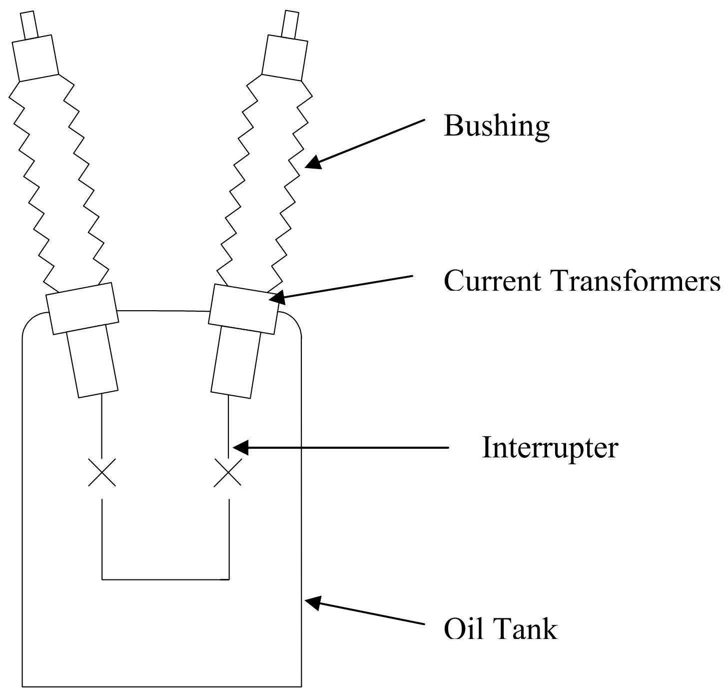


Figure 2.5: Schematic showing a single phase of a High Voltage (HV) bulk oil circuit breaker

2.4.2 Minimum or Small Oil Circuit Breakers

The minimum or small oil circuit breaker, as shown in Figure 2.6, has the circuit breaking unit for each phase located on top of a support column [Lythall, 1972]. Unlike the bulk oil version, the circuit breaker oil is normally confined to the upper circuit breaking chamber.

As described in detail in [Lythall, 1972], the arc control device is built up of fibre plates shaped and arranged to form a series of throats and radial vents. The plates are located by fibre glass spacers and are held in compression in an outer glass-fibre cylinder between a throat washer at the base and the upper fixed contact bracket. A ball valve at the top of the device allows rapid displacement of the residual gases by clean oil after the arc is extinguished.

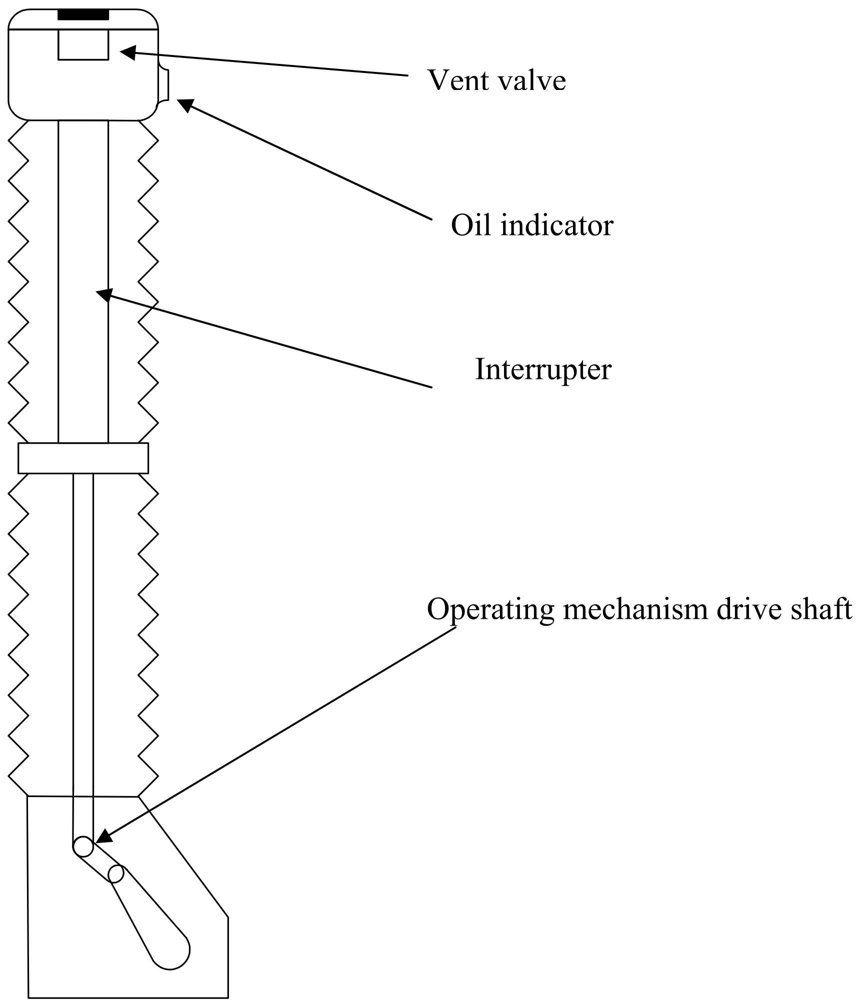


Figure 2.6: Sectional view of one pole of a minimum or small oil circuit breaker

2.4.3 Air Blast Circuit Breakers

Until the advent of the SF_6 type circuit breaker, the Air Blast Circuit Breaker (ABCB) was the most common type of circuit breaker on the 275kV and 400kV transmission system within the UK.

An essential requirement for ABCBs is a supply of compressed air. A typical system is shown in Figure 2.7 and is described in [Lythall, 1972]. Air is compressed to a pressure of 3000 pounds per square inch (psi) and passed through a filter and dryer to a storage receiver. It is then reduced in pressure to typically 400 psi, where it finally passes in to the air ring system through non-return valves. The compression and storage system is automatic and is initiated through pressure control gauges.

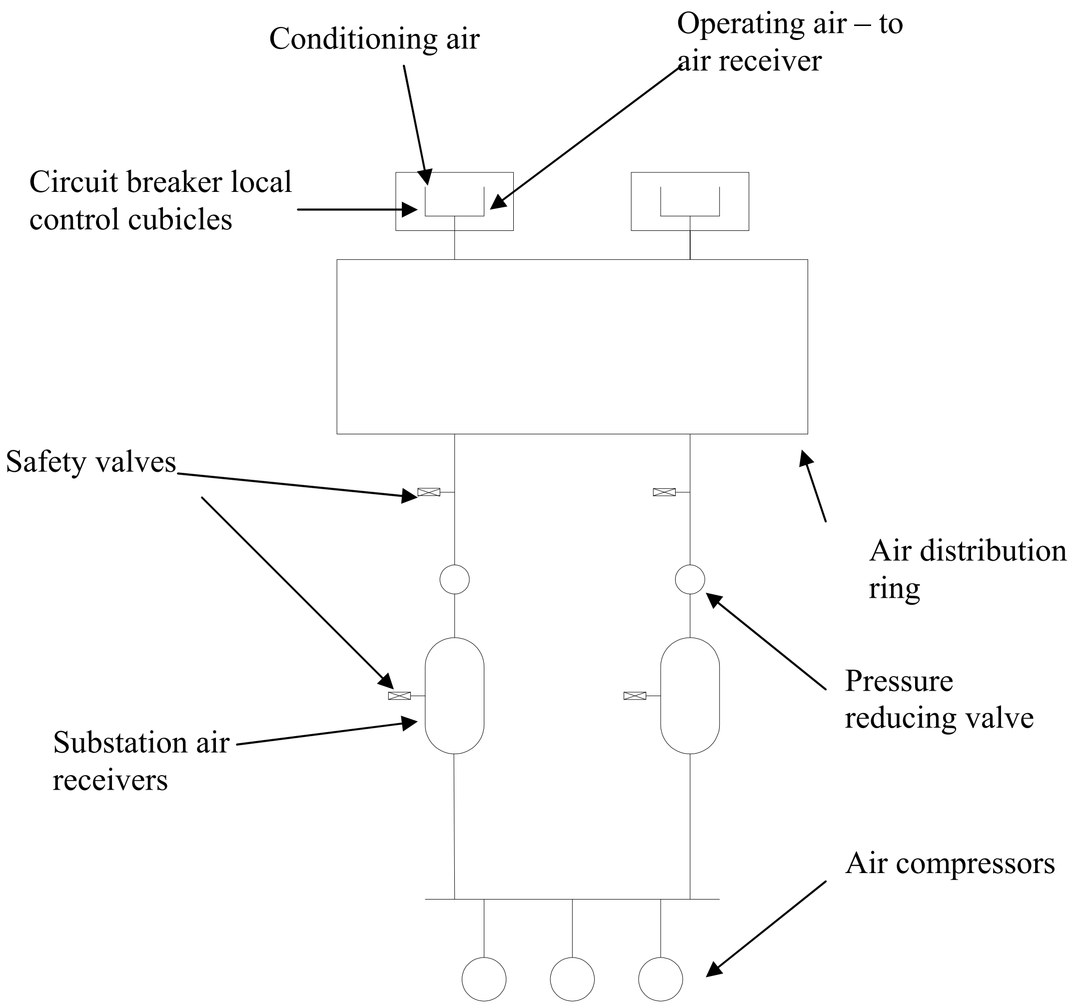


Figure 2.7: Schematic showing a typical ABCB compressed air system

The ABCB design may be categorised as either a non-pressurised head design or a pressurised head design.

Non-Pressurised Head

A schematic diagram of this design of ABCB is shown in Figure 2.8. In this design [Lythall, 1972], when the circuit breaker opens, via blast valves, the interrupters are subject to a blast of high pressure air. Immediately afterwards, the integral series connected sequence disconnector/isolator (isomaker) is opened thus allowing the main contacts and blast valves to close, and therefore return the interrupter heads to normal atmospheric pressure. During the closing sequence, the operation only involves the disconnector closing.

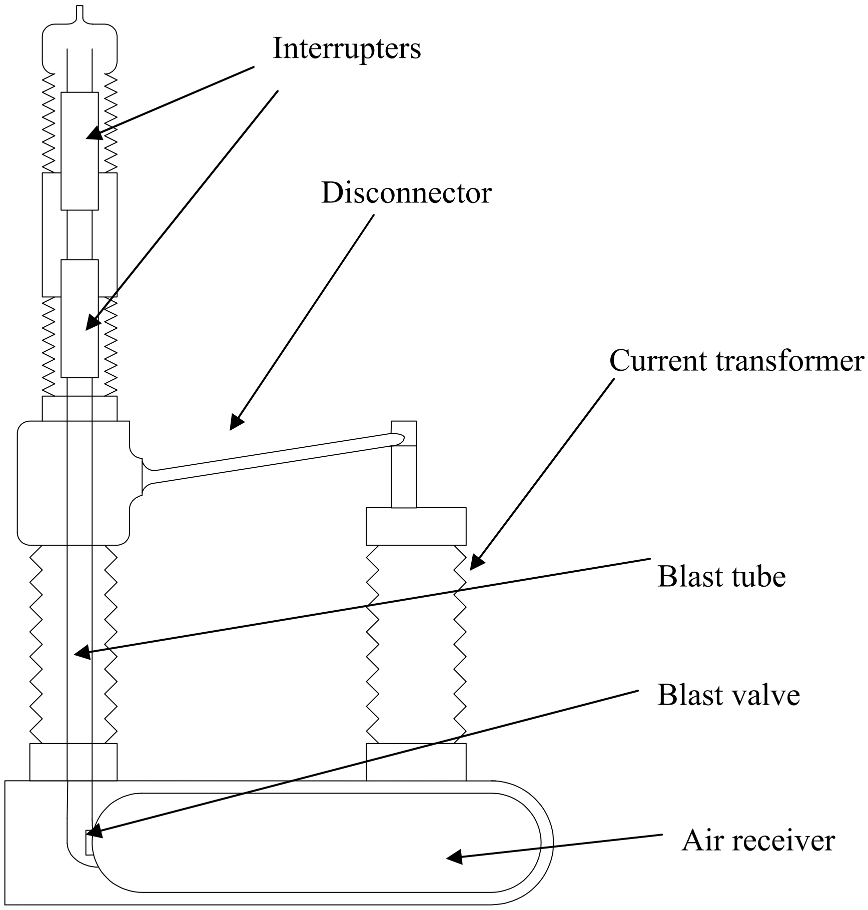


Figure 2.8: Schematic showing an ABCB non-pressurized head design

Fully Pressurised Head

In this design, the interrupter is permanently pressurised from the air receiver and this air also acts as an insulating medium. When the main contacts part, as shown in Figure 2.9, the blast valves open to release high pressure air to atmosphere, which creates a flow through the arcing region to extinguish the arc. The blast valves remains open for a sufficient period to allow interruption to take place and when they close, the interrupter heads are re-pressurised to full pressure with the main contacts normally remaining open. With the air having the dielectric strength to withstand the voltage across the interrupter gap, this design avoids the need for an integral disconnector.

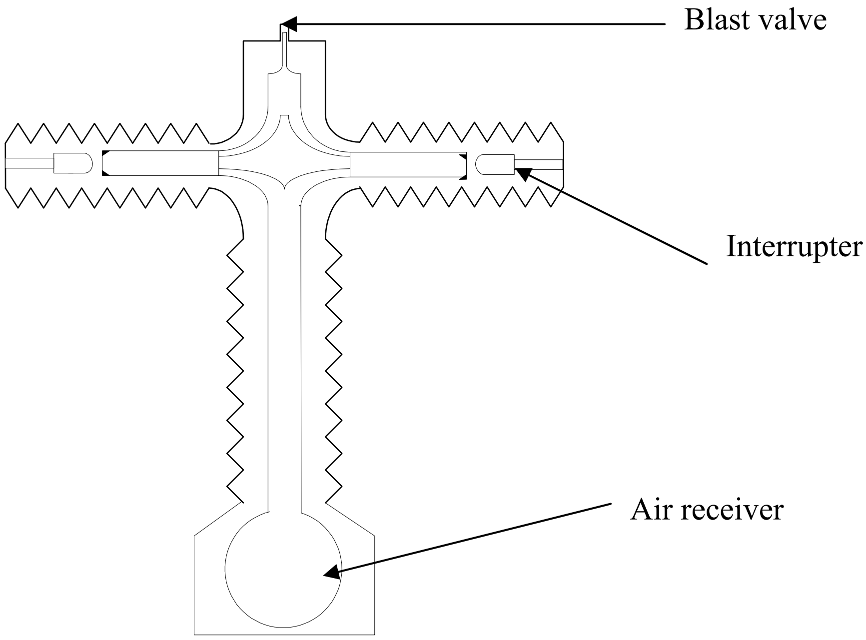


Figure 2.9: Schematic showing an ABCB fully pressurized head design

2.4.4 SF_6 Circuit Breakers

The SF_6 circuit breaker is often referred to as a Gas Circuit Breaker (GCB). Nowadays, at 72.5kV and above the majority of new circuit breakers use SF_6 gas. The advantages of using SF_6 as an insulating medium in circuit breakers arise from its high electric strength and outstanding arc quenching characteristics. SF_6 circuit breakers are much smaller than ABCBs of the same rating, the dielectric strength of SF_6 at atmospheric pressure being approximately equal to that of air at the pressure of 10 atmospheres (atm). Apart from their low capital cost, one of the main advantages when compared to bulk oil and air blast circuit breakers is that the interrupters require minimal maintenance.

Excluding the type of operating mechanism and the control circuit, within the group of SF_6 circuit breakers there are a number of divisions in design. A major division identifier relates to the insulation area, in this case the gas enclosed volume or gas-zone. Namely, it can be sub-divided into:

- Gas Insulated Switchgear (GIS) including the dead-tank and open-terminal variants; and
- Air Insulated Switchgear (AIS) or sometimes known as 'live tank' circuit breakers (porcelain-enclosed).

Similarly the type of interrupter can be used to classify an SF_6 circuit breaker. Namely, it can be sub-divided into:

- Double Pressure System;
- Single Pressure 'Puffer' Interrupter; and
- Single Pressure 'Self Blast or Auto Puffer' Interrupter.

2.4.4.1 Gas Insulated or Dead tank type circuit breakers

In gas insulated circuit breakers the interrupters are housed in an earthed metal tank, usually manufactured from aluminium, mild or stainless steel. The design can either be used in open terminal, air insulated type substations (Figure 2.10) or gas insulated installations (Figure 2.11), where all components, such as busbars, disconnectors, instrument transformers, cable terminations and joints are contained in earthed enclosures filled with SF_6 gas.

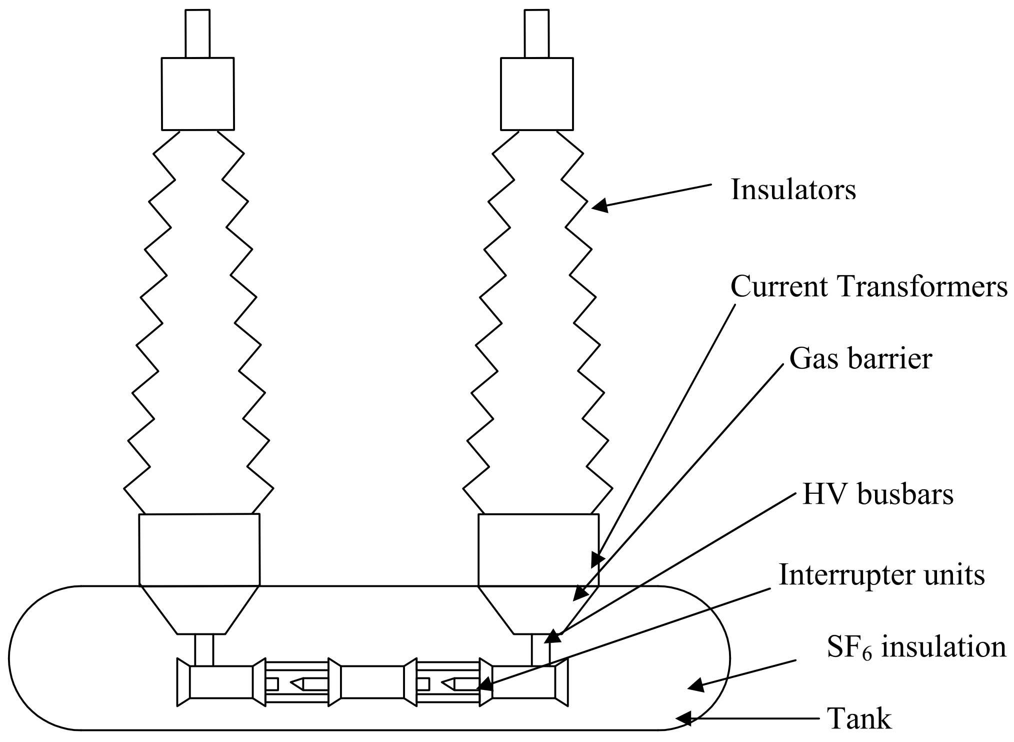


Figure 2.10: Schematic showing a single phase of an SF_6 dead tank circuit breaker

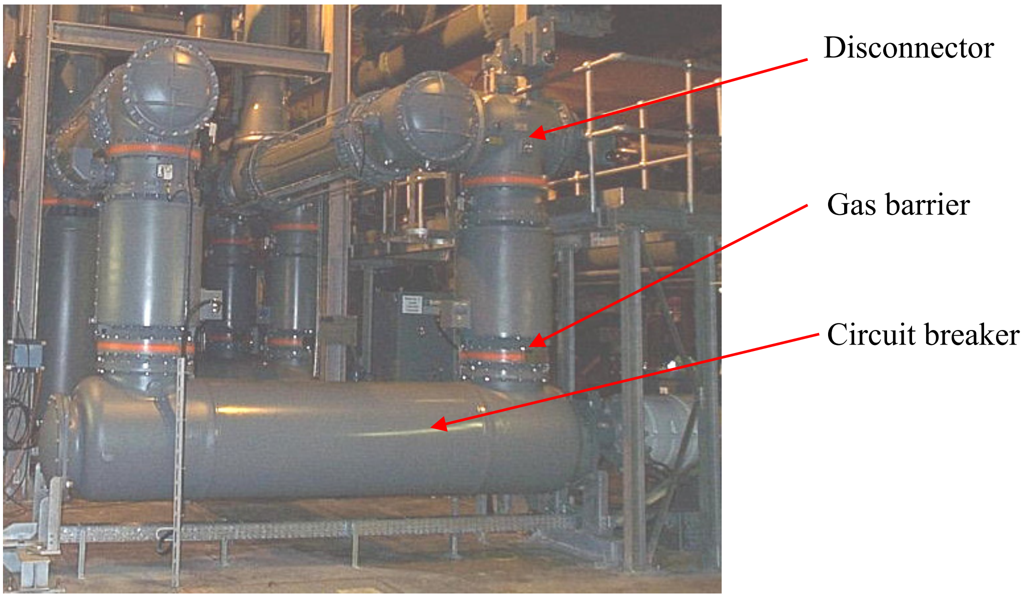


Figure 2.11: Photograph showing an SF_6 gas insulated circuit breaker

2.4.4.2 Air Insulated or Live Tank Circuit Breakers

In live tank circuit breakers the SF_6 interrupters, as shown in Figure 2.12, are housed in porcelain insulators, which in turn are mounted on support insulators on top of a steel or aluminium structure to conform to safety distances [Flurscheim, 1982]. Namely, the interrupter heads are live and rely on air between them and the ground as insulation.

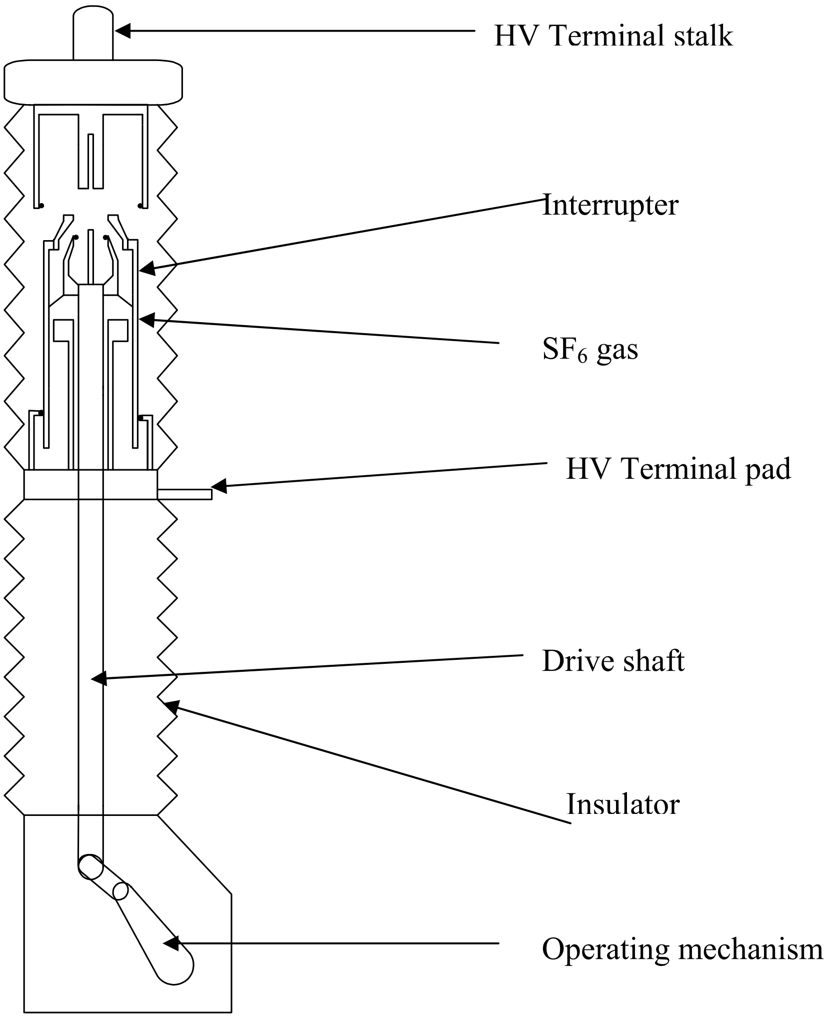


Figure 2.12: Schematic showing a single phase of an SF_6 air insulated or live tank circuit breaker

2.4.4.3 Double Pressure SF_6 Circuit Breakers

The early designs of SF_6 circuit breakers employed a double pressure system in which high pressure gas at 14 to 18 bars, stored in a separate tank, is released into the arcing zone to cool the arc and build up the dielectric strength of the contact gap after arc extinction. The design is similar in principle to the ABCB, the main difference being that the high pressure SF_6 gas is not released to atmosphere but instead is collected in a low pressure chamber, which in turn is compressed before returning to the high pressure tank. A more detailed description can be found in [Lythall, 1972] and a schematic diagram illustrating the operation is shown in Figure 2.13.

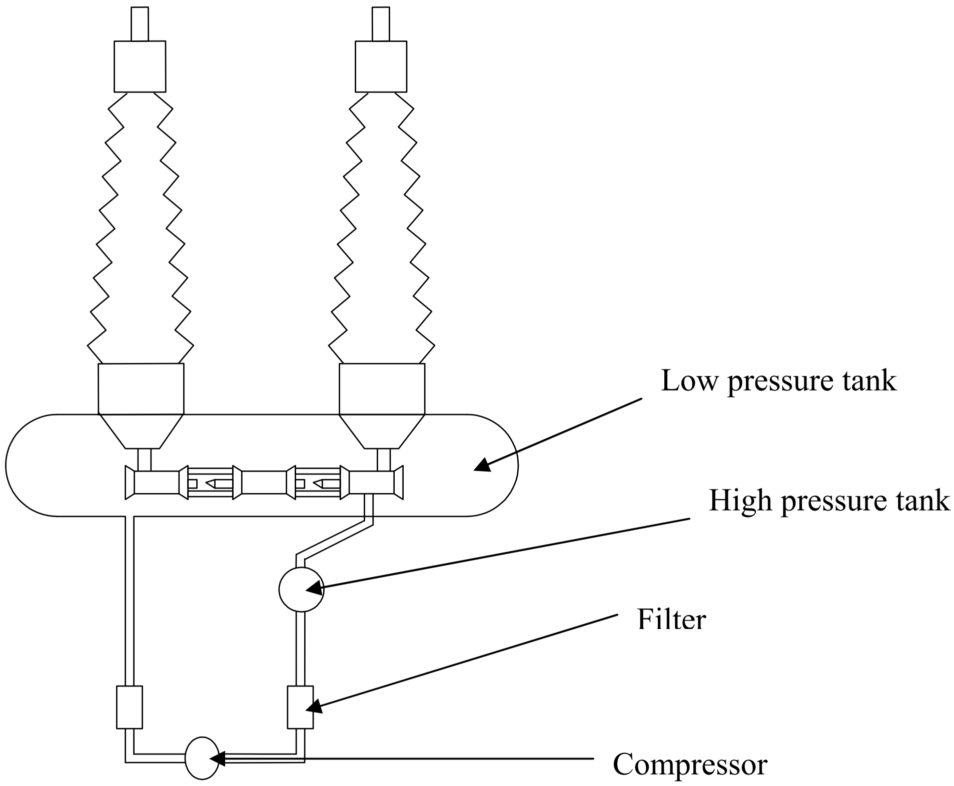


Figure 2.13: Schematic showing a double pressure SF_6 circuit breaker

2.4.4.4 Single Pressure ‘Puffer’ Type SF_6 Circuit Breakers

The next development in SF_6 circuit breakers was the emergence of the single pressure type, sometimes known as the ‘puffer’ type [Maller et al, 1981]. Instead of the conventional two pressure system having a closed gas circuit for arc quenching, the puffer type circuit breakers employ a single pressure system. Compared to the double pressure type, it is a far simpler design as it employs 40% fewer components [Maller et al, 1981] and thus requires less maintenance.

The single pressure or puffer type technique is illustrated in Figure 2.14. Figure 2.14a shows the circuit breaker in the closed position, with the current flowing through the fixed contact, the blast cylinder, the moving contact carrier, the contact rod and the arcing contact fingers.

In Figure 2.14b when the circuit breaker starts to open, the blast cylinder moves away from the fixed contact, allowing the current to flow through the contact rod, arcing fingers and the moving contact carrier. As the blast cylinder and blast piston move towards each other the compression space is reduced, and due to the opening of the nozzle being blocked by the contact rod, the result is that the gas is compressed.

In Figure 2.14c when the arcing contact fingers leave the contact rod, an arc is drawn between them. However, as the contact rod no longer blocks the opening of the nozzle, the compressed gas is directed through the nozzle to extinguish the arc.

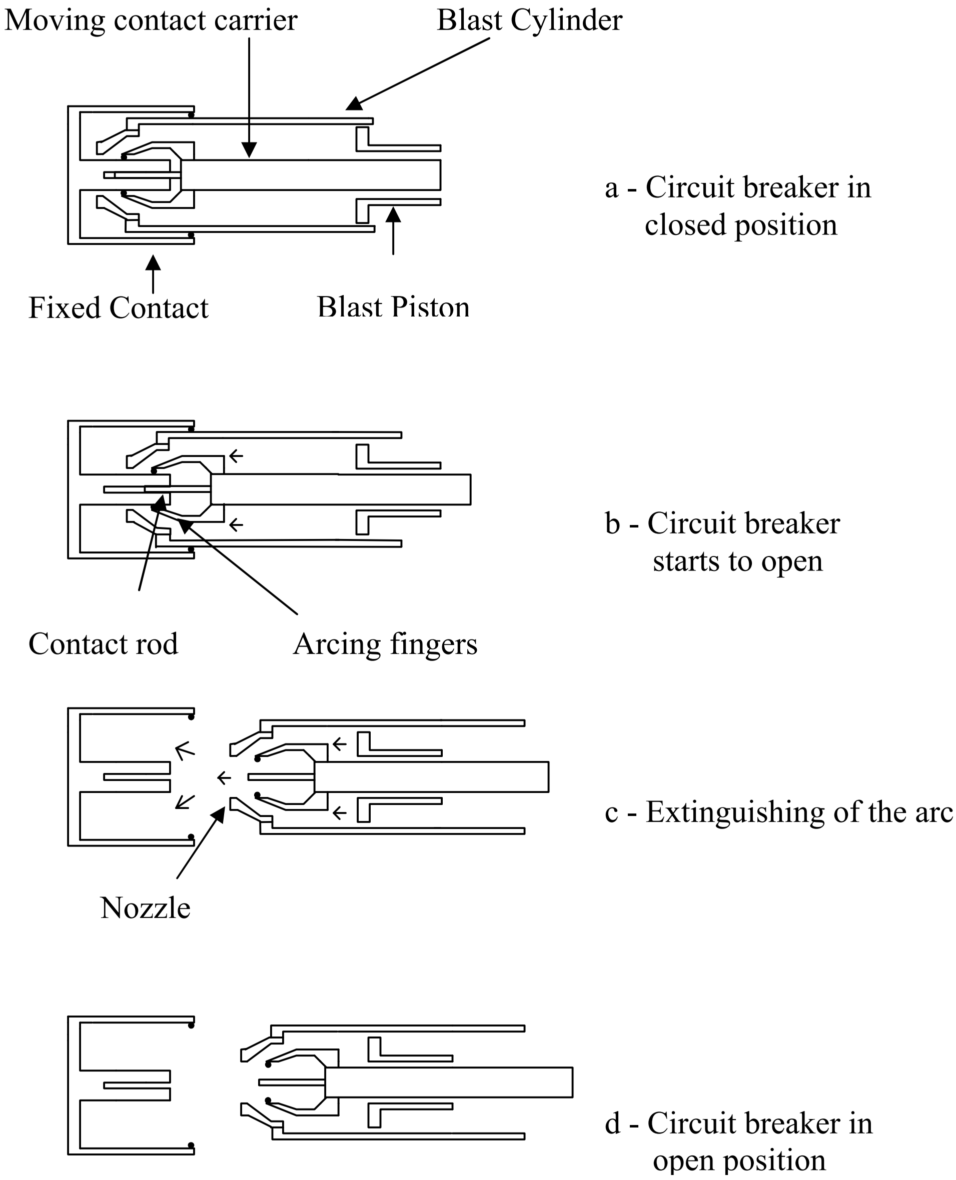


Figure 2.14: Diagram showing the single pressure 'puffer' interruption technique

The technique illustrated in Figure 2.14 is known as the 'monoflow' system, where as shown in Figure 2.15, the gas flow is unidirectional from the piston chamber. However, there are other forms of puffer interrupters [Ryan, 1994], which are categorised according to the flow of compressed SF_6 gas. Namely, as shown in Figure 2.15, the duo-flow principle, whereby the compressed gas flows in opposing directions and in the partial duo blast interrupter, whereby the main flow is through the nozzle, whilst subsidiary flows occur through both contacts, which are hollow.

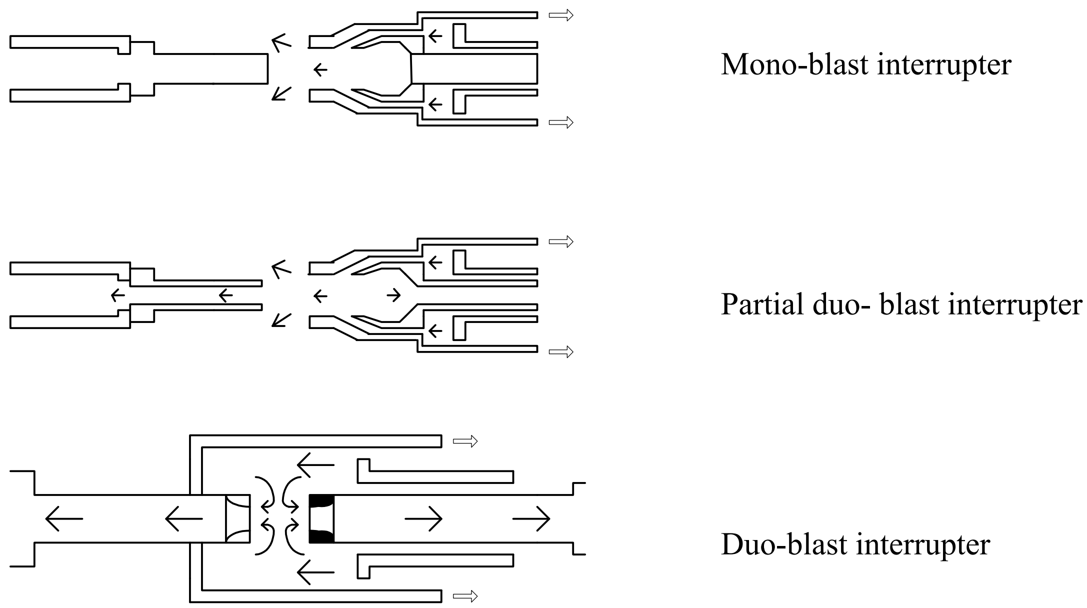


Figure 2.15: Diagram showing different categories of SF_6 puffer interrupters

2.4.4.5 Self Blast or Auto Puffer Interrupters

A further evolution of the puffer principle, with the objective of achieving the same operating performance, but using less operating energy, was the development of the self blast or auto puffer type interrupter [Ryan, 1994].

As with the piston operated puffer method, when currents are small the pressure required to flow through the nozzle and extinguish the arc is created during the opening movement by compressing the gas in the blast cylinder. However, as shown in Figure 2.16, the interrupter is modified by dividing it into two spaces to create an auxiliary puffer chamber and the main pressure chamber. During the interruption of short circuit currents, the resultant arc raises the pressure of the auxiliary puffer chamber and as the contact rod unblocks the opening of the nozzle, the compressed gas in directed onto the arc to extinguish it. This increased pressure does not impose any additional stress on the mechanism, with the result that 20% less operating energy is required compared to a puffer type interrupter [Ryan, 1994].

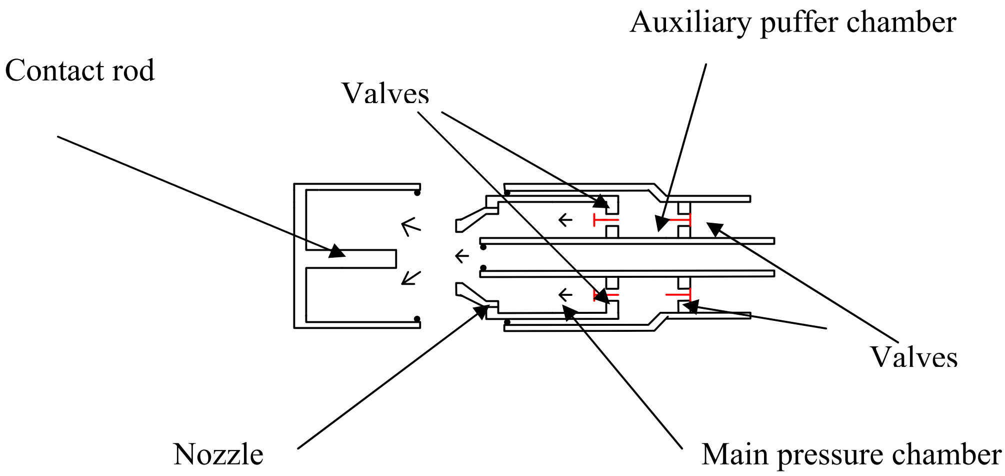


Figure 2.16: Diagram showing the self blast or auto puffer interrupter principle of operation

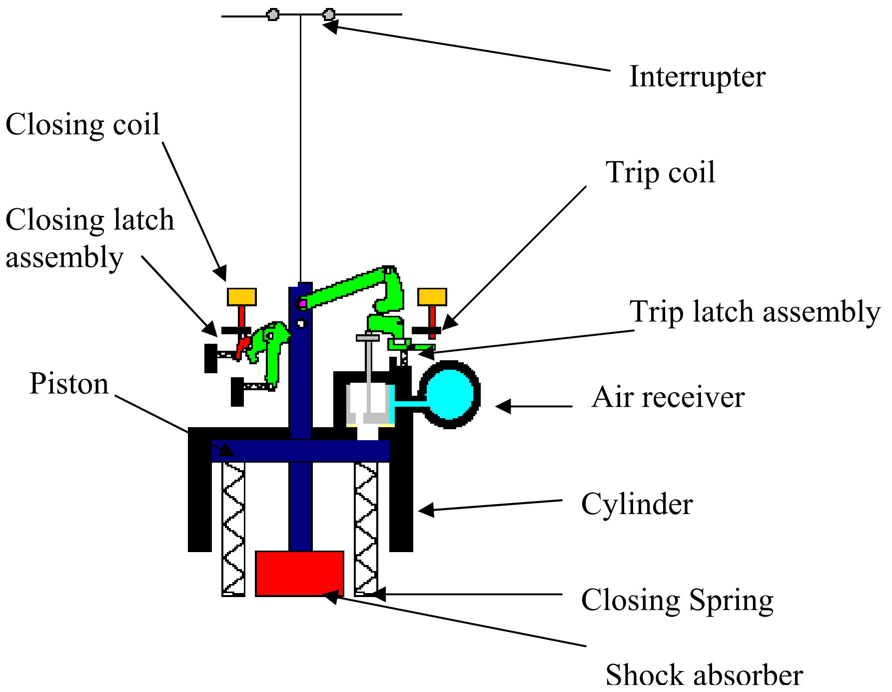
2.4.5 Circuit Breaker Operating Mechanisms

The purpose of the circuit breaker operating mechanism is to transmit stored energy via a mechanical drive to open and close the moving contacts. It is required to operate when requested and within the specified operating times and speeds. The operating mechanism also drives the auxiliary and position indicating switches that are required for the associated control and protection systems.

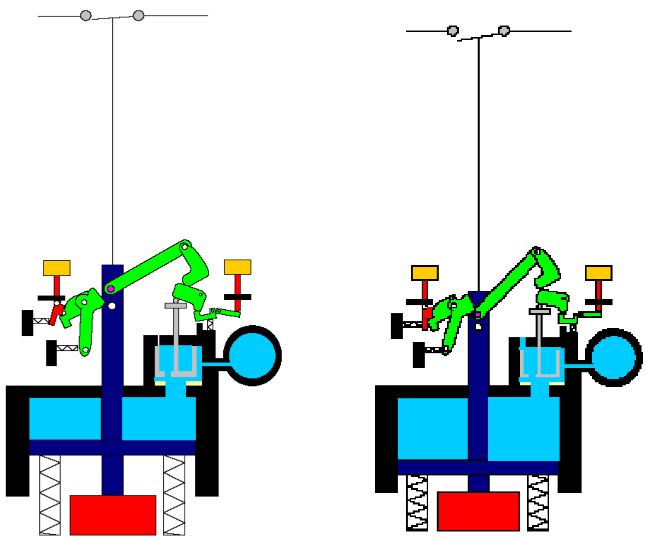
Operating mechanisms can be split into three main categories. Namely:

2.4.5.1 Pneumatic Operating Mechanism

The pneumatic mechanism employs compressed air, which is stored in a receiver mounted directly on the circuit breaker. As described in [Xian, 2003] and shown in Figure 2.17, solenoid valves allow compressed air to pass to the actuator cylinder to open the circuit breaker. At the end of the opening sequence, the air is vented to atmosphere, leaving the circuit breaker in a position whereby it can be closed via the force of the closing spring; the closing sequence being initiated by energising the closing coil, which in turn releases the holding latch.



a) Mechanism in closed position



b) Mechanism opening c) Mechanism in open position

Figure 2.17: Diagram showing the operating principle of a pneumatic type mechanism[5]

[5] Derived from [Xian, 2003].

2.4.5.2 Hydraulic Operating Mechanism

As shown in Figure 2.18, the hydraulic mechanism has a nitrogen accumulator for storing the required energy. A cushion of compressed nitrogen exerts pressure on the hydraulic oil, which in turn actuates the contacts via a hydraulic piston. The system works on the differential piston system. The open (piston rod) side is smaller than the closed (piston face) side by the cross sectional area of the piston rod. The piston rod side is permanently under system pressure. The piston face side on the other hand is subjected to system pressure on closing and relieved on opening. The system is recharged by a motor driven hydraulic pump, which transfers oil from the low pressure volume to the nitrogen storage unit.

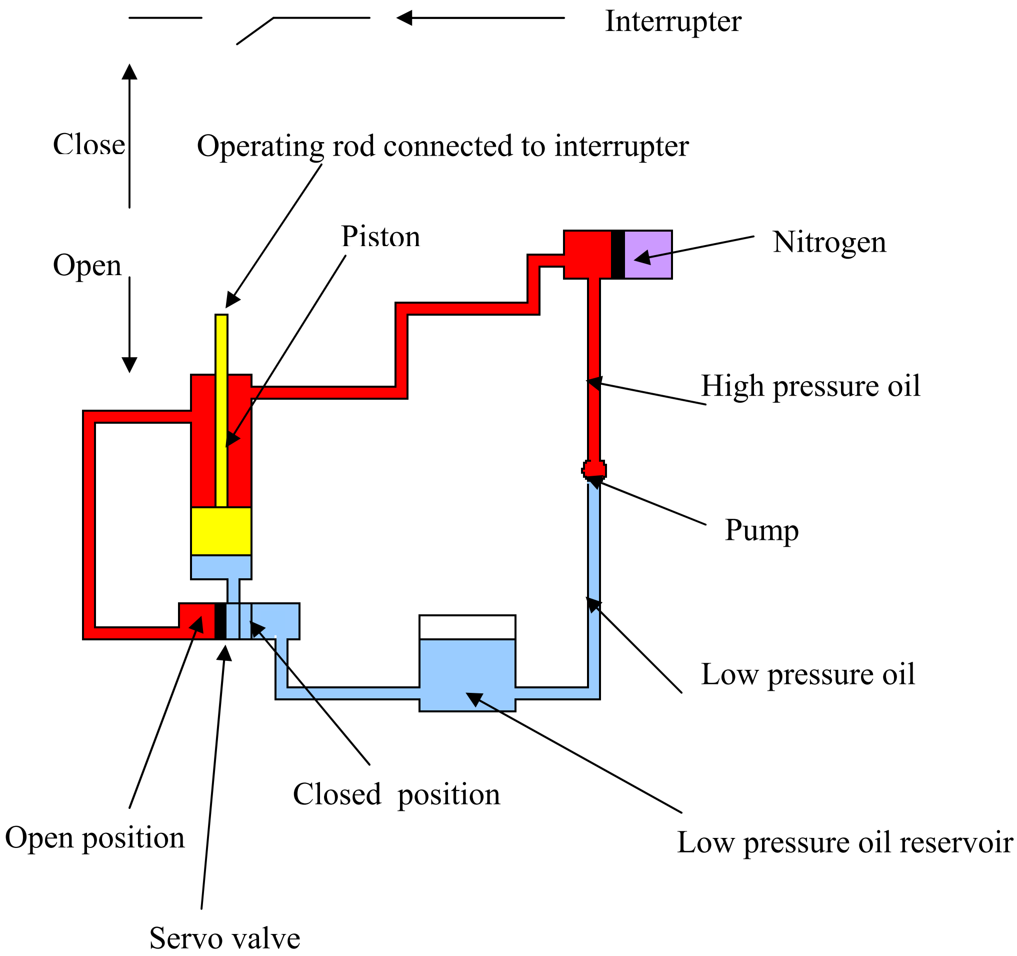
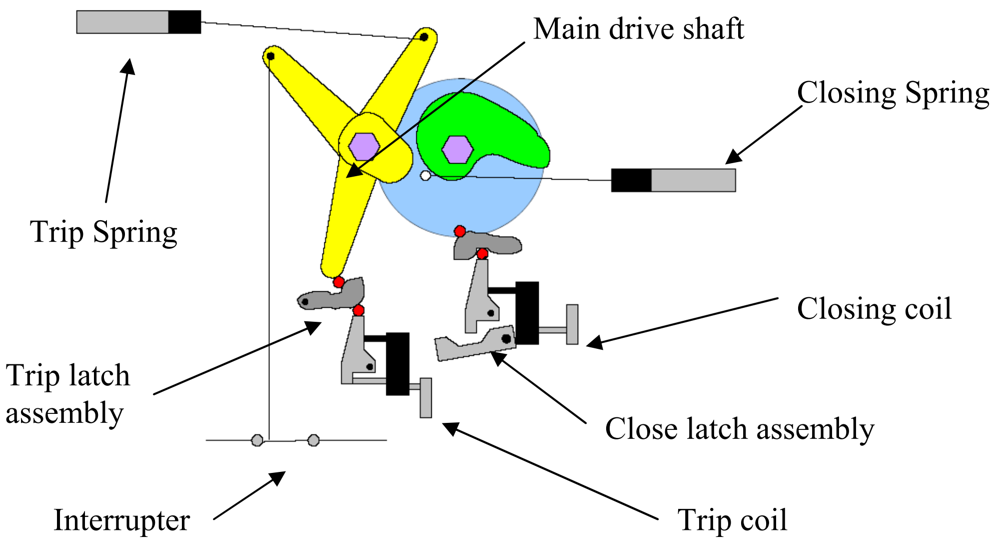


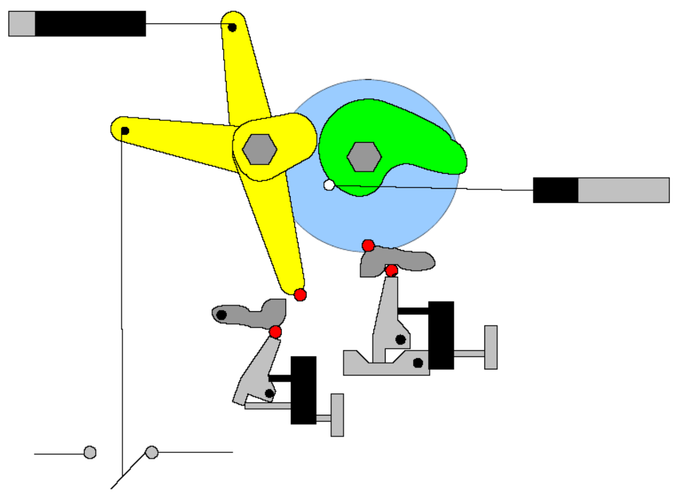
Figure 2.18: Diagram showing the operating principle of a hydraulic type mechanism

2.4.5.3 Spring Powered Operating Mechanism

As described by its title, the spring operated mechanism uses a spring to store the required energy. It is described in more detail in Chapter 6, but in summary a spring is tensioned via an electric motor. It is held, in tension, by a latch assembly, which when the circuit breaker is requested to operate, is released by a solenoid thus allowing the mechanical energy to be transmitted to the moving contacts via the drive shaft. The basic construction is described in [Xian, 2003] and shown in Figure 2.19.



a) Closed Position



b) Open position

Figure 2.19: Diagram showing the operating principle of a spring type mechanism

2.4.5.4 Choice of operating mechanism

The type of circuit breaker and the manufacturers' preference dictates the choice of particular drive mechanism. For bulk oil circuit breakers, the tendency is to use a spring mechanism for lower voltages and a pneumatic system for higher voltage [Harker, 1998]. For obvious reasons, ABCBs will employ pneumatic mechanisms.

With regard to SF_6 circuit breakers, the early designs predominately employed pneumatic mechanisms [Ryan, 1989]. However, the preference is now to use spring mechanisms, although it should be noted that at Extra High Voltage (EHV), hydraulic mechanisms are normally employed for the puffer type interrupters [Ryan, 1989], as they require 20% more energy than the self blast type [Ryan, 1994]. In general spring mechanisms are more reliable than hydraulic and pneumatic systems [Cigré, 83, 1994,] as they offer a secure storage of mechanical energy, accurate and consistent movement, and obviate the need for valves, gaskets and leakage precautions.

2.4.6 Circuit Breaker Control Circuits

The circuit breaker operating mechanism is initiated via an external command, which may be either an operator request or a protection system. This external request is received by the circuit breaker control circuit, which ensures the circuit breaker responds correctly and safely. It includes operating facilities such as operating coils as well as monitoring facilities such as condition and position indication [Cigré, 259, 2004].

This electrical control circuit can either be:

- The conventional electro-mechanical relay and coil type or
- Partially solid state with electronics, transducers and digital indication.

2.4.7 Typical Time Based Maintenance Schedule

As explained previously, maintenance of transmission plant and in particular circuit breakers has been carried out at fixed time intervals, where the actual frequency and content of maintenance is very much dependent on the manufacturers' recommendations. However, it is not uncommon for some utilities to make some relatively modest extensions to the time intervals between maintenance schedules.

The maintenance regime will be specific to the type and category of circuit breaker, but will generally consist of the following tasks:

- Inspection, cleaning and lubricating;
- Replacement of parts, such as seals;
- Operating mechanism checks, such as extent of travel;
- Contact resistance checks to ascertain contact wear;
- Checks on the interrupting and insulating mediums, such as insulation resistance tests;
- Timing tests; and
- Operational tests.

Maintenance that is specific to the type of circuit breaker is described as follows:

2.4.7.1 Oil Circuit Breaker Maintenance

For oil circuit breakers, a sample of oil is normally taken from each tank and bushing to check for contamination and dielectric strength. It is also normal to carry out an internal inspection of the tanks and interrupters.

A typical maintenance schedule for a 275kV bulk oil circuit breaker is shown in Table 2.1 [SP, 1995].

Table 2.1: Typical Maintenance Schedule for a 275kV Bulk Oil Circuit Breaker

No.	Component	Recommended Frequency	Remarks
1	Operational Tests	Annual	
2	Oil Tests		
2.1	Resistivity	2 years	or at 125 operations
2.2	Electric Strength	2 years	or at 125 operations
2.3	Check moisture after refill	4 years	
3	Mechanism	4 years	or at 125 operations
4	Ductor tests	2 years	
5	Air receiver inspection	2 years or 6 years	
6	Gauges, pressure switches - inspection	2 years	
7	Internal Inspection of tanks: Interrupters	4 years	or at 250 operations
8	Bushing tests	4 years	Insulation Resistance Test
9	Bushing oil tests		
9.1	Top cap oil	4 years	
9.2	Bushing main oil		Dependent on condition of top cap oil
10	Timing tests		
10.1	Trip latch circuits	4 years	or at 250 operations
10.2	Check circuit breaker tripping time and record	4 years	or at 250 operations
11	Rewirable fuses	6 years	
12	Safety valve: strip and test (local air receiver)	2 years	
13	Non return valve		
13.1	Test	2 years	
13.2	Strip	6 years	
14	Air stop valves operational check	2 years	

2.4.7.2 Air Blast Circuit Breaker Maintenance

TBM of ABCBs is usually much more involved than oil circuit breakers and involves dismantling interrupters to check components such as blast valves. In addition, the dryness of the air is checked and it is normal to check the calibration of all pressure switches.

A typical maintenance schedule for a 275kV ABCB (non- pressurised head type) is shown in Table 2.2 [SP, 1995].

Table 2.2: Typical Maintenance Schedule for a 275kV ABCB (Non-pressurised head type)

No.	Component	Recommended Frequency	Remarks
1	Operational tests	Annual	
2	Mechanism checks	2 years	
3	Timing tests and air consumption test	2 years	
4	Ductor tests	2 years	
5	Gauges, pressure switches - comparison	2 years	
6	Air receiver inspection	2 years	
7	Interrupters	6 years	
8	Mechanism major maintenance	6 years	
9	Air stop valves operational check	2 years	
10	Blast Valves	12 years	or 2000 operations
11	Non return valves		
11.1	Test	2 years	
11.2	Strip	6 years	
12	Rewirable fuses	6 years	

2.4.7.3 SF_6 Circuit Breaker Maintenance

Routine maintenance is usually recommended to check on the SF_6 dew point, acidity and oxygen content. Most manufacturers also recommend that the interrupters are inspected mid life or after a pre-determined number of fault operations.

A typical maintenance schedule for a 275kV single pressure (puffer type with hydraulic mechanism) circuit breaker is shown in Table 2.3 [SP, 1995].

Table 2.3: Typical Maintenance Schedule for a 275kV SF_6 Circuit Breaker (puffer type with hydraulic mechanism)

No.	Component	Recommended Frequency
1	Operational tests	Annual
2	SF_6 gas check	2-3 years
3	Hydraulic system	
3.1	Hydraulic system operational checks	2-3 years
3.2	Hydraulic oil moisture test	6 years
3.3	Hydraulic system oil change	12 years
4	Timing tests	2-3 years
5	Ductor tests	2-3 years
6	Pump motor	2-3 years
7	SF_6 and oil system	2-3 years
8	SF_6 filling and overpressure valve	6 years
9	Interrupter unit	12-20 years
10	Capacitors	6 years

2.4.8 Experience with Condition Based Maintenance

In the current climate of de-regulation and with increasing system pressures and constraints, there is a strong incentive for utilities to improve plant availability and reliability, whilst at the same time reducing their overall maintenance costs and ensuring safety performance is not compromised. Consequently, some utilities have been investigating the use of plant diagnostics to move from a TBM regime to a CBM philosophy. CBM can involve the use of off-line diagnostic techniques, where plant is taken out of service in order to carry out the diagnostic checks or it can mean on-line techniques, such as condition monitoring, where the plant is continually monitored in service. In some cases, the CBM strategy may involve using both off-line and on-line methods.

There is an argument that the overall life cycle costs of a circuit breaker will not be reduced by CBM, as the manufacturers' maintenance recommendations will still need to be carried out. However, as [Pryor et al, 1999] states, it is utilities that have the operational experience and consequently some of the manufacturers' recommendations may not be required. However, this operational knowledge base needs to be harnessed and used to review existing maintenance practices to examine the feasibility of moving to a CBM strategy.

2.4.8.1 The Technical Feasibility of Applying Condition Based Maintenance to EHV Circuit Breakers

The process of developing a CBM strategy, in particular an off-line approach, can be illustrated by examining the experience of ScottishPower [Pryor et al, 1999], who until 1995 used a TBM philosophy for all types of switchgear; up until that time the actual frequency and content of the maintenance was very much dependent on the manufacturers' recommendations. However, some relatively modest extensions of the time intervals had taken place over the previous twenty years.

With the increasing availability of diagnostic monitoring techniques, a decision was made to fully review the maintenance practices for transmission circuit breakers. The investigation [ITOMS, 1999] considered the current philosophy of maintenance at that time and examined the changes that could be implemented to reduce the incidence of routine intrusive maintenance, whilst maintaining the reliability of the system. In particular, it was tasked with producing detailed proposals for the content and frequency of the maintenance, taking account of the availability of off-line diagnostic techniques, plant type, climatic conditions, operating regime, performance history and known types of defects. Unfortunately, the study could not be extended to on-line condition monitoring, as the commercial availability of these systems was extremely limited at that time.

Overall, it was found that circuit breakers were in general being over-maintained and it was concluded that, in line with the Cigré study [Cigré, 83, 1994], it was unlikely that the existing policy of time based intrusive maintenance would uncover a major fault. It recommended that diagnostic testing should become the cornerstone of any future maintenance policy and that for SF_6 circuit breakers, diagnostic monitoring should be used as the trigger to carry out any intrusive maintenance. However, although it recommended that more reliance should be placed on diagnostic testing for air blast and bulk oil switchgear, it suggested that major intrusive maintenance should still be carried out, but the actual time interval between maintenance schedules should be determined by operating performance and the results of diagnostic testing. The revised maintenance schedules are outlined as follows [ITOMS, 1999]:

Annual Operational Check (All circuit breaker types)

- All circuit breakers should be operated at least once per annum;
- All outdoor mechanism boxes and control cubicles should be checked for ingress of water; and
- Detailed infrared examination, for thermal purposes, should be carried out on interrupter chambers and other current carrying parts.

Routine Testing (All circuit breaker types)

The present 'minor' maintenance, which is carried out at two or four yearly intervals (refer to Tables 2.1, 2.2 and 2.3 for examples) should be replaced by more comprehensive diagnostic testing, lubrication and external inspection, and should include:

Bulk Oil Switchgear

- Timing test of mechanism and contact separation;
- Measurement of trip and close coil currents, and supply voltage during timing test;
- Reduced operating voltage trip test;
- Overall static conductivity test;
- Oil quality test (dielectric and moisture content);
- Mechanism general lubrication;
- Overall visual inspection; and
- Overall system inspection.

Air Blast Switchgear

- Timing test of mechanism and contact separation;
- Measurement of trip and close coil currents, and supply voltage during timing test;
- Air consumption test;
- Reduced operating voltage trip test;
- Overall static conductivity test;
- Conditioning air dew point test and air flow measurement;
- Mechanism general lubrication;
- Overall visual inspection; and
- Overall system inspection.

SF_6 Switchgear

- SF_6 gas quality and moisture content;
- Timing test of mechanism and contact separation;
- Measurement of trip and close coil currents, and supply voltage during timing test;
- Reduced operating voltage trip test;
- Overall static conductivity test;
- Dynamic contact resistance test;
- Mechanism general lubrication;
- Overall visual inspection; and
- Overall system inspection.

Major Maintenance

Oil and air blast circuit breakers should be categorised depending on operating factors to determine the maximum interval between major maintenance. As described previously, the actual interval will be dictated by operating performance and the results of diagnostic testing. Category description and guidance for assessment are as follows:

Category 1 – Light Operating Conditions

Light switching conditions - Typically fewer than ten energised operations with very few fault clearances. Examples include: Bus section, bus coupler, transformer feeders and base load generator circuit breakers.

Category 2 – Medium Operating Conditions

Medium switching conditions - Typically twenty energised operations with relatively few fault clearances. Examples include: Line circuit breakers.

Category 3 – Heavy Operating Conditions

Onerous switching conditions or very frequent operation or high incidence of fault clearance. Examples include: Some ½ switches in 1½ switch layout substations (Refer to Chapter 4, section 4.5); circuit breakers controlling lines subject to severe climatic conditions; circuit breakers subject to severe capacitive/reactive switching conditions; and generator circuit breakers where two-shift operation is normal.

Category 4 – Shunt Reactor oil circuit breakers

Due to the high contact wear and oil carbonisation, shunt reactor circuit breakers should continue to be operation dependent for major maintenance. It was proposed that the maximum time interval between major maintenance schedules should be:

- Category 1 – 12 Years
- Category 2 – 9 Years
- Category 3 – 6 Years
- Category 4 – 50 operations

The content of the major maintenance varies for each individual type of circuit breaker, but generally includes:

Bulk Oil Circuit Breakers

- Pre-maintenance tests;
- Internal examination;
- Stroke and wipe measurement;
- Contact synchronisation checks;
- Resistor and capacitor checks;
- Conductivity tests;
- Pneumatic system examination;
- Operating mechanism examination;
- Bushing insulation and oil test; and
- Post maintenance diagnostic tests.

Air Blast Circuit Breakers

- Pre maintenance tests;
- Interrupter examination where applicable;
- Resistor and capacitor checks;
- Pneumatic system examination;
- Operating mechanism examination; and
- Post maintenance diagnostic tests.

SF_6 Switchgear

As described previously, no invasive examination of SF_6 switchgear was proposed unless diagnostic test results indicate otherwise.

2.4.8.2 An Economic Evaluation of CBM

Using the work developed by [Pryor et al, 1999], a feasibility study has been undertaken to understand the potential economic benefits of moving to an off-line CBM strategy from a TBM approach for bulk oil, air blast and SF_6 circuit breakers. As presented in the previous section, [Pryor et al, 1999] did not examine the effect of OLMSs, as the commercial availability of these systems was extremely limited at that time. Consequently, for this particular study, the economic evaluation has been restricted to off-line CBM. However, as mentioned in Chapter 1, the economic assessment of on-line CBM has been studied as part of this research, but the work is not presented until Chapter 4, as the subject of condition monitoring needs to be first introduced, which is included in Chapter 3.

2.4.8.2.1 Preventive Maintenance Costs

The simplest method to evaluate the economic effect of applying an off-line CBM strategy is to examine its effect on the preventive maintenance costs. As outlined in [Cigré, 167, 2000], the cost can be quantified by examining the existing or proposed TBM requirements of the circuit breaker, and calculating the effect on the material and labour costs of moving to a CBM strategy. The study could be extended to examine the effect on indirect maintenance costs such as spare parts and equipment requirements. However, until a utility gains confidence and experience with off-line diagnostic systems, these costs are difficult to quantify. Consequently, as a first pass and to simplify the process it is recommended that the evaluation be constrained to the direct effect on labour and materials. The study also needs to include the cost of the diagnostics equipment, but it should be noted that this is a shared cost and will be dependent on the number of circuit breakers that the equipment is used to test.

2.4.8.2.2 Corrective Maintenance Costs

With regard to the corrective maintenance costs, apart from the direct effect on labour and materials, through detecting defects that could lead to failures, there could be considerable savings when the consequences of the failures are considered. This may include benefits such as, minimising damage to the circuit breaker and adjacent equipment along with reducing the corresponding outage duration. Each utility will have a different view, which will be dependent on factors such as the parameters they are monitoring and the frequency of the inspections. Consequently, despite the encouraging early results from [Pryor et al, 1999], the study assumed a worst case scenario and did not include the effect on the corrective maintenance costs.

2.4.8.2.3 Off-Line CBM Feasibility Study

Using the recommendations developed by [Pryor et al, 1999], the maintenance schedules for bulk oil, air blast and SF_6 circuit breakers when using off-line diagnostics can be observed in Table 2.4 in a summarised form.

Table 2.4: Recommended maintenance schedule using off-line diagnostics

Activity	**Maximum Interval**	**Main Tasks**
Visual Inspection	2 weeks	Critical items (e.g. Conditioning Air)
	4 weeks	Levels, Pressures, Ground level external inspection and control cubicle checks.
Integrity Check	12 months	Thermo-vision survey
Intermediate	3 years	Control scheme functional checks. Check heating, counter reading, SF_6 pressure. Off-line diagnostics to check: Mechanism, timing & conductivity of interrupters.
Major* (Oil Circuit Breaker and ABCB)	Test/Operating category dependent	Items may include: Contact examination, Bushing inspection and test, Mechanism examination, Pneumatic system examination, Resistor and capacitor checks
Major (SF_6)*	As required	Test result dependent
Painting	As required	

*The term Major does not represent a mid-life refurbishment of the circuit breaker.

The feasibility study covered three circuit breaker types all operating at 275kV (within the EHV classification), but where each is applied in a different operating scenario. The first included an NSC circuit, such as a grid supply point where more than one transformer feeder is in service, the second considered an interconnector circuit and the third a generator circuit. As outlined in section 2.4.8.1, each application has a different maintenance schedule. Furthermore, for a de-regulated market such as the UK, each potentially has a different planned outage cost. For example, for an interconnector circuit, exports may be constrained when a circuit breaker is taken out of service. On the other hand, if it is a generator circuit breaker and the substation layout is a 1½-switch configuration (Refer to Chapter 4, section 4.5) it will be possible to carry out maintenance on each circuit breaker without needing an associated outage on the generator. Therefore, the economic appraisal needs to be case specific.

Using the maintenance schedules presented earlier in this chapter, and using labour and material costs provided by ScottishPower [SP, 2002b and SP, 2002c], the cost difference can be calculated between a TBM and off-line CBM strategy.

Unfortunately, these labour and material costs are confidential, but by calculating the Net Present Value (NPV) for each maintenance strategy over the estimated lifetime of the circuit breaker, the difference between the two strategies can be presented as a percentage increase or decrease per operating year of the circuit breaker.

2.4.8.2.4 Off-line CBM Case Study Results

The potential cost savings when an off-line CBM strategy is employed are presented in Table 2.5. The results are extremely encouraging, particularly when it is considered that the assessment excludes the effect on the corrective maintenance costs. For all circuit breaker applications and types, there would appear to be significant benefits to moving to an off-line CBM strategy. With regard to the NSC circuit breaker application, the savings are greater for the bulk oil and air blast types, as they are more labour intensive compared to the SF_6 type. It is interesting to note that the difference between the two maintenance strategies reduces for the interconnector and generator circuit breaker applications. However, with the exception of the SF_6 generator circuit breaker application, the actual cost savings are higher than the NSC applications due to the reduction in the high planned outage costs that are normally associated with generator and interconnector circuit breakers. In the case of the SF_6 generator circuit breaker, the planned outage cost is avoided due to the substation configuration. As mentioned previously, this point will be covered in more detail in Chapter 4.

Table 2.5: Summary of cost savings when off-line diagnostics are employed

Type of Circuit Breaker (CB)	NSC CB Cost Savings/Year (%)	Interconnector CB Cost Savings/Year (%)	Generator CB Cost Savings/Year (%)
SF_6	29	17	29
Bulk Oil	50	40	23
Air Blast	42	37	29

2.4.8.2.5 Conclusions from off-line CBM case studies

Although the use of off-line diagnostics offers the opportunity to virtually eliminate routine invasive maintenance, with corrective maintenance requirements being dictated by the results of the off-line diagnostics [Pryor et al, 1999], utilities need to be cautious and base their maintenance strategy on their own experience, as it is feasible for the results to be undermined should the off-line diagnostics fail to detect impending failures. Experience so far [Pryor et al, 1999] has shown that the predications are accurate, but a utility needs to carefully consider the parameters that they are proposing to monitor and invest in the research that is required to develop the intelligent software to automatically interpret the results.

2.4.8.3 General Experience with CBM

As with ScottishPower, results from utilities that have moved to a CBM strategy have so far also proved encouraging. In [Damstra et al, 1999 and Smit et al, 1998] the Dutch utility, ENW E-Trans N.V., moved towards a CBM strategy in order to reduce maintenance costs and extend the life of their assets. Compared to the previous TBM strategy, they estimate that using a diagnostic CBM strategy has resulted in approximately a 25% reduction in maintenance costs. The associated benefits also include a reduction of up to 80% in the planned unavailability per year and an 87% reduction in recovery time for circuit breaker maintenance.

In the United States, National Grid [Lastella, 2004] has spent the last 20 years developing a diagnostic CBM maintenance philosophy to manage its assets. They use what they call a Maintenance Priority System (MPS) to determine the inspection interval. Essentially, it is a formula based system that relies on a number of factors such as previous circuit breaker condition, number of routine operations and fault clearances to determine when an inspection should be carried out. Although they have not presented any costs, in general they have found that as experience has been gained they have been able to lengthen the diagnostic inspection intervals. However, they do add that for some specific cases, the inspection intervals have been shortened. They also highlight that this approach has had the additional advantage of helping them develop their circuit breaker replacement programme.

TXU Electric [Speed, 2000] utilises electrical information from a circuit breaker's control circuit to evaluate the condition of its operating mechanism and therefore a means for prioritising its maintenance. As shown in Figure 2.20, it is a fairly simple device that is portable and attached using four leads. Two of the leads are connected across the circuit breaker control supply to measure the trip or/and close supply voltage, the third is a Direct Current (DC) clamp on device to measure the trip and/or close coil current and the forth is an Alternating Current (AC) clamp on device connected to the secondary of the Current Transformer (CT) to measure one phase of the primary current.

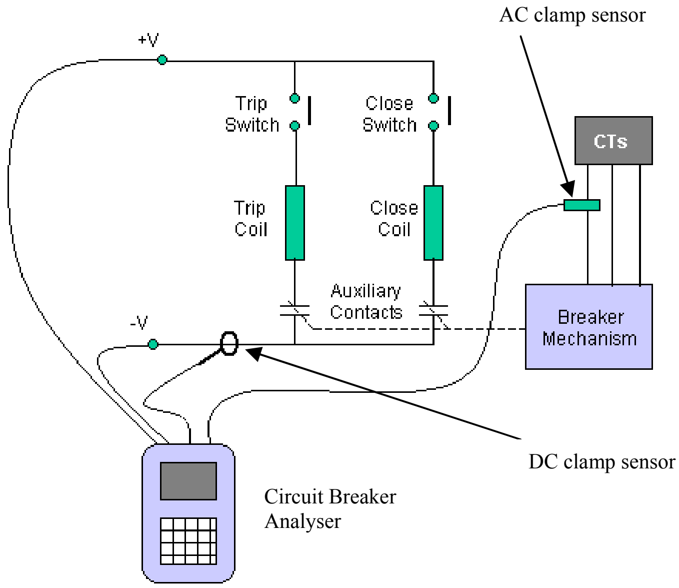


Figure 2.20: Diagram showing the non-invasive connection of a circuit breaker analyser to evaluate the condition of an operating mechanism[6]

The concept of measuring a circuit breaker's control circuit electrical information during operation to provide an insight into the condition of the operating mechanism is not a new development [Nelson et al, 1991]. A typical trace obtained from the circuit breaker analyzer is shown in Figure 2.21 [Speed, 2000]. There are three main features: the main contact time, the DC supply voltage and the trip/close coil current during the operation of the circuit breaker. By comparing a trace with previous traces of a circuit breaker, its performance over time can be tracked. Namely, as is described in more detail in Chapter 3, operating mechanism problems are evident from changes in the characteristics of the electrical traces.

Although the analyser does not provide as much information as a timing trace, such as travel time velocity, it does allow information about the first operation to be captured. TXU Electric [Speed, 2000] have found that if a circuit breaker has been lying dormant for a considerable period, capturing data from the first movement of the mechanism can be critical in identifying an emerging problem. Subsequent operations may not show up the problem, as the circuit breaker mechanism has been 'exercised' or freed up.

[6] Courtesy of [Strachan, 2005a].

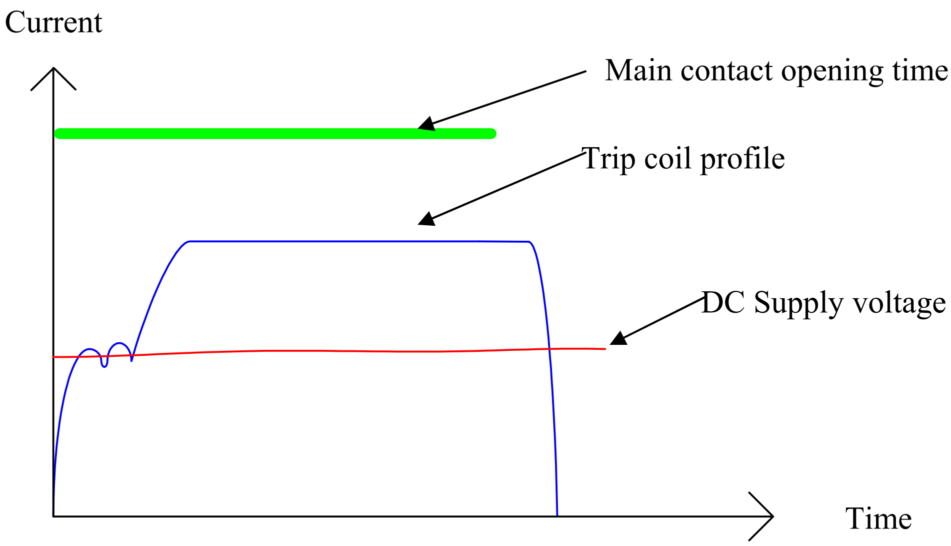


Figure 2.21: Diagram showing a typical circuit breaker operating signature[7]

The results from TXU Electric [Speed, 2000] have been encouraging, where a number of failure modes have been identified and numerous outages have been avoided for 'healthy' circuit breakers. The one disadvantage is that it relies on the operators' skill to analyse and compare plots. For example, although the opening time may be within limits, there is a wealth of information that can be obtained from the trip coil signature (Refer to Chapter 3), which may be used to reveal an emerging problem. With this in mind [Strachan, 2005a and Strachan et al, 2005b] have used Artificial Intelligence (AI) techniques to identify and establish correlations between signature shapes and specific circuit breaker conditions. Using appropriate data visualization techniques the operational features and thresholds characterizing these circuit breaker conditions have been defined and implemented in a rule based system for future circuit breaker condition assessment.

Apart from utilities, some manufacturers support the move to a CBM strategy, particularly with modern single pressure SF_6 circuit breakers. As [Hadorn, 1996] warns, invasive maintenance is relatively complex for SF_6 switchgear and therefore it is important to always test before any intervention. Furthermore, as is discussed in the next chapter, a significant amount of data can be obtained by measuring certain key circuit breaker parameters. For example, as explained by [Hadorn, 1996] and

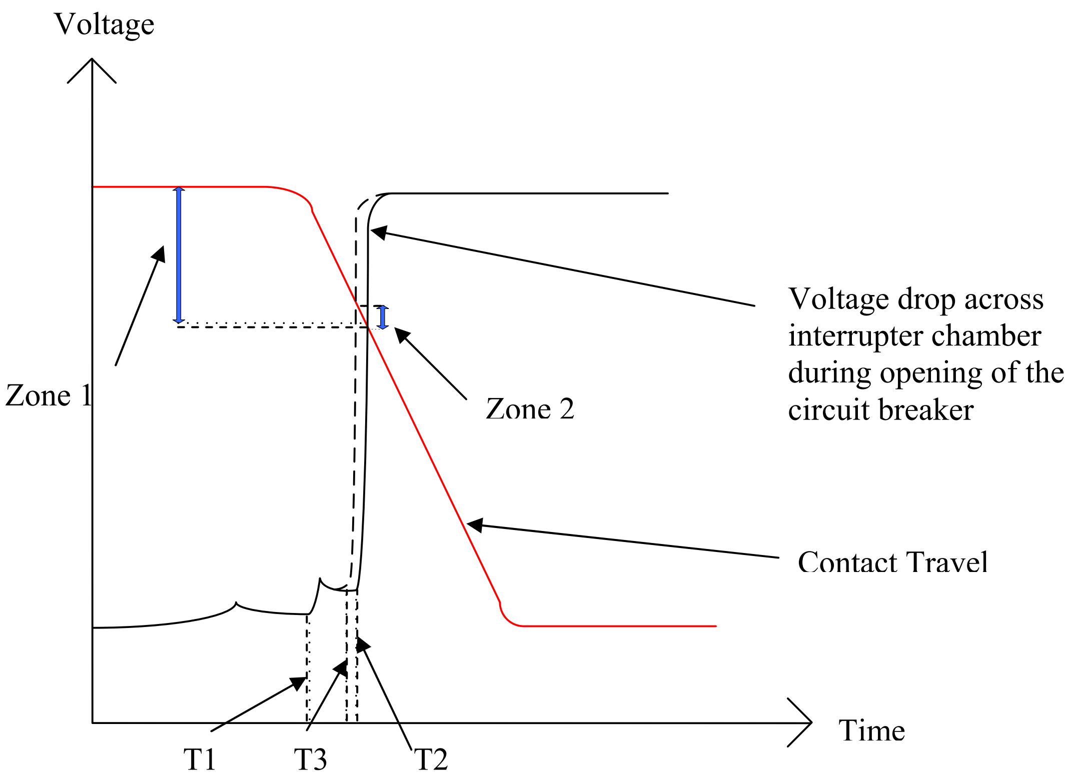
[7] Derived from [Speed, 2000].

reproduced in Table 2.6, considerable information can be obtained about a spring operated circuit breaker by simply measuring the operating time.

Table 2.6: Diagnosis based on operating time changes

Tripping Time	**Closing Time**	**Cause**
Normal	Slower/Faster	Change in the characteristic of the closing system
Slower	Normal	Change in the characteristic of the tripping system
Slower	Faster	Reduced trip spring energy
Slower	Slower	Increased friction in the whole drive system
Faster	Normal	Faulty interrupter puffer or very low SF_6 pressure

Similarly, Siemens have been working with Red Eléctrica de España [Salamanca et al, 1993] to develop an off-line portable diagnostic system that besides measuring the contact timing of a circuit breaker, monitors the wear of the contacts in order to prevent dismantling the circuit breaker. Essentially, it measures the resistance across the interrupter unit as the circuit breakers opens. This measurement is achieved indirectly by injecting current through the interrupting unit and measuring the voltage drop as the contacts separate. As can be seen from Figure 2.22, the interval between the main contacts opening and the arcing contacts opening is between T1 and T2 or T1 and T3. Therefore, by analysing the variations in the resistance or voltage drop these two important stages (main contacts and arcing contacts opening) can be identified. If this interval is related to the graph showing movement of the circuit breaker, the distance travelled between the two contacts can be determined reasonably accurately. By comparing this distance with a new circuit breaker it is then possible to assess the wear of the arcing contact.



where

Zone 1 is the electric contact wear zone

Zone 2 is the arcing contact wear zone

T1 is the opening time of the main contacts

T2 is the opening time for the new arcing contacts

T3 is the opening time for the used arcing contacts

Figure 2.22: Diagram showing voltage drop across an interrupter unit when a circuit breaker is opened[8]

Results have proved the method to be an effective means for accurately predicting the actual arcing contact wear, particularly for SF_6 circuit breakers with insulated nozzles. Combined with other data, such as the travel curve and control coil currents, Siemens and Red Eléctrica de España report [Salamanca et al, 1993] that it provides them with a reliable diagnosis of the circuit breaker condition without having to carry out intrusive maintenance.

[8]Derived from [Salamanca et al, 1993].

Overall, it is clear that there are technical benefits in moving towards a CBM strategy and economic benefits when off-line CBM is considered. As shown in Figure 2.23, there is growing evidence [Cigré, 165, 2000] that more and more utilities are either examining or planning to use a CBM strategy in the future. Whether it is feasible, both technically and economically, to move towards an on-line CBM strategy is subject to much debate and a number of economic models have been proposed to answer this question. However, as Chapter 4 explains, a number of factors need to be considered, particularly the reliability of the condition monitoring system itself. What is clear, as re-iterated by utilities and manufacturers, is that the key factors to any successful CBM strategy are good data management and the skill to interpret the results.

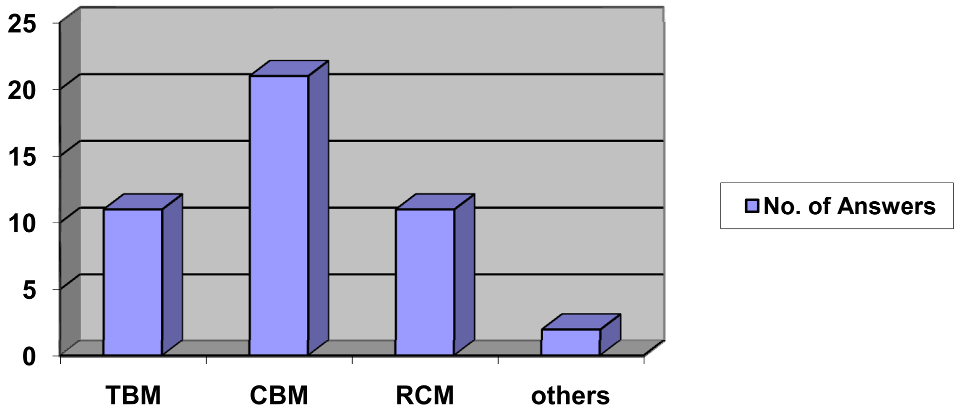


Figure 2.23: Results of a survey showing the maintenance methods to be employed in the future for circuit breakers[9]

2.4.9 Experience with Reliability Centred Maintenance

As described previously, unlike CBM, which determines the maintenance requirements based on the condition of the plant, RCM is a structured methodology that establishes the maintenance requirements based on failure consequences and the probability of failure. In this section, the experiences of utilities that have implemented RCM, in particular with respect to circuit breakers, are examined. The economic analysis and the comparison with the results from other maintenance

[9] [Derived from Cigré, 165, 2000].

strategies is covered in Chapter 5 after the application of on-line condition monitoring has been considered in Chapters 3 and 4.

Most of the experience with RCM resides with utilities in North America. As explained by [Janssen et al, 2000], maintenance programmes based on risk assessment are seldom used, however, for the reasons discussed previously and as shown in Figure 2.23, a number of utilities are considering its use.

One of the first utilities to examine RCM was Bonneville Power Administration (BPA). In conjunction with the Oak Ridge National Laboratory they started looking at RCM in the early 1990's [Purucker et al, 1992 and Purucker et al, 1996]. With growing maintenance backlogs and budget constraints, BPA initiated a pilot study, which initially focused on applying on-line monitoring to one transformer and two circuit breakers [Purucker et al, 1996]. The long-term objective of the project was to develop an expert system to interpret the data and initiate preventive maintenance. If the study proved successful, they planned to apply RCM to all circuit breakers and transformers on their system, and estimated by doing so they would make annual savings of $8,050,000 [Purucker et al, 1992]. Unfortunately, the project was not completed, as its focus was changed to develop a maintenance management system instead of an expert system.

However, in 1994 BPA participated in an Electric Power Research Institute (EPRI) substation RCM study along with six other utilities from North America to establish guidelines and tools for implementing RCM in substations [Sarkinen, 1998]. Two RCM approaches, using the seven step process outlined in section 2.2.4, were developed: the system approach, which concentrated on applying the RCM analysis to a group of equipment within a power system that have a common function; and the equipment approach, which applies RCM to a common type of plant, irrespective of its application.

BPA concentrated on the system approach, which involved applying RCM to all the circuits and terminal equipment at Santiam Substation [Purucker et al, 1996 and Cigré, 165, 2000]. To illustrate the system approach, one of the functions identified in step 1 of the RCM process was "Supply 1000MVA to the Santiam BusBar".

Overall, BPA found that when RCM is applied to a system, the process is extremely tedious and repetitive, as there are too many functions and failure modes to analyse [Cigré, 165, 2000]. Consequently, they streamlined the process by only analysing the dominant functions and failure modes. In addition, they found that some equipment failure modes were independent of system function and were therefore analysed in groups of similar manufacturers and models, e.g. circuit breaker fails to interrupt fault. In conclusion, they believe there are significant savings to be made when applying RCM and consequently they have now applied RCM to their entire system [Cigré, 165, 2000].

Puget Sound Power and Light Company, which participated in the aforementioned EPRI substation RCM study, on the other hand used the equipment approach [Skog, 1995]. Once again they reported favourable results and for circuit breakers they estimate that for preventive maintenance tasks, RCM could reduce the average number of hours for maintaining a transmission circuit breaker from 26.63 to 15.14 hours per year. However, they do add a note of caution that although RCM appears promising, it will be several years before the true results are known.

Outside of North America, there are utilities that have been examining the feasibility of RCM, one being Electricité de France (EDF) [Cigré, 165, 2000]. Although their switchgear maintenance plans have taken account of the criticality of failure modes and the effectiveness of maintenance tasks since 1985, they did not consider their application and importance on the network. Consequently, in 1995, they initiated a pilot RCM study using the system approach on 400kV line and terminal equipment [Cigré, 165, 2000]. Similar to BPA, they decided to simplify the process, but in their case they concentrated on the equipment approach. They have now applied RCM to all their circuit breakers and as described in [Cigré, 165, 2000], they have slightly modified the standard seven step RCM approach described in section 2.2.4. The main difference is that EDF uses a scoring method to select the appropriate maintenance task. Namely, each component failure is first given what is a called a ‘criticality’ score, which is dependent on the failure rate of the component and the seriousness of the resulting failure. Depending on the criticality score, another factor called the applicability score is used to determine the appropriate maintenance task. This factor is dependent on the effectiveness of the task to detect the failure mode and the ease (both technically and economically) of implementing the maintenance task.

Using this approach, EDF have used the criticality factor to create three different maintenance plans [Cigré, 165, 2000], which are dependent on the application of the equipment. Although savings have been made, one of the main benefits is that if equipment is strategically important, it will have a higher level of maintenance than one that is less system critical. In the past, it would often be maintained less frequently due the difficulty in obtaining an outage. However, one of the drawbacks of this approach, compared with the approach proposed by [Moubray, 1997], is that it does not consider the safety implications of a failure.

Tokyo Electric Power Company (TEPCO) have also been evaluating the use of RCM for circuit breaker maintenance [Cigré, 165, 2000]. Their approach compared to EDF and RCM2 is different again. In [Cigré, 165, 2000] they initially listed all the component parts of three different types of porcelain bushing oil circuit breakers. This allowed them to calculate how each part could deteriorate, e.g. where a circuit breaker's contact pressure is insufficient, this could lead to overheating and burning of the contacts, which in turn could result in a circuit breaker being de-rated. Each component part is then given a score depending on the ease of detecting the failure, the consequences of the failure and the probability of the failure occurring. Maintenance is then targeted on the component part with the highest scoring.

Although TEPCO reports [Cigré, 165, 2000] that further work is required to improve their RCM method, they have found that with the circuit breakers used in the study, they have been able to extend the ordinary maintenance interval from two to three years. However, similar to EDF, TEPCO does not consider safety and environmental consequences. In addition, since the evaluation score is obtained by multiplying the score, in how detectible the failure is with the consequence and probability scores, there is a danger that a component part whose failure could lead to serious consequences could be downgraded due to the low score of the other factors.

Statnett in Norway [Gjerde et al, 1998] has also examined applying RCM. Similar to many utilities they have regulatory pressures to increase system reliability whilst reducing operating costs. Although they have reported that RCM has proved an effective process for identifying appropriate and cost effective maintenance tasks, they add a note of caution. In particular, they have concerns regarding the selection of the maintenance frequencies. Selecting a frequency based on historical data may result in frequencies that are lower than necessary and similarly selecting frequencies based on technical data may overlook design problems. Clearly, if on-line condition monitoring is available and is effective (both technically and economically) at detecting the failure mode, then this problem could be avoided. However, as is discussed in the next two chapters, standard OLMSs have not been readily available until recently and there are other issues that need to be considered; namely their reliability and the parameters that need to be monitored to detect the impending failures.

In [Chan et al, 2005] the authors have taken the basic principles of RCM and developed a decision making tool that determines the maintenance for a particular circuit breaker based on its condition and its relative importance to the system. It uses a scoring system for each parameter and once they have been determined they are placed on a 2-dimensional decision map as shown in Figure 2.24.

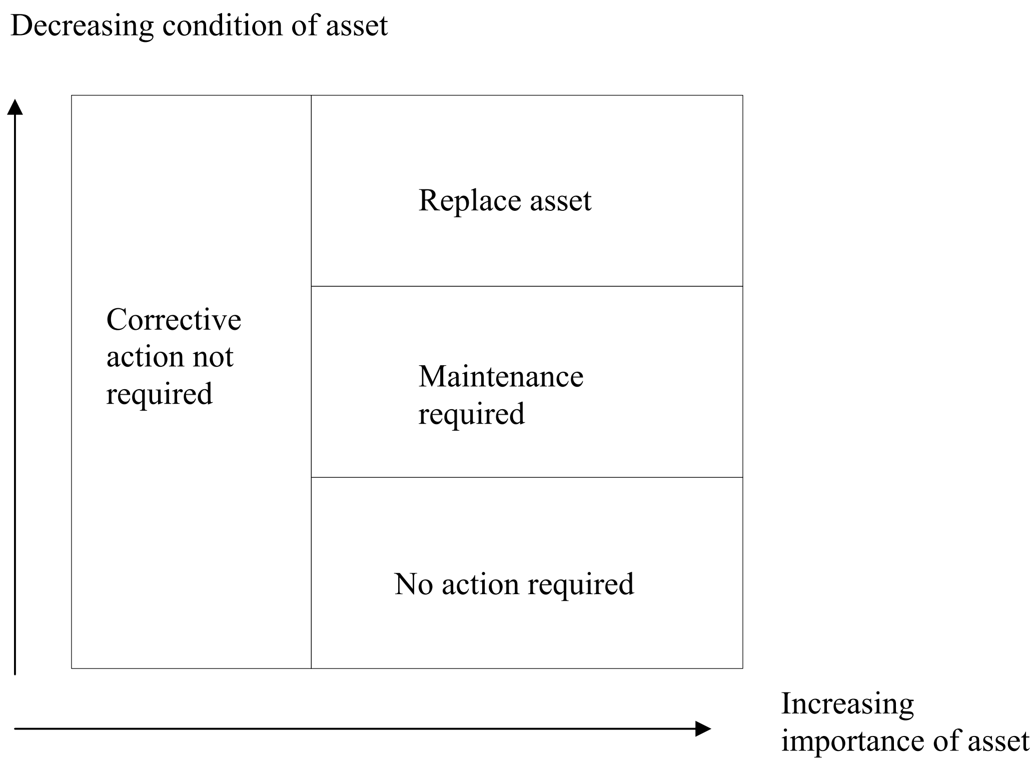


Figure 2.24: Diagram showing a decision making map for maintenance action[10]

It can be seen that there are four different types of maintenance actions and if, for example, the importance of the circuit breaker to the network were below a particular threshold, then regardless of the condition of the circuit breaker, corrective action would not be taken until the device had failed.

The authors state that the importance index is based on the financial or social cost of an outage, but when safety and environmental issues are involved, apart from being difficult to cost, the legal system in some countries will not permit a company to make a decision based purely on financial terms.

It is evident that more and more utilities are using or are planning to use RCM. There are numerous papers, particularly from North America [Gjerde et al, 1998; Sarkinen, 1998; Foley, 1998; Pottenger, 1998; Stead, 1998; and Moon et al, 2006], outlining users' experience, whether it is at a system or equipment level. As has been

[10] Derived from [Chan et al, 2005].

explained, many users are modifying the RCM process to either simplify it or target specific items of plant. In some cases [Moubray, 1997] the changes are so drastic that the resulting method bears little or no resemblance to the original RCM method. Consequently, considering that the original method is a highly structured and proven methodology, there is a danger that the original objective of RCM will be lost and the user will be left with a method that reduces cost, but does not consider the resultant effect on the reliability of the equipment [Moubray, 1997]. In addition, some would argue [Endrenyi et al, 2001] that any heuristic technique, whether it is RCM or CBM, requires experience and time to accurately judge maintenance frequencies and the effect of the maintenance strategy on reliability. Therefore, an alternative approach may be to employ mathematical models that link the equipment deterioration and the condition improvement brought about by the maintenance task to determine the optimum maintenance schedule. This subject is an important development in maintenance management and as a result is discussed in more detail in Chapter 7, where the results will be compared with more traditional maintenance strategies, such as RCM.

2.5 Chapter Summary

This chapter presented an overview of the history and the purpose of maintenance. It explained that it is a tool that seeks to extend the lifetime of a device or at least the mean time until the next failure, where the cost of that failure could be expensive. There are other methods available, such as providing redundancy or employing more reliable components. However, in industries such as the utility sector, which are regulated in a number of countries, companies are forced to minimise costs whilst gaining more out of their assets through more efficient operating and maintenance regimes. In essence, maintenance has become a significant and important part of asset management.

The chapter explained that where utilities have traditionally used a TBM strategy, that view is now being challenged and other techniques such as CBM and RCM are now either being employed or are being considered for future use.

After describing the principles of CBM and RCM, the potential benefits of moving to an off-line CBM strategy from a TBM approach were demonstrated by presenting the work undertaken by [Pryor et al, 1999] and carrying out a feasibility study for various circuit breaker types and applications to analyse the economic difference between the two strategies. Although the use of OLMSs would appear to be the next logical step, it was highlighted that their application is not as straightforward as many would believe. Issues such as the reliability of a condition monitoring system and the parameters to be monitored need to be considered in detail. Consequently, Chapter 3 is devoted to introducing the concept of condition monitoring, the different types of parameters that could be monitored for a circuit breaker and the application challenges.

The chapter concluded with a discussion on the experience of utilities in applying off-line CBM and RCM to their networks, and to circuit breakers in particular. Initial results proved promising, but the experience with CBM highlights the need for a robust model to evaluate the economic effects of moving to an on-line CBM approach. Furthermore, it questions whether OLMSs are the most appropriate method of detecting an impending failure. Therefore, as presented in Chapter 4, one of the main contributions of this research is to develop such a model and prove through case studies and sensitivity analysis that factors such as the reliability of a condition monitoring system and how they are applied cannot be ignored. This leads to the second contribution of this research, which is to demonstrate through an RCM study in Chapter 5 that a utility needs to carefully consider the role of on-line monitoring, as in some applications it may be more appropriate, whether that be economically or technically, to employ an alternative maintenance technique, such as a scheduled replacement of a part regardless of its condition.

The experience with both CBM and RCM highlights the importance of understanding the failure modes of a circuit breaker. Although the latter provides a structured methodology to try and achieve that objective, there is a need to understand the quantitative link between each component part and the overall reliability of a circuit breaker to help with identifying the critical failure modes. The risk of doing this qualitatively, as suggested by BPA [Cigré, 165, 2000], is that the criticality of some failure modes may be underestimated. Consequently, the third main contribution of this research is the development of a fault tree model, as presented in Chapter 6, which reveals how each component part contributes to the overall availability of a circuit breaker. Apart from allowing the critical failure modes to be identified, it also provides a valuable insight into the accuracy of the RCM method.

The other area of concern about the CBM and RCM techniques is that as they are heuristic in nature, it may be many years before their true effect on reliability is known [Endrenyi et al, 2001]. Therefore, in Chapter 7, the use of mathematical models is explored, where the reliability of condition monitoring is incorporated into the mathematical models. This allows a full comparison between the different techniques to be undertaken and leads to the fourth and final contribution of this research, which is to develop a methodology to determine the optimal maintenance strategy for high voltage circuit breakers.

Chapter 3

3 Condition Monitoring

The following chapter introduces the subject of condition monitoring and provides a description of the main techniques that are available along with examples of where and why they are employed. Initially, the description is kept general, before focussing on the Electricity Supply Industry and in particular the various parameters that can be measured for a circuit breaker.

The chapter concludes by examining and reviewing the experience that currently exists for circuit breaker condition monitoring, and then identifies the main challenges that need to be overcome if the full potential of condition monitoring is to be realised as part of a future maintenance strategy.

3.1 What is Condition Monitoring?

As described in [Davies, 1990], one formal definition of condition monitoring is provided in British Standard BS3811: 1984, which states that Condition Monitoring is:

"*The continuous or periodic measurement and interpretation of an item to determine the need for maintenance*".

In the same standard, the definition is further qualified by the following statement:

"*Condition Monitoring is normally carried out with the item in operation, in an operable state or removed but not subject to major stripdown*".

It is therefore a means by which maintenance strategies such as CBM could be carried out, where the parameters that can reflect the condition or future performance of plant, structures or systems, are continuously or periodically measured to determine any deterioration that could lead to an impending failure.

It is used by many industries such as the Aerospace, Nuclear, Manufacturing, Utility and Petrochemical sectors, and as described later in this chapter can include a wide range of techniques such as vibration, acoustic and temperature monitoring.

3.2 The Need for Condition Monitoring

As mentioned in the previous chapter, all plant, regardless of how well they are designed, will fail at some time in their lifetime whether that be due to natural deterioration, being operated beyond their limits, a design fault, an operator or maintenance error, or a manufacturing defect. There could be numerous reasons, but whatever the cause of the failure, it is undesirable as it will involve expenditure whether that be to repair it or through a loss of revenue as a result of the equipment being unavailable for service. In some cases the failure may cause consequential losses and in the worst case it may result in safety or environmental breaches. Clearly if evidence of the impending failure can be detected, it may be possible to take action to prevent it from failing completely and avoid the associated consequences.

However, condition monitoring techniques are not the only means of detecting impending failures. The human senses (sight, sound, touch and smell) could be utilised and have the advantage that they are able to detect several signs of failure simultaneously. So what are the advantages of condition monitoring and why should its use be considered as part of any maintenance strategy? To answer this question it is helpful to examine what happens in the final stages of a failure. Figure 3.1 is called the P-F curve by [Moubray, 1997] and shows how a failure starts and progresses to the point (P) where it can be detected. The point where it can be detected is called the potential failure and beyond that point it continues to deteriorate until eventually it reaches the point of failure (F).

The interval between the potential failure point and the point where there is a functional failure is called the P-F interval or the warning period and needs to be known in order to determine the interval when checks must be carried out in order to detect the potential failure. The inspection frequency is dealt with in detail in Chapter 5, but clearly if the inspection period is greater than the P-F interval then there is a risk that failure will not be detected. In some cases, the earlier the functional failure can be detected the better, as there may be a rapid acceleration beyond the functional failure point to such an extent that there may be insufficient time to do anything about the failure.

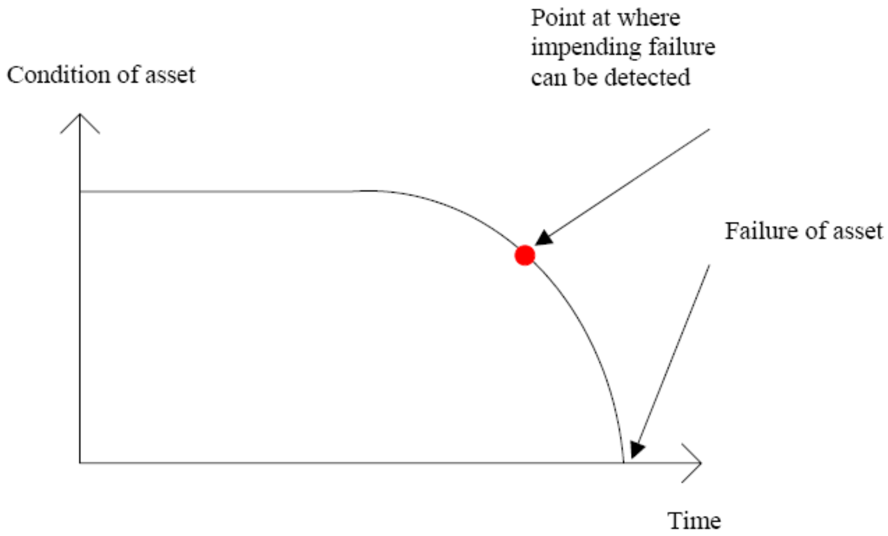


Figure 3.1: Diagram showing how a failure starts and progresses to the point where it can be detected

However, as shown in Figure 3.2, as the height of the detection point on the curve is increased it normally means that the deviation from the initial condition decreases [Moubray, 1997]. Unfortunately, most small deviations are beyond the range of human senses and can only be detected by special instrumentation designed to interface with condition monitoring. As is discussed in Chapter 5, the selection of the inspection period is not an easy task and is normally based on judgement. Consequently, at first glance, on-line condition monitoring offers a number of advantages compared to off-line monitoring. However, as is discussed later in the chapter and shown through case studies in Chapter 4, there are also a number of potential disadvantages.

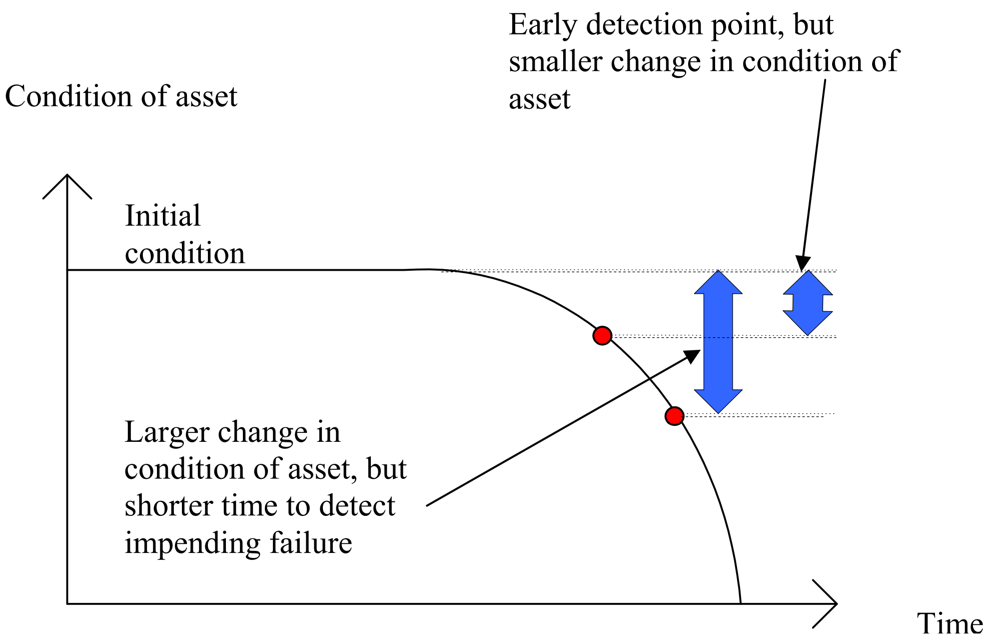


Figure 3.2: Diagram showing how change in condition of an asset varies with time [11]

The need and use of cost efficient condition monitoring becomes even more evident when some of the following facts and figures are considered for plant [Rao, 1992]:

- A Department of Trade and Industry (DTI) study revealed that poor and dangerous maintenance practices are costing the UK industry £1.3 billion a year;
- The same DTI study revealed savings of up to £1.5 billion per year could be realised if machine availability was increased by 5%;
- Losses due to corrosion of plant and machinery in the UK, USA and several other countries are of the order of 3 to 4% of Gross National Product (GNP).
- In highly automated, integrated and critical manufacturing facilities, it is claimed that scheduled maintenance is 30% cheaper than breakdown

[11]Derived from [Moubray, 1997]

maintenance and that condition monitoring is 30% cheaper again when compared on the basis of total costs incurred;

- ICI plc reported savings of £2.175 million after implementing vibration monitoring at a number of their sites; and

- Over a four-year period, a paper plant saved £1.62 million by using condition monitoring to reduce the number of plant stoppages.

3.3 The Benefits of Condition Monitoring

As outlined in sections 2.2.3 and 2.4.8, by using condition monitoring to move to a CBM strategy, there are a number of potential technical and economic benefits. In addition, a useful feature of condition monitoring is that many of the techniques used can be implemented using microprocessor based systems, which can then be interfaced with plant control, data management or expert systems to:

- Automatically and in real time monitor critical areas of plant or equipment on a periodic or continuous basis;

- Activate alarm systems and provide fault and maintenance recommendations;

- Identify any failure trends; and

- Automatically capture store, analyse and interpret data.

The latter point is of particular importance, as the captured data may be used by computational intelligence techniques, such as model, case and knowledge based reasoning and neural networks [McDonald et al, 1997 and Warwick et al, 1997] to extract meaningful information from the raw data to provide fault diagnosis and maintenance recommendations. As shown in Figure 3.3, there is also the opportunity to integrate and use the condition monitoring data as part of an overall asset management model for the plant or the system as a whole.

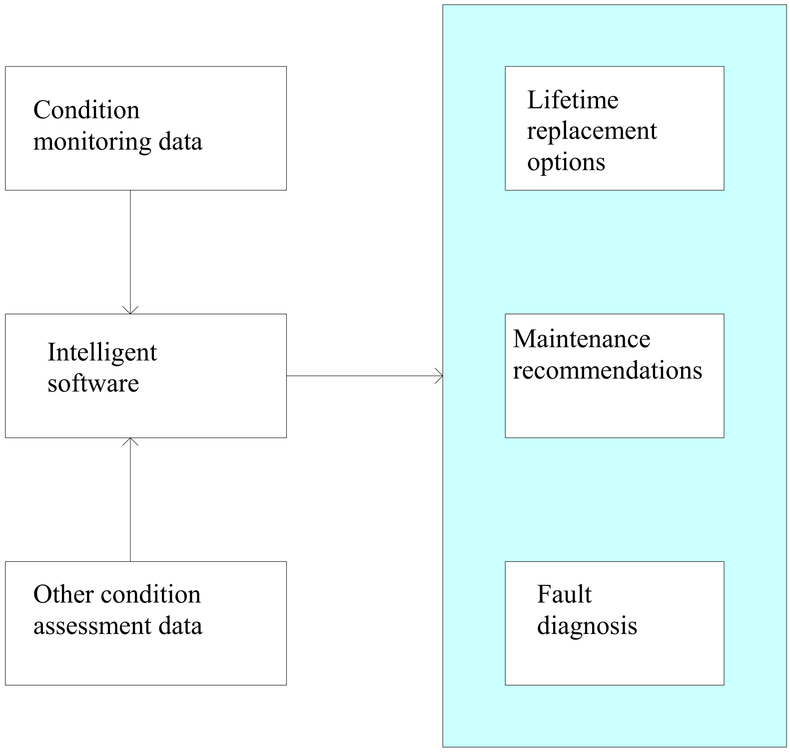


Figure 3.3: Diagram showing a plant asset management model

Finally, condition monitoring can be used to verify the condition of new, repaired or rebuilt plant. Such analysis is frequently used and invaluable when commissioning and accepting new capital equipment. Apart from acting as a quality assurance check, the data can be used as a base reference for future trend comparisons.

3.4 Condition Monitoring Techniques and Strategies

The list of condition monitoring techniques is endless. Since the earliest recorded application when Canadian Pacific Railways employed spectrometric oil analysis in response to a shortage in manpower during World War 2 [Davies, 1990], there has been an explosion in the research and development of new ideas and methods. The main categories of monitoring are described as follows, but for the interested reader, the many different techniques are detailed in [Moubray, 1997].

3.4.1 Dynamic Monitoring

Dynamic monitoring is where the potential failure is detected through an abnormal release of energy emitted through waves such as noise and vibration.

3.4.2 Particle Monitoring

Particle monitoring techniques consists of methods such as ferrography, which can be used to measure the density of particles in liquids, such as engine oil, to ascertain the degree of wear, fatigue or corrosion.

3.4.3 Chemical Monitoring

Chemical monitoring techniques consist of methods such as spectrometric oil analysis; gas and liquid chromatography; and infrared, fluorescence, ultra-violet and visible spectroscopy. Similar to particle monitoring, chemical detection of contaminants in liquids is normally used to detect a potential defect elsewhere in the system as opposed to a failure of the liquid itself, e.g. it could be used to detect the presence of aluminium as an indicator of wear in pistons or journal bearings.

3.4.4 Temperature Monitoring

Temperature monitoring consists of techniques such as infra-red scanning, which monitor the level of heat generated from loose or corroded electrical connections or heat generated from friction caused by faulty bearings or lack of lubrication. The sensors measure the level of radiation emitted and this is converted into an electrical signal, which in turn is processed to provide a visible colour image relating to temperature.

3.4.5 Physical Effects Monitoring

Physical effects monitoring consists of techniques such as liquid dye penetrants, which are used to detects surface irregularities such as cracks, discontinuities and shrinkage. Normally, a liquid penetrant (dye) is applied to the surface, such as a weld, and allowed time to penetrate into any discontinuity. After removing the excess dye, a developer such as chalk dust is applied to the surface to expose any irregularities.

3.4.6 Electrical Effects Monitoring

Electrical effects monitoring consists of techniques such as electrical resistance measurements, where the change in the resistance of a metal can be used as indicator of the loss of metal, which as described previously could be due to wear or corrosion.

3.5 Condition Monitoring in the Electricity Supply Industry

Condition monitoring equipment is not new to the electricity supply industry. It has existed in one form or another for as long as engineered systems have existed. Even with on-line systems, Partial Discharge Monitoring (PDM) systems have been applied successfully to GIS substations since the early nineties. More recently significant advances have been made with transformer and cable on-line systems [Judd et al, 2004 and Lewin, 2005]. Essentially, with the rapid expansion of sensor technology, mainly through other industries, there is an increasing capability to monitor everything.

Consequently, with the potential benefits that condition monitoring offers, many utilities are considering whether to replace or supplement traditional maintenance regimes with these available systems and techniques. This task is not as easy as it first appears and there are a number of challenges that need to be overcome. Namely:

- What items of plant or equipment do they target?
- What parameters do they measure?
- How do they integrate the systems, particularly when some of the plant may be 30 or even 40 years of age?
- How do they ensure that the monitoring systems, particularly on-line ones, do not affect the reliability of the plant and instead of improving availability make it worse?
- How do they justify their recommendations technically and economically? As many utilities have found out to their peril, some of the condition monitoring systems are more unreliable than the plant they are monitoring.
- How do they manage and interpret the data? Even for new equipment this task may be difficult as manufacturers usually do not have any operating experience and sadly for many utilities the technical specialist is becoming a dying breed.
- Do they and how do they integrate monitoring systems into other substation control facilities?
- How do they use the condition monitoring data to provide information as part of an overall asset replacement/refurbishment strategy?
- How do they verify the systems and avoid the old adage "garbage in, garbage out"?
- How do they ensure they have sufficient trained staff to manage the systems and develop them in conjunction with the manufacturers and research establishments, such as universities?

Although there are many other questions and challenges that could be listed, as is shown in the forthcoming chapters, there is a role for condition monitoring. The important point is that its development and application needs to be considered carefully. That will require the co-operation of utilities, research establishments and manufacturers. If that does not happen, then systems will be developed sporadically and independently with little overall plan, as has happened with switchgear on-line monitoring [CEA 485, 1996]. Unfortunately that usually results in missed opportunities, as users lose confidence in it and then are tempted to revert back to more traditional methods of carrying out maintenance.

3.6 Application of Condition Monitoring to High Voltage Circuit Breakers

The IEEE [IEEE C37.10.1, 2000 and Nelson, 2001] and Cigré working group 13.09 has reported [Cigré, 167, 2000] that it is possible to monitor a wide range of circuit breaker parameters. To understand how some of the circuit breaker condition monitoring development and application issues can be resolved, it is important to have an understanding of these parameters and why they could prove useful to monitor, whether off or on-line. Using [Cigré, 167, 2000] as a guide, the main measured parameters can be listed as follows:

3.6.1 Trip Coil Current/Time

The measurement of the trip coil current profile is a well-established method [Speed, 2000; Strachan, 2005a; and Strachan et al, 2005b] of providing an indication of the timings associated with circuit breaker components during the opening cycle. The correlation between the circuit breaker opening operation and the trip coil current signature for a spring type mechanism can be illustrated by examining Figures 3.4 and 3.5.

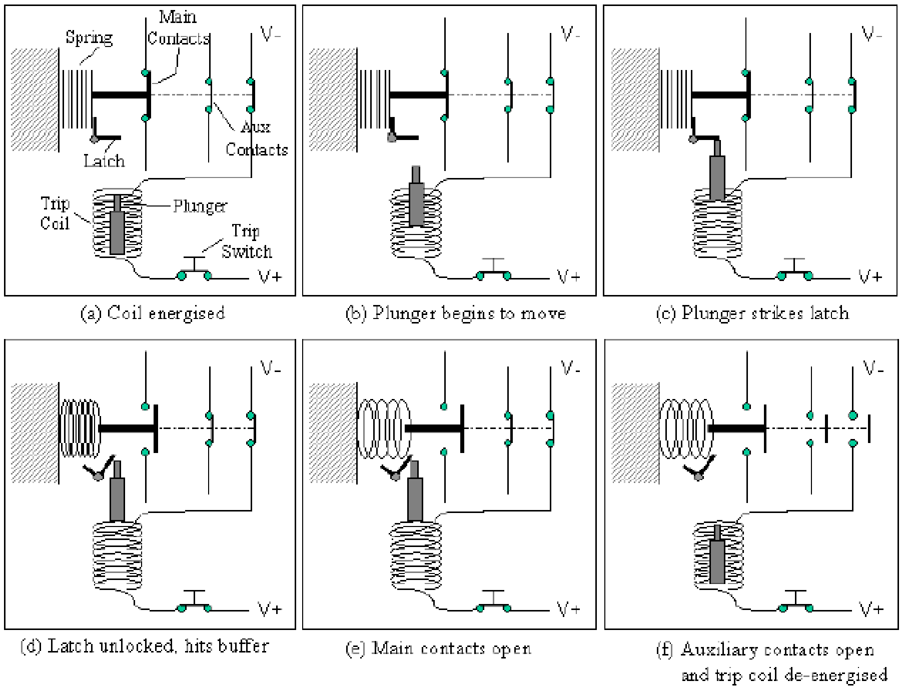


Figure 3.4: Diagram showing the energisation and movement stages of the trip solenoid during the opening sequence of a circuit breaker[12]

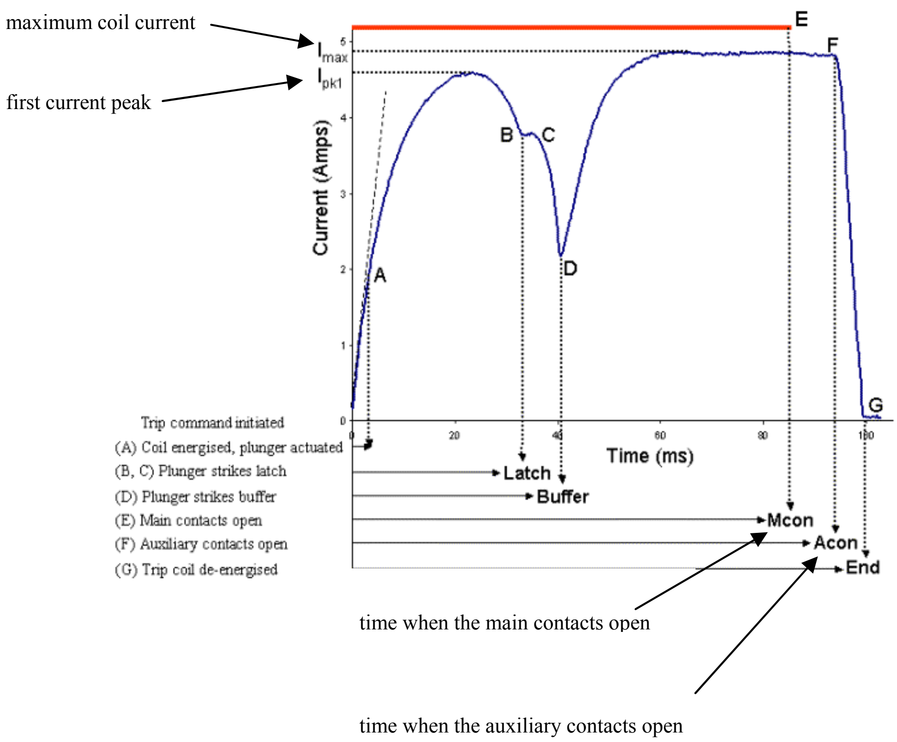


Figure 3.5: Diagram showing a typical circuit breaker trip coil current signature[13]

[12] Courtesy of [Strachan 2005a].
[13]Courtesy of [Strachan, 2005a].

The trip coil and plunger arrangement can be described as a solenoid. Therefore, when the trip command is initiated, the coil is energised and the DC current increases, which causes the plunger to move. As the plunger accelerates, the coil currents drops off due to the back electromagnetic force generated from the accelerating plunger. Eventually the plunger strikes the latch mechanism where a sudden reduction in the velocity of the plunger results in a slight increase in the coil current. As the plunger and the latch continue to move together, the coil current decreases until a point where the plunger and latch hit a buffer causing the coil current to then increase again. With the operating mechanism released, the coil current will continues to flow until the circuit breaker auxiliary contacts open (they indicate the circuit breaker is open) causing the trip coil to be disconnected from the trip voltage supply. The trip coil current then decays quickly to zero in accordance with the coil inductance and the plunger returns to its initial position.

The trip signature described previously provides a detailed record of the sequence of operation, or the operational stages leading to the tripping of the circuit breaker. Given a trip coil signature that is representative of a correctly operating circuit breaker any subsequent signatures from the same circuit breaker or type that it belongs to, which shows significant deviations may be indicative of some operational failure or deterioration in the circuit breaker condition. Sticking plungers, delayed latch tripping, faulty trip coils, delay or non-operation of the main contacts and dirty or misaligned auxiliary contacts are some of the problems that will manifest themselves in the circuit breaker trip coil signature.

3.6.2 Closing Coil Current/Time

The closing coil current signature is of similar importance to the trip coil current. For a spring type mechanism, the profile follows the same shape, the difference being that the information is relevant to the closing latch assembly and mechanism.

Even if the circuit breaker mechanism is either a hydraulic or pneumatic type, both the close and trip coil currents still provide invaluable information about the timings of the circuit breaker during operation.

3.6.3 Trip and Close Coil Control Voltages

As the operating times of a circuit breaker vary with coil control voltage, it is sometimes desirable to monitor this parameter. In addition, if the voltage across the coil is measured, it can provide similar information to the coil current characteristics.

3.6.4 Circuit Breaker Travel Curve

The circuit breaker travel curve (open and close) displays the distance travelled by the main contacts with respect to time and offers precious information about the state of the circuit breaker. During the opening operation, as shown in Figure 3.6, it is possible to calculate the speed at which the main contacts separate, which is a critical factor in determining if the circuit breaker is capable of interrupting. In addition, it is possible to check the deceleration of the contacts to ensure the damping is optimally set. Insufficient damping, as shown in Figure 3.7, allows the moving parts to undergo severe shocks, which can cause considerable damage to the circuit breaker. On the other hand, overdamping results in the kinetic energy developed by the circuit breaker being absorbed over a short period of time, which can cause just as much damage as underdamping.

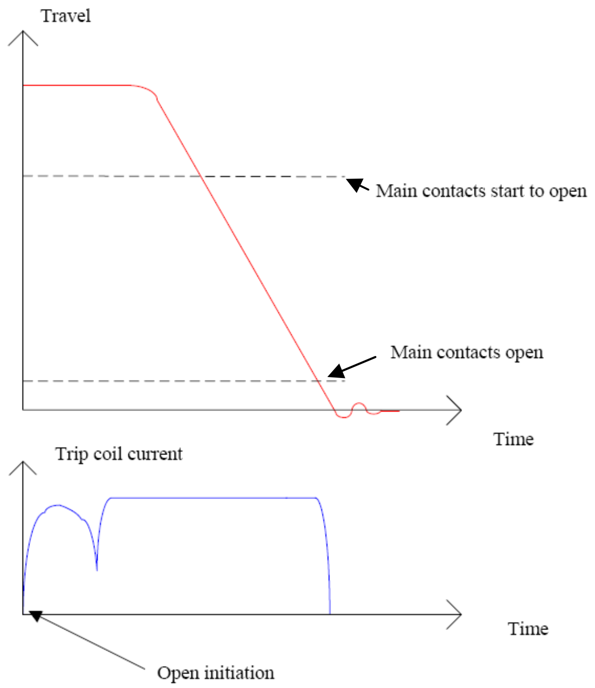


Figure 3.6: Diagram showing a typical circuit breaker opening travel curve

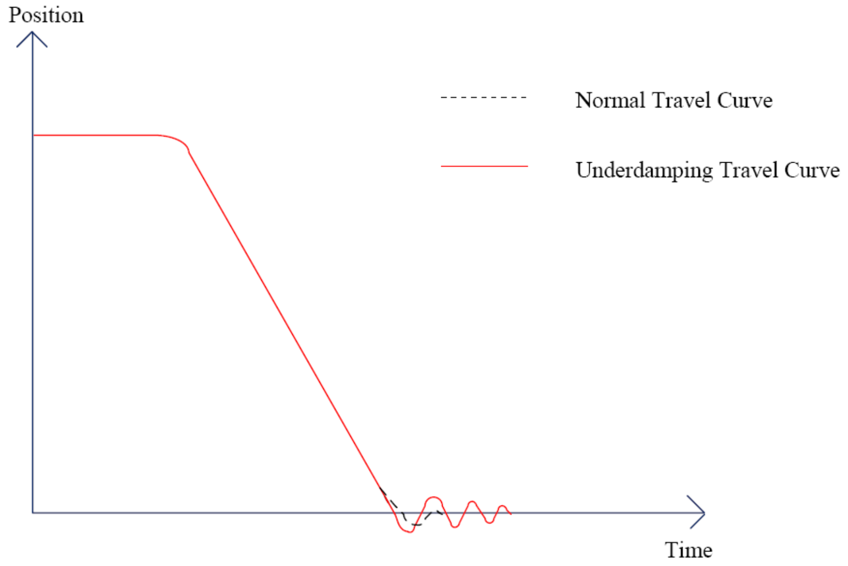


Figure 3.7: Diagram of a circuit breaker travel curve showing underdamping

The closing travel curve (Figure 3.8) is just as important, as parameters such as the speed at which the main contacts touch can be calculated. This factor is important in limiting premature wear of the contacts.

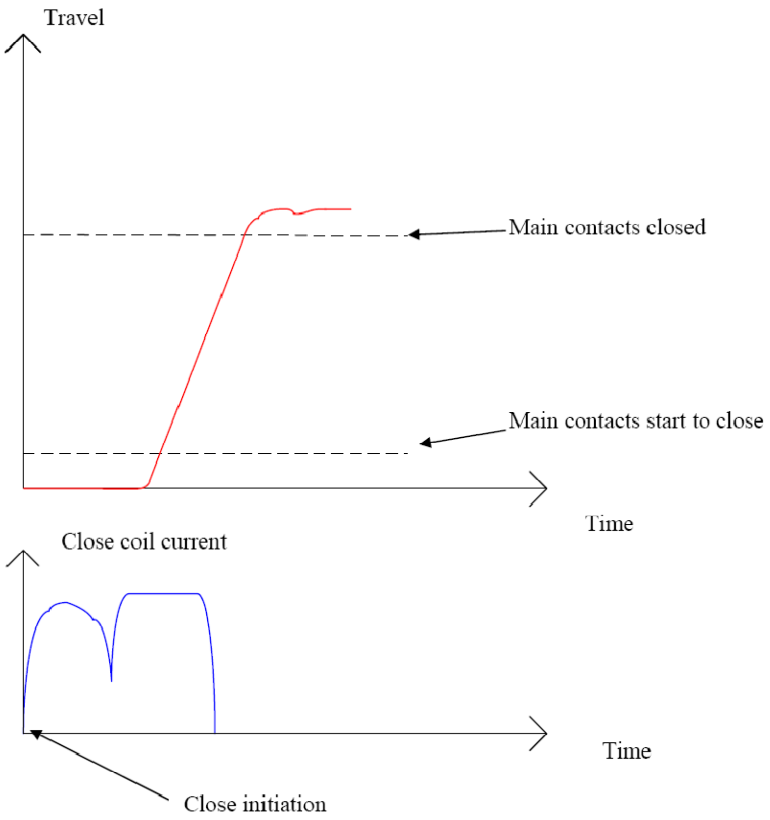


Figure 3.8: Diagram of a typical circuit breaker closing travel curve

By being able to follow the entire movement of the circuit breaker from beginning to end, the data can be combined with other information, such as the trip and close coil current characteristics to establish other key parameters such as the exact moment the contacts start to move.

3.6.5 Mechanism Cabinet Temperature

As the operating time of a circuit breaker varies with temperature [Alstom, 1999], as shown in Figure 3.9, it is not uncommon to measure this parameter. In addition, if the circuit breaker is an outdoor type some utilities will also measure the outside temperature to establish if there has been any deterioration of the mechanism cabinet.

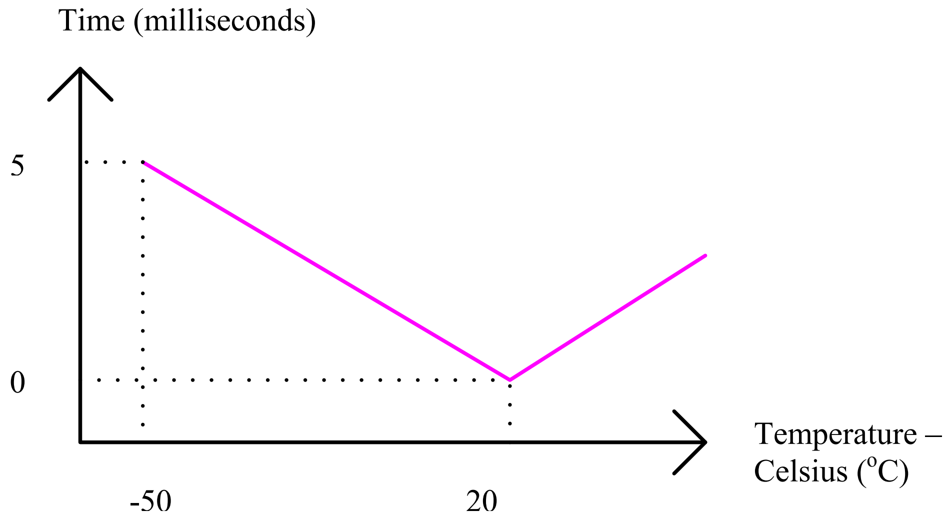


Figure 3.9: Diagram showing how a circuit breaker operating time can vary with temperature [14]

3.6.6 SF_6 Density

For an SF_6 type circuit breaker this parameter is directly related to its performance. As Figure 3.10 shows, the insulating properties of SF_6 decrease rapidly with decreasing pressure [Maller et al, 1981]. Unfortunately, regardless of how well the circuit breaker is designed, there will always be a small SF_6 leakage. Current international standards (IEC) [IEC 62271-203, 2003] limit this SF_6 leakage figure to 0.5% per annum, however some manufacturers can achieve 0.1% per annum.

[14] Derived from [Alstom, 1999].

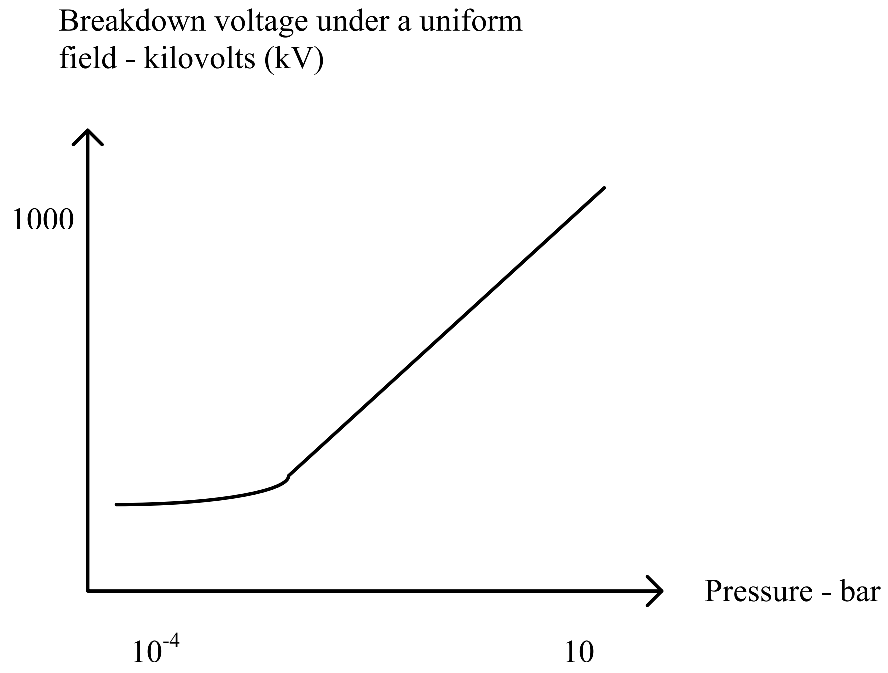


Figure 3.10: Graph showing breakdown voltage versus pressure for SF_6

Normally the SF_6 density is monitored continuously with thresholds set to indicate when the circuit breaker needs refilling and in the worst case there is also a lockout level to prevent operation when the circuit breaker is no longer capable of fulfilling its function.

More recently, long term trending and extrapolation has been carried out to ascertain if the leakage is symptomatic of a more serious problem and also to anticipate when circuit breakers will require to be refilled. This allows utilities to plan and co-ordinate their resources better.

3.6.7 Hydraulic Pressure

Measurement of the hydraulic pressure of a circuit breaker provides an indication of the energy stored in the operating mechanism and therefore whether the circuit breaker has the capability to operate as intended. As with the SF_6 density measurement, trending of the hydraulic pressure over time can be carried out to ascertain if there are any leakages.

3.6.8 Motor for Charging Mechanism

For each different type of mechanism, there will be a motor which is used to either charge the closing spring if it is a spring type mechanism, actuate the pump to pressurise the fluid if it is a hydraulic type mechanism or actuate the compressor if it is a pneumatic type mechanism.

Therefore, by measuring the motor running time or the number of operations in a given time it is possible to provide an early warning of an impending problem. For a hydraulic or pneumatic system, excess running time or an increased number of operations would indicate there is a leakage problem. Alternatively, for a spring type mechanism it could be gearing friction or a problem with the motor. In extreme cases it has also been known for some utilities to measure the motor current with sufficient resolution to allow them to examine the starting characteristic.

3.6.9 Primary Current

Measurement of the primary current can be combined with the travel curve information to provide further information of the operation of a circuit breaker. In addition, in [Cigré, 167, 2000] it is explained that for SF_6 type circuit breakers the integral of the square of the current broken by the arcing contacts can give a good indication of the main contact electrical wear. Namely:

$\int_{t_{arc}} i^2 \, dt$, where t_{arc} is the accumulated arcing time

However, guidance needs to be taken from the manufacturer as others [Cigré, 165, 2000; ETRA, 1996; and Cigré, 262, 2004] have reported that the exponent for the endurance rate can be different or dependent on the type of application, such as reactive and capacitive switching.

3.6.10 Number of Operations

When a circuit breaker is type tested, it must be able to carry out a minimum number of operations within its performance specification and not show any undue signs of distress, such as a change in the operating time that is greater than the allowed tolerance limit, at the end of the testing sequence [IEC 62271-100, 2001]. Normally this figure is 2,000 operations, but for special applications, such as reactor or capacitor bank switching, the figure can be as high as 10,000 operations. Consequently, many manufacturers recommend that this figure should be used as measure of the wear and tear on the mechanism, and as a guide to when a utility should carry out a major overhaul of a circuit breaker.

On the whole, the number of operations is a useful measurement, but some utilities have found that its relationship to the mechanical condition of a circuit breaker is not always valid. Namely, some circuit breakers will lie static in the closed position for a considerable period of time and may not operate for up to three years. Consequently the seals become brittle and the lubricating grease hardens so that when the circuit breaker is requested to operate, it results in a failure.

3.6.11 Insulating Oil

Insulating oil readily absorbs moisture, gases and particulate matter all of which lower the insulation strength and ultimately present a fire risk. In addition, carbonisation occurs from switching operations, which again affects the dielectric strength. Therefore, it is normal to check the condition of the insulating oil for both the oil circuit breaker tanks and the bushings to ensure properties such as sludge, oil flash point, viscosity, electric strength, water content, loss angle and resistivity are all within acceptable limits.

3.6.12 Resistance of Contacts

As described in section 2.4.8.3, some utilities [Salamanca et al, 1993] prefer to measure the dynamic resistance of the interrupters as a method to ascertain the electrical and mechanical wear of the arcing contacts.

Alternatively, some utilities will measure the resistance of the contacts in the closed position as a measure of their condition. This test is sometimes known as a "ductor test". A high resistance value would indicate there has been deterioration that could lead to a failure to interrupt or overheating of the contact assembly.

3.6.13 Air Pressure and Flow

As with SF_6, the circuit interrupting ability and electric strength of air increases as the gas density increases. Therefore, for ABCBs density, or more often pressure, is a critical parameter to measure. Apart from providing alarm and lockout thresholds to ensure safe operation, the parameter can provide information on an impending leakage problem.

As air under pressure has a higher concentration of moisture than at atmospheric pressure, any moisture in the air could condense onto insulation surfaces during a cold spell and result in insulation breakdown. Therefore to ensure that the spaces between the pressurised chamber of the ABCB and the porcelain are kept dry, it is normal to monitor the flow of what is usually known as the conditioning air. This is low pressure air, which is bled from the main inlet valve to the circuit breaker (refer to Figure 2.7).

3.6.14 SF_6 Gas Quality

During normal switching operation, the arcing in the SF_6 produces small amounts of arcing products due to reactions between the hot plasma and the contact materials. These arc products react with water, both in the liquid and gaseous phase, to produce a series of acidic compounds that can corrode the metal parts of a circuit breaker and damage certain types of insulating materials.

Although most of the impurities are eliminated by means of absorbing materials (normally activated alumina), which also absorb moisture, utilities will often still carry out periodic checks to measure the acidity, dew point and oxygen levels of SF_6. The latter causes oxidation, which contributes towards contact abrasion when breaking high currents.

3.6.15 Auxiliary Switches

Apart from being used to indicate when a circuit breaker is open or closed, measuring the time between the appropriate auxiliary contacts operating provides a simple method to determine the opening and closing times of a circuit breaker. This information can then either be used on its own or with other data, such as the trip and close coil current characteristics, to ascertain the condition of a circuit breaker.

3.6.16 Vibration Signatures

When a circuit breaker operates, a considerable amount of energy (up to 1kJ for a 50kA circuit breaker [Ryan, 1989]) is required to accelerate the mass of the moving parts, overcome friction, and cope with electromagnetic forces and pressure in the interrupter/arcing chamber. Consequently, vibration patterns will be generated and by measuring any deviations from the standard “fingerprint” it is reported [Runde et al, 1996 and Landry et al, 2008] that, by knowing when various parts operate during the opening or closing cycle, it is possible to identify which subcomponent has failed or is about to fail. The measurements are obtained using accelerometers and a typical trace will be shown in Figure 3.13.

3.6.17 Trip Circuit Supervision

It is common for utilities to continuously monitor important control circuits, such as the trip circuit, by injecting through it a small DC current. Any interruption of the circuit will generate an alarm thus alerting the utility operator to the failure.

3.6.18 Thermal Imaging

Infrared thermal imaging cameras are commonly used by utilities to detect any high resistance joints or contacts, which overheat and therefore emit thermal radiation.

The method is quick and easy to use and, provided an experienced operator is employed, can achieve reliable results. Apart from GIS circuit breakers, which are less accessible due to the surrounding enclosure, early warning of an impending failure can be detected, as modern cameras are sensitive to a change of one degree Celsius.

3.6.19 Arc Current Monitoring

In [Colombo et al, 1994] the application of an optical system is described to assess the internal condition of an HV circuit breaker interrupter unit. The system developed in [Colombo et al, 1994] uses a spectroscopic measuring system to analyse the light that is emitted from the arcing current to determine the temperature of the arc and the amount of material eroded from the contacts.

3.6.20 Heater Current/Control Circuit

Since the operating time of a circuit breaker varies with temperature, an alternative method to measuring the temperature within the mechanism cabinet is to monitor the heater current or more simply the heater circuit for any discontinuities.

The method is not as comprehensive as measuring the actual ambient temperature, but it does give an indication that there is a continuous heater control circuit.

3.6.21 Partial Discharge Monitoring

As will be described in Chapter 4, defects or foreign particles in GIS generate partial discharge activity some time before failure occurs. The Ultra High Frequency (UHF) method of Hampton and Meats [Hampton et al, 1988] is an effective means of detecting partial discharge in GIS so that action may be taken to prevent failures. In the UHF method, couplers as shown in Figure 3.11, are installed at intervals on the GIS to monitor and detect UHF energy radiated by discharging defects. Monitoring can either be performed during periodic site surveys by engineers using portable instruments or can be continuous, where the data can be accessed either locally or remotely. Using pattern recognition software, the data is analysed to determine the nature of the defect.

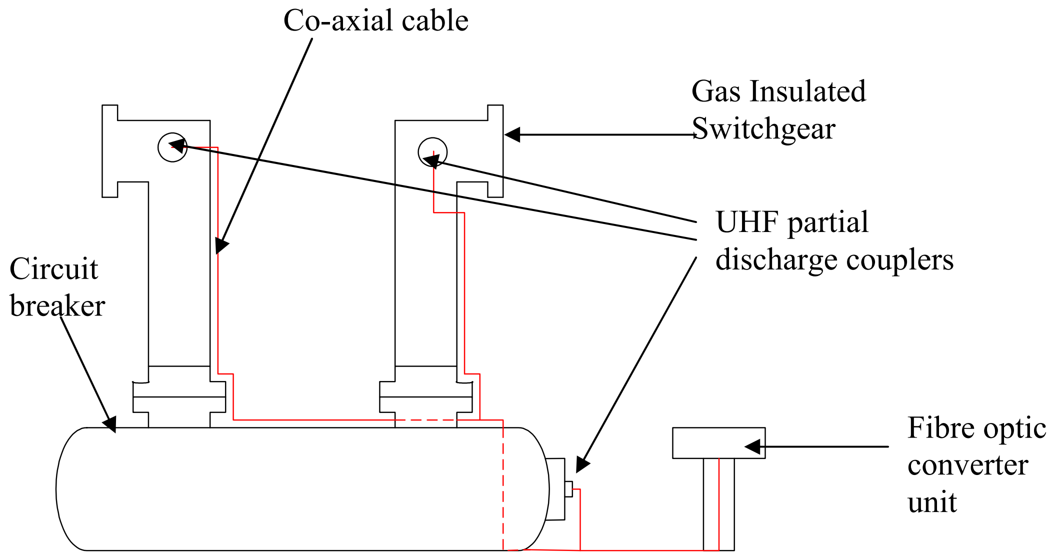


Figure 3.11: Diagram of a typical partial discharge monitoring system for GIS

3.7 Existing Experience with Circuit Breaker Condition Monitoring

There are currently many circuit breaker monitoring devices in commercial use or in the research and development stage that monitor either one or a selection of the parameters detailed in the previous section. These include OLMSs such as RTR-84 [Turnbull, 1994], CB Watch 2 [Alstom, 1999], BCM [Siemens, 2000], OLM [ABB, 2003], PCM-1 [Beattie et al, 1994], MONITEQ [Rajotte et al, 1996a], INSITE [Woodward et al, 1995; Woodward, 1996; and Sweetser et al, 2000], ESDM [Harris, 1996], Optimizer [Eastman, 1996], or off-line systems such as the STS120 [Pryor et al, 1999] and TR3000 [Wasfy, 1996] to name a few. However, the purpose of this section is not to review each of the circuit breaker monitoring devices currently available, but to examine the experience of users, particularly utilities, who have been examining the effectiveness of different monitoring techniques and condition monitoring in general as a future maintenance and asset management tool for HV circuit breakers.

The first of these examples is the experience of Swedish utilities who, in order to improve circuit availability and optimise maintenance procedures, have been examining the role and benefits of condition monitoring. For several years they have been employing off-line CBM for circuit breakers and as reported in [Hoff et al, 1992], the results so far have been extremely encouraging. The main parameters that are monitored are contact resistance, operating time and contact travel. However, depending on the type of circuit breaker and mode of operation, other parameters may be monitored such as trip and close coil currents. The main disadvantage that has been found with this strategy is that the time between functional checks can be long. On-line condition monitoring offers a potential solution to the problem, but the Swedish utilities have found a number of drawbacks, namely:

- The only parameter that a continuous measurement copes better with is the accumulation of interrupting current;
- For circuit breakers with a low operating frequency, there is a severe shortage of data as most of the measurements are taken only when the circuit breaker operates;
- For some failure modes, such as corrosion and loose bolts, it is not possible to apply on-line condition monitoring to measure their degradation;
- The Mean Time Between Failures (MTBF) for circuit breakers is in the order of ten times the MTBF for the electronic monitoring equipment; and
- It has been found uneconomical to apply on-line condition monitoring to old types of circuit breakers and circuit breakers that operate infrequently.

Although they conclude that there is still insufficient service experience to ascertain if on-line condition monitoring offers improved maintenance efficiency, they believe that for certain applications it can offer reduced maintenance costs and increased system availability. These applications include:

- Operation in an onerous climatic environment;
- Daily switching operations;
- At critical locations in the network where failure could result in a high financial cost; and
- A point in the network where the operating duty is severe, such as those involving reactor switching.

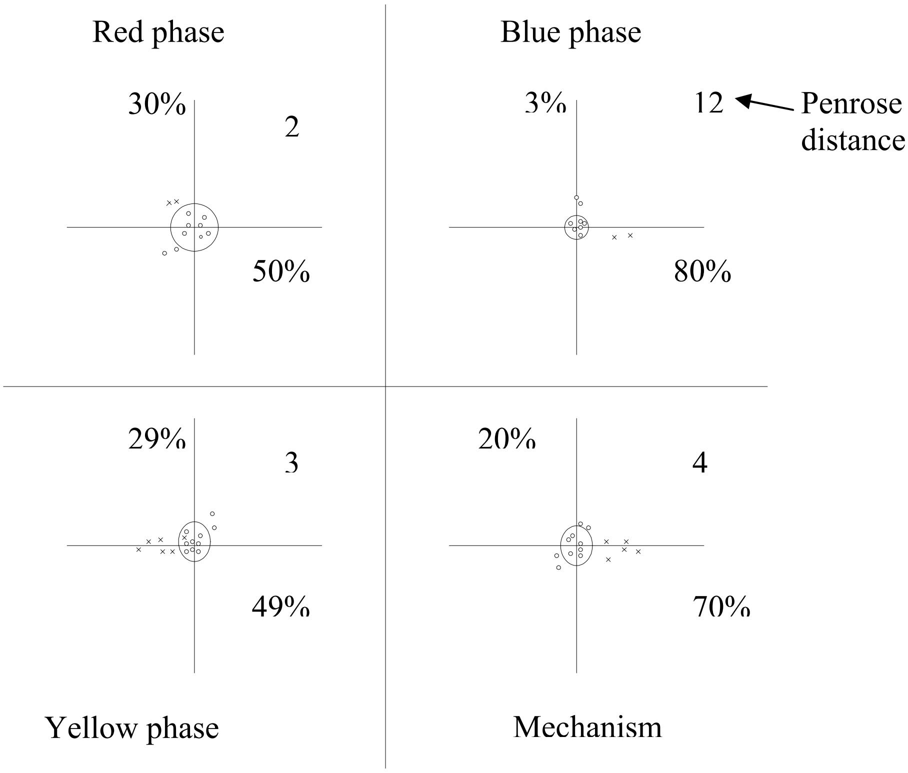
In addition, it is stated that, longer term, on-line condition monitoring of circuit breakers could be integrated into an overall substation monitoring system.

Following a number of circuit breaker interrupter failures, which resulted in considerable damage to the breakers themselves and neighbouring plant, the Power Grid Corporation of India decided to employ the Dynamic Contact Resistance Measurement (DCRM) technique to assess its remaining population of EHV circuit breakers [Tyagi et al, 2004]. Previously, maintenance of the interrupters had been carried out at predetermined intervals or after a specific number of operations as recommended by the manufacturers. However, after conducting a number of internal inspections of the circuit breaker interrupters, they found in a few cases that there was erosion of the main contacts well before any of the prescribed inspection periods. After introducing the DCRM technique they found thirty circuit breakers that could have failed catastrophically at any time and a further forty circuit breakers with defects that could have led to a major failure. Some of the defects found led them to re-design certain parts of the circuit breakers and since completing the exercise they have not suffered any major failures.

Using the trip coil current profile analysis technique described in section 3.6.1, TXU Electric [Speed, 2000] has been able to ascertain the condition of their circuit breaker population to prioritise their maintenance programme, thus minimising circuit outages. Initially they targeted their most problematic set of circuit breakers, which identified a number of failure modes such as damaged trip and close coils, lack of mechanism lubrication, and substation battery problems.

To carry out the programme of works required a two-man team, who took two months to test over 700 circuit breakers. For each circuit breaker they initially compared two sequential shots, to determine if the operating mechanism was sluggish and then they compared shots with other circuit breakers of the same type to prioritise it on the maintenance plan. The data was stored for future tests and using simple measurement criteria, such as whether the circuit breaker would de-latch within a certain time period, they were able to ascertain if a problem existed and the nature of the fault.

The development of a vibration monitoring system and the results of field tests are presented in [Voumard, 1994]. The system was developed with the objective of reducing maintenance costs by extending maintenance intervals through the use of non-invasive condition assessment techniques. However, unlike other condition monitoring techniques that compare the changes in the same key parameters or features for circuit breakers of the same type or model, the author [Voumard, 1994] describes that the effectiveness and accuracy is reduced considerably if this approach is adopted for vibration monitoring. For example, there can even be large deviation for circuit breakers that are manufactured from the same batch. Consequently, the programme that has been developed automatically selects the parameters or features that maximise the discrimination capability between healthy and faulty for each individual circuit breaker. A condition map, as shown in Figure 3.12, is then used to display the results where one point represents each feature. For the two features that contribute most towards discrimination power, the percentage contributions to discrimination are indicated for each axis. In addition, the "Penrose" distance is shown in the top right hand side corner of each graph, which is a measure of the distance for a cluster of key features between a healthy and a fault condition.



Note: Normal operation for red and yellow phases, with a fault existing on the blue phase.

where

0 = Healthy condition

X = simulated fault

Figure 3.12: Diagram showing a condition map analysis[15]

The results proved to be 95% accurate when tests were carried out to identify simulated faults; out of ninety-six tests, there were ninety-two positive identifications. However, when tests were conducted on data representing a healthy condition, the success rate was only 58%. Although it appears a poor result, the remaining 42% of data was marginally close to the healthy data set and the system classified the remainder as unknown as opposed to a fault condition. When the system was further developed to incorporate Artificial Intelligence (AI) techniques and an expert system, the diagnostic accuracy was increased to 90% from 58%. The

[15] Derived from [Voumard, 1994].

cost, on the other hand, increased in terms of computer time and space, but compared to the first system, it does not require a skilled operator to interpret the results.

In [Runde et al, 1996 and Høidalen et al, 2005] further experience and the potential benefits of vibration monitoring are presented. Like [Voumard, 1994], [Runde et al, 1996] reports that obtaining vibration patterns is relatively straightforward, whereas developing methods to interpret the patterns is far more difficult. As opposed to using AI techniques [Voumard, 1994], [Runde et al, 1996] uses Fourier analysis and dynamical time warping, where the latter is a technique that allows two vibration patterns to be synchronised to ensure that corresponding events are compared. As shown in Figure 3.13, the output of the analysis produces two graphs; Figure 3.13(a) shows the change in frequency content and amplitude between two vibration signals and Figure 3.13(b) displays the deviation in time between two signals. The reasoning behind the two graphs is that it enables all types of faults to be detected, e.g. a circuit breaker could have a serious fault, such as a mechanism misalignment, but still operate with the same speed and timing. Namely, there will be a change in the frequency content and amplitude graph, but it is unlikely that it would result in a change in the time versus time output. Similarly, a slow operation, through lack of lubrication, would not result in a change of the frequency content and amplitude of the vibration signal, but would be shown in the time versus time graph.

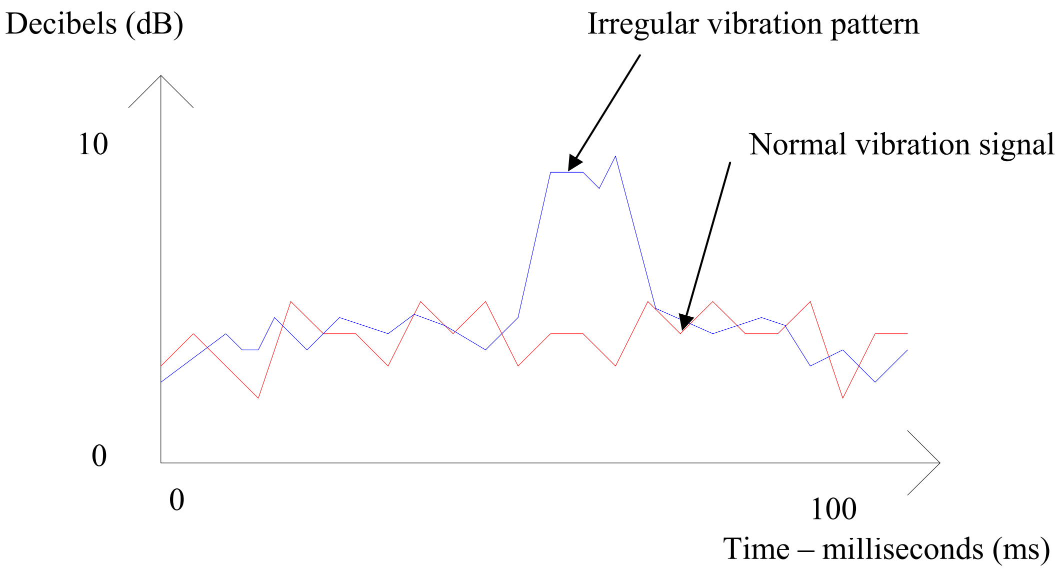


Figure 3.13a: Graph showing the deviation in amplitude versus time from the vibration analysis of a circuit breaker opening signal[16]

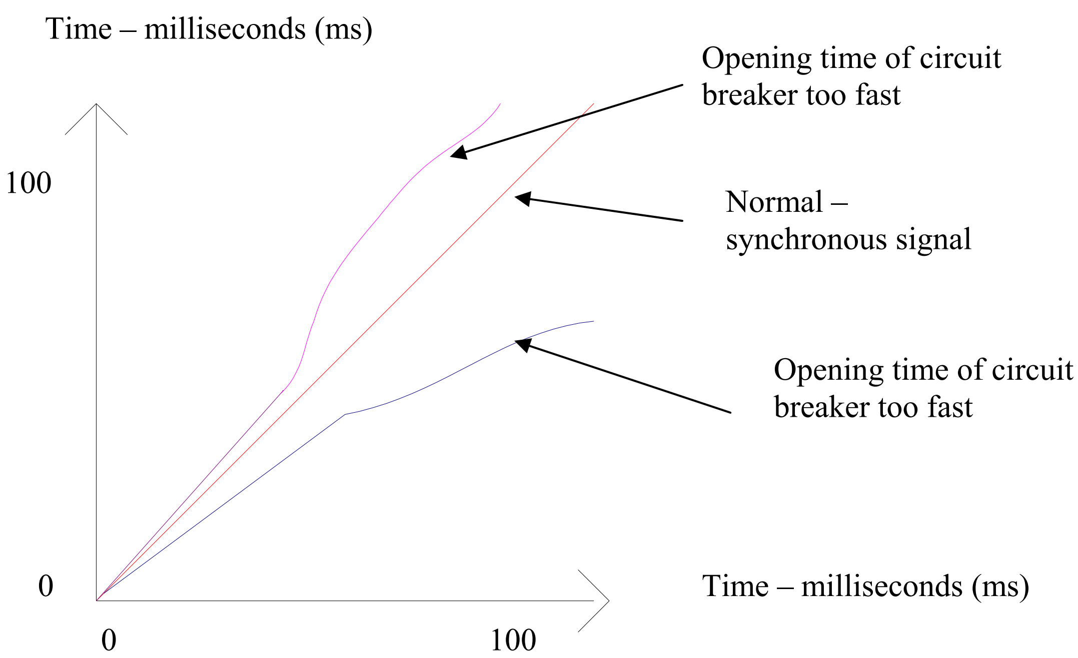


Figure 3.13b: Graph showing the deviation in time from the vibration analysis of a circuit breaker opening signal[17]

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[16] Derived from [Runde et al, 1996].
[17] Derived from [Runde et al, 1996].

Unlike [Voumard, 1994], the authors in [Runde et al, 1996] have found that corresponding sensor locations on different units are usually fairly similar. Consequently, by comparing different phases of the same circuit breaker or against previous "fingerprints", they have proved through field tests that their method produces encouraging results. Out of ninety-three identical spring operated single-phase SF_6 puffer circuit breakers, they concluded that eight units displayed clear signs of poor lubrication and three units indicated problems within the arcing chambers. Unfortunately, the utilities failed to act on the advice and within six months there were two severe malfunctions of the investigated circuit breakers from the group that displayed signs of poor lubrication. Investigations proved the authors to be correct and of the eight suspect units it was found that seven of them had been lubricated with the wrong grease during a previous overhaul. In addition, of the three units that displayed problems within the arcing chamber, it was found that two of them contained serious faults.

In [Høidalen et al, 2005], the technique of vibration monitoring is taken a step further, where the experience with an on-line system is reported. Using the same analysis techniques as previously described, a three-year in service trial was undertaken on the operating mechanisms of three different spring operated SF_6 circuit breakers. The results proved promising, with the system identifying a deviation in one of the circuit breakers, which later caused it to fail on command to open. However, a number of invaluable lessons were learned about OLMSs and what needs to be improved to make them a viable technical and economical proposition. In particular, the instrumentation needs to be robust and reliable for a substation environment.

More experience of on-line systems is reported by Southern California Edison (SCE) [Turnbull, 1994] who carried out pilot studies using a device called the RTR-84 that measures the response time of a circuit breaker by monitoring the following parameters:

- Trip coil current;
- Close coil current;
- Trip initiation signal;
- Close initiation signal;
- DC supply voltage; and
- Auxiliary contacts.

Overall they identified numerous problems, such as defective control coils, main contact bouncing and defective auxiliary switches. Consequently, since 1990 SCE has replaced the annual trip test with the RTR-84 and has moved from a TBM strategy to a CBM strategy for its population of circuit breakers. Although specific figures are not given, it estimates that labour savings of $1.2 million/year (1989 value) are possible through this strategy.

Similarly, China Light and Power (CLP) has been using on-line condition monitoring to monitor parameters such as gas pressure, timing of operation, and hydraulic and pneumatic system operation to reduce preventive maintenance and increase circuit breaker availability. More recently, they have been developing a system [Chan et al, 1996] to store the on-line data and perform a more detailed analysis of circuit breaker failures. Field trials at 400kV and 132kV voltage levels have been promising where the system has been responsible for preventing permanent damage to in service circuit breakers. Overall, the system would appear to strengthen CLP's existing CBM strategy for circuit breakers.

In 1990 the New York Power Authority (NYPA), Consolidated Edison Company of New York (Con Edison) and Hydro Quebec, in co-operation with the Empire State Electric Energy Research Corporation (ESEERCO) joined forces to research and develop a commercially viable OLMS capable of successfully predicting malfunctions within substation equipment, particularly circuit breakers, in an attempt to minimize costs and man hours. The system is called MONITEQ and the parameters monitored vary from circuit breaker to circuit breaker. However, from field results, the developers and users of MONITEQ profess significant cost savings as a consequence of this technology. For example in [Rajotte et al, 1996a], it is reported that the system allowed Hydro Quebec to analyse recorded temperature and pressure data to identify a problem with the thermal insulation of one of the tanks of an SF_6 circuit breaker. Without the system, they would not have had the data and therefore they believe that they would have incorrectly diagnosed the problem as a heater fault. This could have led to a further lockout of the circuit breaker costing $200,000/day.

Idaho Power Company (IDP) has used the INSITE system [Woodward et al, 1995; Woodward, 1996; and Sweetser et al, 2000], which is another OLMS that uses a combination of hardware and expert system software to continually monitor the health of substation equipment such as circuit breakers. Field trials have proved promising [Angell et al, 1997] where the system has already detected a number of circuit breaker defects. Although IDP do not give any specific figures, they are confident that the system and on-line condition monitoring in general is cost effective and reliable [Angell et al, 1999], and overall has helped them defer the replacement of ageing circuit breakers.

The Australian utility, Transgrid, has fitted on-line monitoring to more than sixty circuit breakers and through a web based system they are able to manage the data either locally or from a central remote location [Jones et al, 2003]. They have found that on-line monitoring has allowed certain planned periodic maintenance tasks to be reduced, such as interrupter timing, SF_6 gas density monitoring and the condition of the operating mechanism energy source. On the other hand, they have also concluded that there are some maintenance activities, such as contact resistance checks, that cannot be replaced with on-line condition monitoring.

Like [Høidalen et al, 2005], Transgrid raise concerns about the reliability of the condition monitoring, but they have a further concern about the ability of on-line condition monitoring to detect all potential deterioration trends that could lead to a failure of a circuit breaker. However, although it is not quantified and the circuit breakers currently fitted with on-line condition monitoring have yet to develop any faults, they still believe that on-line monitoring has helped to reduce maintenance costs and increase circuit availability. Consequently, they have plans to expand the current strategy to all new 330kV and 500kV circuit breakers, with particular emphasis on those installed on critical feeders.

The same reliability concerns are raised by the State Power Grid of China [Huang et al, 2006]. They have fitted on-line monitoring to approximately sixty circuit breakers and disconnectors, mainly measuring operating mechanism vibration, trip and close coil current, and accumulative switching current. However, although statistics are not given specifically for switchgear, the overall fault figures for on-line monitoring, which include four thousand systems covering transformers, surge arresters, GIS, voltage transformers and switchgear are highly alarming. Namely, the figures include:

- 170 faults with sensors and transducers;
- 130 faults related to computer or processor faults; and
- 110 communication interface faults.

Coupled with the high of number of false alarms and as re-iterated in [Li et al, 2006], it emphasises the need for improved reliability if OLMSs are to have a part to play in a utility's future maintenance strategy.

3.8 Future Challenges for Circuit Breaker Condition Monitoring

As has been discussed in the previous section, there are a number of commercially available circuit breaker condition monitoring systems. They differ in a variety of ways, from the type of sensors used to the overall design of the system. There have been many papers on the benefits of condition monitoring, such as [Beattie et al, 1994; Jones et al, 1994; CEA 485, 1996; Rajotte et al, 1996a; Rajotte et al, 1996b; Stanek et al, 2000; Nelson, 2001; Sweetser et al, 2002; Jones et al, 2003; and Kezunovic et al, 2005], where the arguments put forward range from a reduction in maintenance costs to the forecasting of equipment failures. However, apart from being economically viable, it is essential that these systems measure the correct parameters and do not affect the reliability of the circuit breaker itself. From a technical perspective, the selection will largely be dictated by the critical failure modes of a circuit breaker [Sanchis, 1996]. Thereafter, as will be demonstrated in the next chapter, careful attention should be paid to the installation of the transducers. For example, through practical experience the following guidelines are recommended:

- Transducers that are an integral part of a circuit breaker should be included in the type tests of a circuit breaker to prove their reliability;

- For similar reasons, where possible transducers should be non-invasive. For example, Hall effect devices for DC measurements and CTs for AC measurements should be employed as opposed to shunts. The former is required to accurately record parameters such as trip and close coil characteristics, as CTs only respond to changing current. Namely, a CT will give a zero output when there is a steady state coil current. Similarly, external triggering should be initiated from volt-free contacts to avoid compromising protection or control circuits;

- As described in [Dalke, 2005] there may be existing equipment, such as digital protection relays, that are already measuring some of the parameters;

- In order to minimise costs and prevent the possibility of introducing an operator error, any transducer should be capable of being replaced or removed without requiring major re-alignment of a circuit breaker mechanism and the associated testing to re-commission it;

- The replacement of pressure related transducers, such as hydraulic sensors, should not compromise the integrity of the system that they are measuring and careful consideration should be given as to how they are

- Similarly, the replacement of the S_{F6} gas density transducer should not require a circuit breaker to be de-gassed; and
- Any transducer that is exposed to rain, ice, snow, wind or extremes of temperature should have a suitable rating for operation in that hostile environment and be adequately protected to prevent damage from the weather.

The other major challenge for condition monitoring of circuit breakers is the storage and the interpretation of the data. Decision support tools such as expert systems, based on techniques such as Knowledge Based Systems (KBS), Case Based Reasoning (CBR) or Model Based Reasoning (MBR) [Jackson, 1990; Russell et al, 1995; McDonald et al, 1997; and Warwick et al, 1997], could be used to analyse the data to provide diagnosis of the failure mode.

3.9 Chapter Summary

This chapter has explained why there is a need for condition monitoring. It has explained briefly the current status of condition monitoring in the electricity supply industry and in particular explained its application, both off and on-line, to HV circuit breakers. As explained, there are many different techniques, which measure various aspects of the performance of circuit breakers, and the challenge for the user is to identify the failure modes and select the most appropriate method that will detect an incipient fault.

Through the experience of some utilities it is clear that condition monitoring can have a direct effect on costs, but there is a note of caution from some users with regard to the reliability of the monitoring equipment itself. Ideally it should be non-invasive, but with certain techniques that is not possible. Consequently, as is discussed in more detail in the next chapter, the user must ensure that the potential benefit is not offset by increased unreliability.

One other consideration is that with the demise of the "expert" within some utilities, it is vital that diagnostic tools to manage and interpret the data are developed. This will require close co-operation between research establishments, manufacturers and utilities.

Chapter 4

4 Development of an Economic Model for On-Line Condition Monitoring

This chapter reviews the existing economic models that are available to assess the viability of on-line condition monitoring for circuit breakers and by highlighting their shortcomings a revised model is developed. Through case studies it is shown that a utility needs to carefully consider factors such as the reliability of the OLMS itself and the selection of the monitored parameters, otherwise there is a risk of increasing the unavailability of a circuit breaker and its overall lifetime cost.

The chapter concludes by showing how this modified model can be easily adapted to other monitoring systems for other types of assets. In particular, it assesses the economic viability of applying a PDM system to a GIS substation.

4.1 Introduction

The development of a model to assess the economic viability of on-line condition monitoring is not an easy task. The key is to derive a method that allows the user to be able to calculate the lifetime cost of a circuit breaker with and without condition monitoring with relative ease, but at the same time provide sufficient accuracy to have confidence in the results.

As described in [Sanchis, 1996], an OLMS must reduce the lifetime cost of a circuit breaker to be justified from an economic point of view. This lifetime cost will include all expenditure associated with a circuit breaker's initial purchase, its maintenance and repair costs, and its decommissioning cost. Indirect costs such as insurance premiums and spares holding will also contribute to the lifetime cost of a circuit breaker.

It is also important to consider the lifetime cost of the condition monitoring equipment and its effect on a circuit breaker's lifetime cost if a true economic analysis is to be achieved.

4.2 Economic Approaches

In order to develop an economic model to assess the viability of on-line condition monitoring for a circuit breaker, the current economic evaluation approaches need to be reviewed as there are lessons to be learned, which will influence the development of the model presented later in this chapter.

One method for assessing the economic impact of OLMSs on preventive and corrective maintenance costs is presented in [Rajotte et al, 1996a and Rajotte et al, 1996b]. The authors recommend that the approach is applied individually to each type or model of plant and costs that are difficult to quantify are excluded at the initial stage in the assessment. These costs could include:

- Safety improvements;
- Increased knowledge of equipment and their associated failure modes;
- Increased remedial action efficiency in responding to equipment failures; and
- Reduction in environmental consequences from equipment failures.

To ascertain if on-line condition monitoring can be justified, [Rajotte et al, 1996a] uses equation 4.1, which in summary states that for an OLMS to be economically viable, its overall cost must be less than or equal to the savings in both preventive and corrective maintenance costs that are associated with applying on-line condition monitoring.

Examining equation 4.1 in more detail, the first step is to identify the cost of the condition monitoring. This is expressed by variable C and includes the purchase cost along with its installation and annual maintenance cost. It is interesting to note that the authors emphasise that the condition monitoring sensors should be non-intrusive to the equipment and be reliable. In addition, the parameters being monitored should be critical to the behaviour of the plant and its associated failure modes.

Having identified the plant to be monitored and the OLMS cost, the next steps in the assessment can be described as follows:

- List all maintenance actions and the frequency of carrying them out;
- Classify the importance of each maintenance action to determine if it is critical or is simply being carried out to maximise the use of an outage and resources;
- Ascertain the impact of the OLMS to determine whether the maintenance action is still required and, if so, whether its frequency can be reduced;
- Assess the savings obtained through the replacement or reduction in the maintenance actions;
- Convert the savings into an actual cost, which will be different for each utility, as it will be dependent on factors such as the cost of labour, transport and materials. This figure is expressed by variable B in equation 4.1; and
- Establish the impact of the OLMS to reduce costs associated with equipment failures. Only major failures are considered, such as those requiring fifty man-hours or more, as the authors believe the effect on minor failures is negligible (unfortunately, evidence is not provided to support this statement). Therefore, the first stage in this step is to calculate the major failure cost per item of equipment, expressed by variable D in equation 4.1, by examining the database of failures for the family of apparatus involved and the cost of each failure. The next stage is to consider the effectiveness of the OLMSs in detecting the signs leading up to the failure and the resultant reduction in major cost. This concept of effectiveness can be expressed as variable E in equation 4.1, which is the product of the probability that the OLMS will detect the impending signs of a major failure and the percentage decrease in the repair cost due to detection of an impending failure.

$$C \leq B + (D \times E) \tag{4.1}$$

where

B: Discounted annual monetary benefits of staggered inspections

C: Cost of the monitoring system

D: Discounted annual cost of major repairs and failures

E: Effectiveness index of the monitoring system

A different model is developed in [Sanchis, 1996], but generally the objective is similar to the previous model in that the author seeks to calculate the effect of the OLMS on the preventive and corrective maintenance costs of the plant under question. However, there are some important differences and assumptions between the two models. Namely:

- For corrective maintenance costs, apart from the effect on major failure costs, the effect on minor failure costs is also considered. Unlike the previous model, far from being negligible, the minor failure repair cost is considered equivalent to the major failure repair cost. In addition, explosive failures are considered as a separate item, as the cost in comparison to a major failure can be considerable. This allows the maintenance costs, without an OLMS to be defined as:

$$C_{maint} = PM + (\lambda_{MF} + \lambda_{mf} - \lambda_{expl}) \times (repair\ cost) + \lambda_{expl} \times (explosion\ cost) \tag{4.2}$$

where

λ_{MF}: The major failure rate of the plant

λ_{mf}: The minor failure rate of the plant

λ_{expl}: The explosive failure rate of the plant

PM: Preventive maintenance cost

C_{maint}: Cost of preventive and corrective maintenance without an OLMS

- Although the previous model may have included it within the major failure repair cost, this model treats the interruption to supplies that results from a major failure as a separate item, C_{outage}, and defines it as follows:

$$C_{outage} = \lambda_{MF} \times (delay\ to\ repair) \times (cost\ of\ outage\ per\ unit) \tag{4.3}$$

- If an OLMS is applied, the impact and difference between the maintenance costs can be defined as:

$$C_{maint} - C'_{maint} = PM - PM' - monitoring\ cost + (\lambda_{MF} + \lambda_{mf} - \lambda_{expl} - \lambda'_{MF} - \lambda'_{mf} + \lambda'_{expl}) \times (repair\ cost) + (\lambda_{expl} - \lambda'_{exp}) \times (explosion\ cost) \tag{4.4}$$

where

λ'_{MF}: The major failure rate of the plant with an OLMS

λ'_{mf}: The minor failure rate of the plant with an OLMS

λ'_{expl}: The explosive failure rate of the plant with an OLMS

PM': Preventive maintenance cost with an OLMS

C'_{maint}: Cost of preventive and corrective maintenance with an OLMS

- Similarly, the authors state that the difference in the outage disruption cost when an OLMS is applied can be defined as follows:

$$C_{outage} - C'_{outage} = (\lambda_{MF} - \lambda'_{MF}) \times (delay\ to\ repair) \times (cost\ of\ outage\ per\ unit) \tag{4.5}$$

where

C'_{outage}: The outage disruption cost with an OLMS

- The effect on the preventive maintenance costs is ascertained in a similar way to the previous model in that the maintenance actions are listed and an assessment is made as to whether the actions can be replaced or decreased in frequency through the use of an OLMS.

The approach described in [Hoff et al, 1992] is similar to the previous model in that it calculates the effect of an OLMS on the disturbance and maintenance costs for different types of circuit breakers. However, unlike the previous methods it attempts to include the effect on indirect costs, such as storage of spare parts and materials, and any effect on the organisation responsible for carrying out the maintenance. Unfortunately, the authors do not give much detail on how the costs and savings are calculated, but simply state them as a percentage of the purchase cost of the circuit breaker under question. Nevertheless, there are some important observations to note, namely:

- The authors recommend that the economic assessment for an OLMS should be carried out not just on the same family of circuit breakers, but also on different applications such as reactor switching;

- It is recognised that a failure does not always lead to a disturbance cost. The authors estimate the probability of creating a disturbance cost to be 25%, but unfortunately do not expand upon this point; and

- The authors treat any reduction in corrective maintenance through an OLMS as a preventive maintenance cost.

Another method of assessing the economic impact of an OLMS is presented in [Cigré, 167, 2000] and called the analytical or microscopic approach. As its name suggests, it is extremely detailed and lists all possible sources of preventive and corrective maintenance, and assesses individually the impact of an OLMS on each item.

To analyse the effect on corrective maintenance, it recommends that initially a Failure Mode Effects and Criticality Analysis (FMECA) should be carried out to identify each different type of failure. Having identified the failure modes, it proposes for each of them that the failure rate should be calculated and a judgement made as to whether an OLMS would be able to detect the signs of the impending failure. If the early signs of the failure can be detected, the impact on the corrective costs can then be assessed. Namely, the costs associated with a reduction in the repair time, labour and material benefits, and any saving in the cost of the outage. The information required can be summarised as shown in Table 4.1 and the savings can be calculated using equation 4.6.

$$S_{cm} = t_s \times S_{ts} \sum_j \lambda_j (C_{spFj} + \Delta t_j \times C_{oFj}) \qquad (4.6)$$

where

t_s: time span of observations (years)

S_{ts}: discount factor cumulated over t_s to obtain net present value

λ_j: rate of major failure "j" (failures/year)

Δt_j: reduction of outage duration due to OLMS (hour)

C_{spFj}: reduction in the cost of spare costs and manpower due to OLMS for failure "j"

C_{oFj}: outage cost for failure "j" (per hours)

S_{cm}: savings in corrective maintenance due to OLMS

Table 4.1: List of OLMS detectable corrective maintenance failures[18]

Type of Failure	Failure Rate	Reduction of Cost for Spare Parts and Manpower	Outage Cost	Reduction of Outage Duration
1	λ_1	C_{spF1}	C_{oF1}	Δt_1
.	.	.	.	.
j	λ_j	C_{spFj}	C_{oFj}	Δt_j
.	.	.	.	.
n	λ_n	C_{spFn}	C_{oFn}	Δt_n

With regard to the preventive maintenance costs, the analytical approach involves listing all the actions and making an assessment as to whether they could be replaced or postponed by an OLMS. Compared with the methods presented in [Rajotte et al, 1996a; Rajotte et al, 1996b; Sanchis, 1996; and Hoff et al, 1992], the analytical approach treats each maintenance action in isolation and attempts to assess the individual saving in either outage or manpower costs when an OLMS is employed. Converting the costs to an NPV and summing them allows the total preventive maintenance savings to be calculated according to equation 4.7:

[18] Derived from [Cigré, 167, 2000].

$$S_{pm} = \sum_j (C_{mj} + C_{oj})/t_s \left(\sum_{k=1}^{ts/yjk} 1/(1+\tau) \right)^k \quad (4.7)$$

where

t_s: time span of observations (years)

C_{mj}: manpower cost of the task "j"

τ: rate of discount for actualisation of costs

y_{jk}: frequency of task "j" (1 year, 5 years, etc)

C_{oj}: outage cost for failure "j"

S_{pm}: Savings in preventive maintenance due to an OLMS

k: period of maintenance task "j"

Overall, the analytical approach has the potential to be extremely accurate, but as is shown later in the chapter it would be difficult to implement due to a lack of data for each of the specific failure modes. In addition, through case studies, it has been shown that it is impractical to allocate cost savings against each individual preventive maintenance task.

A more high level method is the resource driven or macroscopic approach described in [Cigré, 167, 2000 and IEEE C37.10, 1995]. Through an FMECA analysis or field trial the user identifies the impact on resources when employing an OLMS strategy. Compared to the previous methods, there is no longer a need to analyse the impact on each maintenance task or failure mode. Therefore, it should be easier to implement, particularly when there is a lack of input data. However, apart from being extremely subjective, the approach does not allow for factors such as disturbance costs to be captured, which, as is shown later in the chapter, can be enough on their own to justify an OLMS.

The final method to be considered is the synthesis approach [Cigré, 167, 2000]. This method can be viewed as a compromise between the analytical and resource driven approaches or a further development of the approaches described in [Rajotte et al, 1996b and Sanchis, 1996]. Unlike the resource method, the synthesis approach has the potential to provide more accuracy, whilst at the same time be more practical to implement than the analytical method, as it utilises parameters where the source data can be readily obtained from either a utility's own historical records or internationally published material. Like the method described in [Sanchis, 1996], it recognises the importance of minor failures and outage costs, but expands upon the treatment of the latter.

As described in [Cigré, 167, 2000] for corrective maintenance costs, the synthesis approach treats minor, major and explosive failures separately, and develops equations for each of them to ascertain the cost with and without an OLMS. It also makes an important distinction between minor and major failures, which is discussed later in the chapter. Namely, it assumes that major failures and explosive failures will always lead to an unplanned outage. However, for minor failures there will always be time to plan the outage, which means that an OLMS will not have any effect on either the cost to repair the minor failure or the cost of the outage. Therefore the equations to calculate the corrective cost for minor failures, with and without an OLMS, are the same and can be defined as follows:

$$m_1 = mfr(mrc + (mrt \times poc)) \tag{4.8}$$

$$m_2 = mfr(mrc + (mrt \times poc)) \tag{4.9}$$

where

- m_1: minor corrective cost without an OLMS
- m_2: minor corrective maintenance cost with an OLMS
- *mfr*: minor failure rate
- *mrc*: minor failure repair costs , including materials, labour and transport
- *mrt*: minor failure repair time or outage duration
- *poc*: planned outage cost, which includes factors such as constraining generation, interconnection or compensation to customers.

As for the major failure corrective costs, the synthesis approach uses similar terms to the method described in [Sanchis, 1996] to allow for the reduction in the major repair cost and major failure rate when an OLMS is able to detect the signs of an impending failure. However, it introduces a new term to differentiate between a planned and unplanned outage cost. Therefore the equations to calculate the corrective cost for failures with and without an OLMS can be defined as follows:

$$M_1 = MFR(MRC + (MRT \times UOC)) \tag{4.10}$$

$$M_2 = P_d \times MFR((P_c \times MRC) + (P_c \times MRT \times poc)) + (1-P_d)MFR(MRC + (MRT \times UOC)) \tag{4.11}$$

where

M_1: major corrective cost without an OLMS

M_2: major corrective maintenance cost with an OLMS

MFR: major failure rate

MRC: major failure repair costs, including materials, labour and transport

MRT: major failure repair time or outage duration

UOC: unplanned outage cost

P_d: probability of detecting the signs of an impending major failure

P_c: percentage reduction in major failure cost due to early detection by an OLMS

poc: planned outage cost

Finally, the probability of detecting the early signs of an explosive failure is treated as a major failure repair cost by the synthesis approach. Therefore, the equations to calculate the corrective cost for failures with and without an OLMS can be defined as follows:

$$E_1 = EFR(ERC + (ERT \times UOC)) \quad (4.12)$$

$$E_2 = Pd \times EFR((Pc \times MRC) + (Pc \times MRT \times poc)) +$$

$$(1\text{-}Pd)EFR(ERC + (ERT \times UOC)) \quad (4.13)$$

where

E_1: explosive corrective maintenance cost without an OLMS

E_2: explosive corrective maintenance cost with an OLMS

EFR: explosive failure rate

ERC: explosive failure repair costs, including materials, labour and transport

ERT: explosive failure repair time or outage duration

Considering equations 4.8 to 4.13, the overall benefits associated with an OLMS, with regard to corrective maintenance costs can be determined as follows:

$$(m_1 + M_1 + E_1) - (m_2 + M_2 + E_2)$$

$$= P_d \times MFR[(1\text{-}P_c)MRC + MRT(UOC\text{-}(P_c \times poc))] +$$

$$P_d \times EFR[(ERC - (P_c \times MRC)) +$$

$$((ERT \times UOC) - (P_c \times MRT \times poc))] \quad (4.14)$$

As for the preventive maintenance costs, the synthesis approach calculates the savings from an OLMS in exactly the same way as [Sanchis, 1996]. Namely it lists the preventive inspections, routine maintenance and overhauls required throughout the life of the plant and assesses whether an OLMS could replace or postpone any of the maintenance tasks. Unlike the analytical approach, it assesses the cost for each inspection or overhaul as a whole, as opposed to trying to allocate a cost to each individual maintenance task. Even if nine out of ten maintenance actions are replaced with an OLMS, the one remaining action can still cost a considerable amount due to the fixed cost aspects such as travelling, set up and outage costs. This is one of the reasons why [Rajotte et al, 1996b] suggests differentiating between the critical maintenance tasks and the secondary tasks, which are being included to maximise the use of maintenance resources or the outage period. Having identified the revised inspection, maintenance and overhaul costs with an OLMS, an NPV analysis can be used to calculate the preventive cost for the life of the plant and therefore establish the benefit by comparing the figure with the preventive maintenance costs when an OLMS is not employed.

Of all the methods considered so far, the synthesis approach would appear to be the most promising both from a practical and accuracy point of view, as it concentrates on the benefits that are easily quantifiable and justifiable. There are other potential benefits that are less easily quantifiable. For example, it has been suggested that through more frequent inspections [Anders, 2004], which can be achieved through devices such as an OLMS, the life of a circuit breaker could be extended. This is turn will lead to a saving through a delay in investing in a replacement circuit breaker. However, these claims will take a number of years to prove or disprove. Similarly, there are so-called benefits that on closer inspection are not savings at all. For example, suggestions that an OLMS could reduce the time and resources required to commission a circuit breaker [Cigré, 167, 2000] has been found by a domain expert to be counter balanced by the additional effort required for the commissioning of the condition monitoring system itself. Consequently, the synthesis approach should be adopted with a view to introducing these possible longer-term benefits at a later stage. However, there are limitations with the synthesis approach and these must be addressed otherwise there is a risk of drawing the wrong conclusion regarding the economic viability of an OLMS for HV circuit breakers.

The main limitation, in common with all the other methods, is that the approach does not consider the reliability of an OLMS. In particular, it is shown that if the reliability of an OLMS is ignored it could result in misleading conclusions about the viability of an OLMS.

4.3 Reliability of On-line Condition Monitoring Systems

Ideally the condition monitoring system should not impact on the performance of a circuit breaker, be completely reliable and have an asset life that is equal to or greater than the monitored circuit breaker. Unfortunately, in reality, this is not the case. Experience has shown that even if a failure of the condition monitoring system does not result in a forced or planned outage of the circuit breaker, a cost is still incurred in repairing it. Consider the scenario where a temperature transducer that is located within a circuit breaker marshalling kiosk fails. Although it is non-intrusive to the circuit breaker and can be replaced without taking an outage, someone still needs to travel to the site to replace it. Depending on the geographical coverage of the utility concerned, this could involve up to one or more days. Therefore, despite it initially appearing as a negligible cost it soon adds up, particularly if it happens on a number of occasions. Consequently, the synthesis approach needs to be modified to take into account the failure rate of an OLMS.

A failure of an OLMS can affect a circuit breaker in three ways. The first is where the failure of the condition monitoring system, whether it is a transducer or the microprocessor unit, results in a failure that does not require a planned outage to repair and re-commission it. An example would be the failure of the temperature transducer. The second scenario is where the failure results in a planned outage. For example, a failure of a travel transducer would probably necessitate an outage to re-commission it whether this is due to safety implications or simply to re-calibrate the transducer. This point highlights the importance of ensuring, where possible, the need to test the transducers as part of the circuit breaker type tests [IEC 62271-100, 2001 and IEC 62271-203, 2003]. For both these aforementioned failure scenarios, the work could be planned and would not result in an unplanned outage cost. However, for the third scenario, depending on how the condition monitoring system is applied to a circuit breaker, a failure may result in an unplanned outage. For example, a failure of a hydraulic pressure transducer, for an operating mechanism, could lead to this situation. This point is extremely important and emphasises why there is a preference for a non-invasive design.

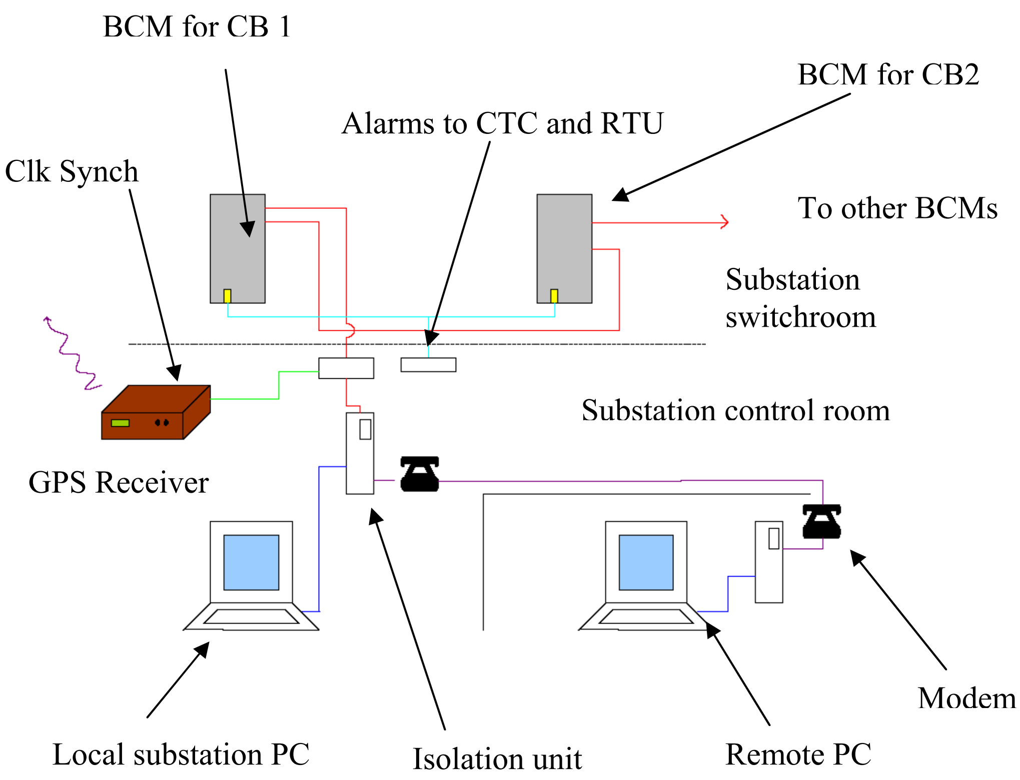
As the repair work for the first two failure scenarios could be planned and would not result in an unplanned outage cost, they have been classified as a minor failure. However, the third failure mode has been classified as a major failure due to the possibility of it causing an unplanned outage. The word possibility has been used deliberately, as it is linked to the definitions of major and minor failures. The implication for the equations that are used by the synthesis approach is covered in more detail later on in this chapter. However, as an interim explanation, if the definitions given in [Cigré, 83, 1994] are considered, a major failure does not always cause an unplanned outage cost. Namely, it is defined as:

"A major failure will result in an immediate change in the system operating conditions, e.g. the backup protective equipment being required to remove the fault, or will result in mandatory removal from service for non scheduled maintenance. (Intervention required within 30 minutes)."

For completeness, the probability of an OLMS fault causing an explosive failure was considered, but it is believed that this scenario is extremely unlikely and therefore has not been pursued any further.

4.4 Life time costs of a condition monitoring system

Apart from the costs associated with the minor and major failure rates of an OLMS, as discussed in [Rajotte et al, 1996b and Sanchis, 1996], it is essential to include the initial purchase and installation costs. As shown in Figure 4.1, this figure needs to include the costs of any support equipment such as personal computers and any associated software. It is also important to consider the lifetime costs and whether an OLMS will need to be replaced during the life of a circuit breaker. For example, in the UK [NGTS 2.2, 1999] switchgear is generally specified for a minimum life of forty years where as monitoring systems are typically specified for fifteen to twenty years [TGN 157, 2001 and SP, 2005] due to the life of electronic components. Consequently, it is highly probable that an OLMS will need to be replaced, at least once during the life of a circuit breaker. Furthermore, examining the annual drift rate of some of the transducers and considering the manufacturers' recommendations [Trafag, 2002], it is likely that calibration checks on the system will be required every 5 to 10 years. Therefore all preventive maintenance costs for an OLMS need to be included in the economic viability study as well.



where

BCM: Breaker Condition Monitoring

GPS: Global Positioning System

Clk Synch: Clock Synchronisation

PC: Personal Computer

CTC: Circuit Termination Cubicle

RTU: Remote Terminal Unit

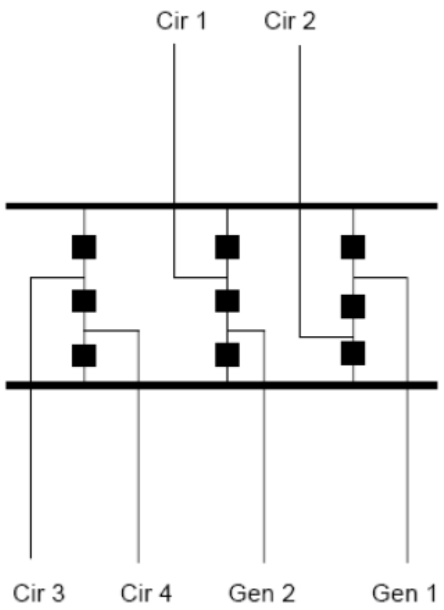
CB: Circuit Breaker

Figure 4.1: Diagram showing a typical circuit breaker on-line condition monitoring system

4.5 Planned and Unplanned Outage Costs

With regard to the treatment of unplanned outage costs, experience has shown that there is an element directly related to the repair time of a circuit breaker, but there is another element that is not [SP, 2002a and SP, 2002d]. For example, consider a nuclear generating site where a circuit breaker failure that results in a loss of generation may be returned to service long before the generator is restored to full load due to the time to re-start a reactor. In addition, there is also the possibility that, depending on the nature of the failure, such as an SF_6 leak, there may be time to remove a circuit breaker from the system before it causes an unplanned outage cost. Therefore, in the revised model, shown in section 4.7, the unplanned outage cost has been left as a single factor, unrelated to the duration of the outage, but multiplied by a factor to account for the probability of whether it will occur or not. It is also the reason why in the previous section the statement was made that not all major failures lead to an unplanned outage cost.

The outage cost that is related to the duration of the outage has been defined as the planned outage cost in the revised model. Clearly, whether a cost results is also dependent on the substation configuration. For example, for a one and half switch substation arrangement, as shown in Figure 4.2, unless there is an outage of the adjacent circuit breaker, there is an alternative electrical path and therefore an outage cost can be avoided. However, for a double busbar configuration, as shown in Figure 4.3, an outage cost is unavoidable. Consequently, the planned outage cost (*poc*) has been modified by a factor (α), which takes a value of unity if the failure of a circuit breaker directly affects the loss of generation or supplies.



where

Cir: Circuit

Gen: Generator

■ : Denotes a Circuit Breaker

Figure 4.2: Diagram showing a one and a half switch substation configuration

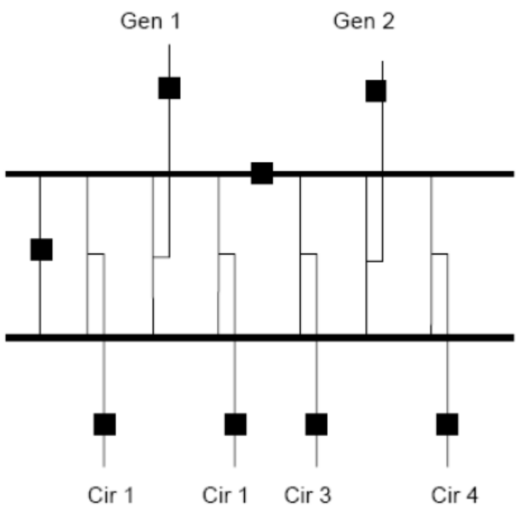


Figure 4.3: Diagram showing a double busbar substation configuration

4.6 Major and Minor Failure Repair Costs

In [Rajotte et al, 1996b] the statement was made that if an OLMS is able to detect the impending signs of a major failure, the cost of the repair can be treated as equivalent to a minor failure. From analysing a major UK utility's circuit breaker failure history over an eighteen-year period [SP, 2002a] it is considered that this statement is a reasonable assumption and therefore the synthesis approach equations have been modified accordingly. The minor repair cost for condition monitoring faults can be treated in the same manner, with a value equal to the minor failure cost of a circuit breaker.

4.7 Modified Synthesis Approach

Considering the aforementioned points, the equations given for the synthesis approach for the corrective maintenance costs, with and without an OLMS, can be re-written as shown in equations 4.15 to 4.20.

Examining equation 4.15 to calculate the minor failure cost when on-line condition monitoring is not employed, the cost includes the labour and material resources (minor repair cost – *mrc*) to repair the fault (mfr_{cb}) and depending on the substation layout (α) the cost per hour of taking an outage (planned outage cost - *poc*), which is directly proportional to the repair time (*mrt*).

On the other hand when an OLMS is applied, the minor failure cost, as shown in equation 4.16, also includes the probability of detecting (P_d) a major failure of a circuit breaker (MFR_{cb}) early. Similar to before this includes the repair cost along with any planned outage cost. In addition, as discussed previously, the minor failure cost needs to allow for detecting any major failures associated with an OLMS (MFR_{cm}) as well as any minor failures. This includes OLMS minor failures that necessitate an outage (mfr_{cmo}) and minor failures that can be repaired without taking an outage (mfr_{cmn}), but still incur a resource and material repair cost.

Minor Failures:

$$mf = mfr_{cb}(mrc + (mrt \times poc \times \alpha)) \quad (4.15)$$

$$mf_{cm} = mfr_{cb}(mrc+(mrt \times poc \times \alpha))+ P_d[MFR_{cb}(mrc+(mrt \times poc \times \alpha)) + MFR_{cm.}(mrc+(mrt \times poc \times \alpha))]+ mfr_{cmo}(mrc + (mrt \times poc \times \alpha)) + mfr_{cmn} \times mrc \quad (4.16)$$

As shown in equation 4.17 for the major failure cost, when an OLMS is not applied, the cost includes the material and labour resources (*MRC*) to repair the fault along with any planned outage cost, which similar to the minor failure cost is directly proportional to the major failure repair time (*MRT*). However, unlike the minor failure cost, the probability (P_t) of causing an unplanned outage cost (*uoc*) also needs to be included.

With reference to equation 4.18, when an OLMS is applied, the major failure cost consists of the costs associated with any major failures that are not detected by an OLMS $(1-P_d \times MFR_{cb})$ along with the costs to repair any major failures associated with an OLMS. Similar to before, an OLMS major failure could result in an unplanned outage cost.

Major Failures:

$$MF = MFR_{cb}(MRC + (MRT \times poc \times \alpha) + (P_t \times uoc)) \quad (4.17)$$

$$MF_{cm} = (1- P_d)[MFR_{cb}(MRC + (MRT \times poc \times \alpha) + (P_t \times uoc)) + MFR_{cm}(MRC + (MRT \times poc \times \alpha) + (P_t \times uoc))] \quad (4.18)$$

As shown in equation 4.19 for the explosive failure cost, when an OLMS is not applied, the cost includes the material and labour resources (*erc*) to repair the fault (*efr*) along with any planned and unplanned outage costs where the former is directly proportional to the time to repair the failure (*ert*). However, unlike the major failure cost, the unplanned outage cost is unavoidable.

With reference to equation 4.20, when an OLMS is applied, the explosive failure cost consists of the costs associated with any explosive failures that are not detected by an OLMS $(1\text{-}P_d \times efr)$ along with the costs to repair any explosive failures that can be detected early by an OLMS, which can treated as equivalent to repairing a major failure.

Explosive Failures

$$ef = efr(erc + (ert \times poc \times \alpha) + uoc) \quad (4.19)$$

$$ef_{cm} = (1\text{-}P_d)efr(erc + (ert \times poc \times \alpha) + uoc) +$$

$$P_d \times efr(MRC + (MRT \times poc \times \alpha) + (P_t \times uoc)) \quad (4.20)$$

where

MRC: the major failure repair cost

mrc: the minor failure repair cost

erc: the explosive failure repair cost

MRT: the major failure repair time

mrt: the minor failure repair time

ert: the explosive failure repair time

MFR_{cb}: the major failure rate of the circuit breaker

mfr_{cb}: the minor failure rate of the circuit breaker

efr: the explosive failure rate of the circuit breaker

Pd: the probability that the condition monitoring will detect a failure before it occurs

mfr_{cmn}: the minor failure rate of the condition monitoring system when it can be repaired without causing an outage of the circuit breaker

mfr_{cmo}: the minor failure rate of the condition monitoring system that will cause an outage of the circuit breaker to repair or re-commission it

MFR_{cm}: the failure rate of the condition monitoring system that will cause a major failure of the circuit breaker

α: a factor that assumes the value of unity if the failure of the circuit breaker directly affects loss of generation, interconnection or customers, otherwise it assumes a value of zero

mf: the cost due to minor failures without an OLMS

mf_{cm}: the cost due to minor failures with an OLMS

MF: the cost due to major failures without an OLMS

MF_{cm}: the cost due to major failures with an OLMS

ef: the cost due to explosive failures without an OLMS

ef_{cm}: the cost due to explosive failures with an OLMS

P_t: the probability that a major failure will cause an unplanned outage cost

poc: the planned outage cost

uoc: the unplanned outage cost

4.8 Case Studies Using the Modified Synthesis Approach

Using the modified synthesis approach this section presents the results from three case studies to examine the economic feasibility of implementing an on-line CBM strategy. Each one involves a 300kV SF_6 single pressure circuit breaker with a spring mechanism, but applied in various scenarios to examine the effect of different unplanned outage costs. The first examines an NSC application, the second an interconnector circuit and the third a generator circuit. In the first scenario the unplanned outage costs are low, whereas for the other examples it is the opposite situation. With regard to the condition monitoring system, a commercially available system was used, which is manufactured by the same manufacturer as the circuit breaker used in these case studies.

4.8.1 Preventive Maintenance

From Chapter 2, a typical TBM strategy for an SF_6 single pressure circuit breaker with spring mechanism is as shown in Table 4.2:

Table 4.2: Typical TBM Schedule for an SF_6 single pressure circuit breaker

Maintenance Frequency	**Main Tasks**
Monthly Check	Visual
Annual	Thermovision Survey
3 Yearly Minor	Check heating, counter reading, SF_6 pressure & operate circuit breaker. Timing and conductivity testing. Pressure switches/control scheme functional checks.
20 Year Overhaul/ mid - life condition assessment	Major maintenance & Inspect Interrupters*

* Dependent on number of operations

If an OLMS is applied, from discussions with experienced utility operational personnel, it is believed that the monthly inspections and the annual thermovision survey would still be required. However, provided a circuit breaker is opened and closed remotely every year and calibration checks are carried out every ten years, the minor maintenance could be eliminated. Furthermore, by monitoring the parameters that give an indication of interrupter wear, it is believed that eliminating the need to open up the interrupters could reduce the twenty-year overhaul costs. On the other hand, the overhaul will need to include the replacement costs for the condition monitoring system, as it is assumed that it will only have a twenty-year life.

4.8.2 Corrective Maintenance

Equations (4.15) to (4.20) were used to calculate the corrective maintenance costs for the three scenarios with and without on-line condition monitoring. As reliability figures did not exist for the condition monitoring system, an estimate was calculated for its component parts (system and transducers) from standard commercially available reliability data [Oreda, 2002]. To enhance the accuracy of this method, the data was selected from plant that operates in a similar environment and application.

The minor and explosive failure rates were taken from [Cigré, 83, 1994]. However, for the major failure rate, figures from [SP, 2002a] were used as they have sponsored this research and it was found that there was a large difference when compared with [Cigré, 83, 1994]. Similarly, minor, major and explosive failure costs and repair times were derived from the information received from [SP, 2002b and SP, 2002c], which is a major UK utility. With regard to the probability that the condition monitoring will detect a failure before it occurs, circuit breaker fault statistics from [SP, 2002a], going back nearly twenty years, were analysed to determine a value. The same method was used to determine a value for the probability that a major failure would result in an unplanned outage cost. Planned and unplanned outage costs were calculated by first determining the loss of capacity or load that would result when the circuit breaker under question needs to be removed from service due to a major or explosive failure. By using average generation costs from [SP, 2002d] and the minimum time to restore capacity or load, the potential loss of profit and consequential loss was determined. Unfortunately, the figures from [SP, 2002d] are confidential and therefore cannot be published. However, as stated previously, a utility should be able to calculate their own figures with relative ease.

Table 4.3 summarises the change in operating costs when on-line condition monitoring is applied based on the aforementioned data. The values are given as a percentage increase (+) or decrease (-) of the costs when on-line condition monitoring is applied.

Table 4.3: Summary of cost savings when a circuit breaker (CB) is fitted with on-line condition monitoring

Maintenance Type	**NSC CB Cost Savings/Year (%)**	**Interconnector CB Cost Savings/Year (%)**	**Generator CB Cost Savings /Year (%)**
Preventive	-3	59	-3
Corrective	8	35	39
Total	6	42	32

Note: A symbol (-) denotes a cost increase

It is clear that where there is a high unplanned outage cost, there is an economic argument for on-line condition monitoring, whereas for the NSC circuit breaker, the case is more marginal. However, had the reliability and maintenance costs of the condition monitoring system been ignored, Table 4.4 illustrates how a different conclusion could have been reached. Namely, it appears from this perspective that there is a strong economic justification to fit condition monitoring to all circuit breakers.

Table 4.4: Summary of cost savings when condition monitoring system reliability and maintenance costs are ignored

Maintenance Type	**NSC CB Cost Savings/Year (%)**	**Interconnector CB Cost Savings/Year (%)**	**Generator CB Cost Savings/Year (%)**
Preventive	7	65	7
Corrective	61	67	69
Total	47	66	59

4.9 Sensitivity Analysis

With regard to the data for the model, this must be chosen with care. Through carrying out sensitivity studies, by varying each parameter in turn whilst keeping the others constant, Table 4.5 illustrates that the critical parameters are the major failure rate for the circuit breaker, the probability to successfully detect the early signs of a major failure, the minor repair cost and the minor failure rates of the condition monitoring system (highlighted in bold in Table 4.5). Clearly, when the cost justification is marginal, other factors become influential, like the major repair cost. In addition, a user may need to allow for variance in more than parameter. For example, from the previous case studies consider the scenario where the two parameters that present the most uncertainty are varied simultaneously by a factor of 0.1 and 10; namely the circuit breaker explosive and minor failure rates. Examining the NSC circuit breaker application, this scenario yields a variance in savings between 0.5% and 27% per year, respectively, which again emphasises that a user must exercise caution when selecting their data and give careful consideration to where the most uncertainty exists.

Table 4.5: Summary of cost savings when a sensitivity study is conducted on the condition monitoring reliability and circuit breaker data

Case Study	**NSC CB Cost Savings/Year (%)**	**Interconnector CB Cost Savings/Year (%)**	**Generator CB Cost Savings/Year (%)**
MFR_{cm} x0.1 to x10	7 to -4	43 to 33	33 to 23
mfr_{cmn} & mfr_{cmo} x0.1 to x10	40 to -339	61 to -155	54 to –183
mfr_{cb} x0.1 to x10	6 to 3	44 to 28	34 to 22
MFR_{cb} x0.1 to x10	-75 to 59	-3 to 68	-58 to 68
efr_{cb} x0.1 to x10	3 to 23	41 to 45	32 to 40
***mrc* x0.1 to x10**	50 to -228	44 to 19	61 to –151
MRC x0.1 to x10	-88 to 67	41 to 50	8 to 68
erc x0.1 to x10	3 to 23	42	32 to 40
poc x0.1 to x10	Not applicable	51 to 37	32
uoc x0.1 to x10	Not applicable	41 to 44	10 to 67
P_t (0 to 1)	Not applicable	41 to 42	6 to 52
P_d (0 to 1)	-42 to 18	-9 to 55	-29 to 49

4.10 Discussion of Results

Using the modified economic model, it is shown that for a new EHV SF_6 circuit breaker, fitted with on-line condition monitoring, the initial perceived savings for the corrective maintenance costs can reduce by as much as 86% when the reliability of the condition monitoring system is taken into account. Similarly, when the maintenance requirements of the condition monitoring system are also considered, the preventive costs can increase by as much as 17% per year. Consequently, despite many evaluation methods either ignoring the reliability of an OLMS or making the assumption that it is more reliable than a circuit breaker, the results show that this is a gross over simplification. If careful consideration is not given to the reliability of the transducers for an OLMS and how their effect on a circuit breaker performance can be minimised, then the initial apparent economic justification for condition monitoring is greatly reduced. However, even if a transducer is completely non-intrusive, such as an optical device for measuring the travel curve, it will probably require an outage to re-commission it. Therefore, consideration must be given to the number of parameters monitored, as it has a direct effect on the overall reliability of the condition monitoring system and the associated costs. In some cases, the results of the sensitivity studies reinforce the view that when the economic or system benefits are marginal, the on-line condition monitoring should be kept as simple as possible. Furthermore, the results demonstrate that a utility should carry out its own analysis and use its own data, even when assessing the economic viability for circuit breakers where there is a large unplanned outage cost. In addition, they should carry out an analysis for each type of OLMS, due to the difference between manufacturers' systems.

4.11 Application of Model to Assess the Economic Viability of Applying PDM Systems to GIS Substations

The modified synthesis approach, presented previously, has been specifically developed for EHV circuit breakers. In this section, the feasibility of using it or adapting it to other types of plant or a complete system, such as a substation, is explored. In particular, it is used to assess the viability of applying on-line PDM to a 400kV gas insulated substation, which includes not just the circuit breakers, but disconnectors, earth switches, voltage and current transformers, cable sealing ends, busbars and enclosures. This analysis will demonstrate whether the same principles and rationale that were used to develop an economic model to assess the viability for on-line condition monitoring for EHV circuit breakers can be extended to other assets.

4.11.1 Introduction

The technique of detecting Partial Discharge (PD) at UHF in EHV gas insulated substations, explained in Chapter 3, has had considerable success over the past years [Hampton, 2006]. To recap, it enables a condition such as free metallic particles or an insulation void, both of which might lead to complete breakdown of the GIS, to be found at an early stage when remedial action can still be taken. However, with increasing GIS reliability [Kopejtkova et al, 1992] and considering that these systems represent a significant capital expenditure for users [SP, 2002b], their use needs to be economically justified. As with an OLMS for EHV circuit breakers, this means that their effect on the corrective and preventive costs of the GIS needs to be evaluated against the life cost of the on-line PDM system.

4.11.2 Economical Considerations

Apart from the treatment of explosive costs, the same modifications that were made to the synthesis approach can be made when considering GIS substations. Namely:

- If the PDM system detects the early signs of an impending major failure, the repair cost can be treated as equivalent to a minor repair [SP, 2002a];
- A major failure does not always cause an unplanned outage cost;

- Unplanned outage costs are unrelated to the length of the outage and planned outage costs are dependent on the substation configuration; and

- The reliability of the PDM system could affect the operation of the GIS in the same three ways as an OLMS for a circuit breaker. Namely, as some designs of PD couplers are intrusive to the GIS, see Figure 4.4, there is the possibility that a failure of a coupler could result in a major failure of the GIS. Similarly, as the coupler works on the principle that the busbar to earth capacitance and the coupler capacitance to earth form a voltage divider, as shown in Figure 4.5, an outage, for safety reasons, would be required for a minor failure such as a connector failure.

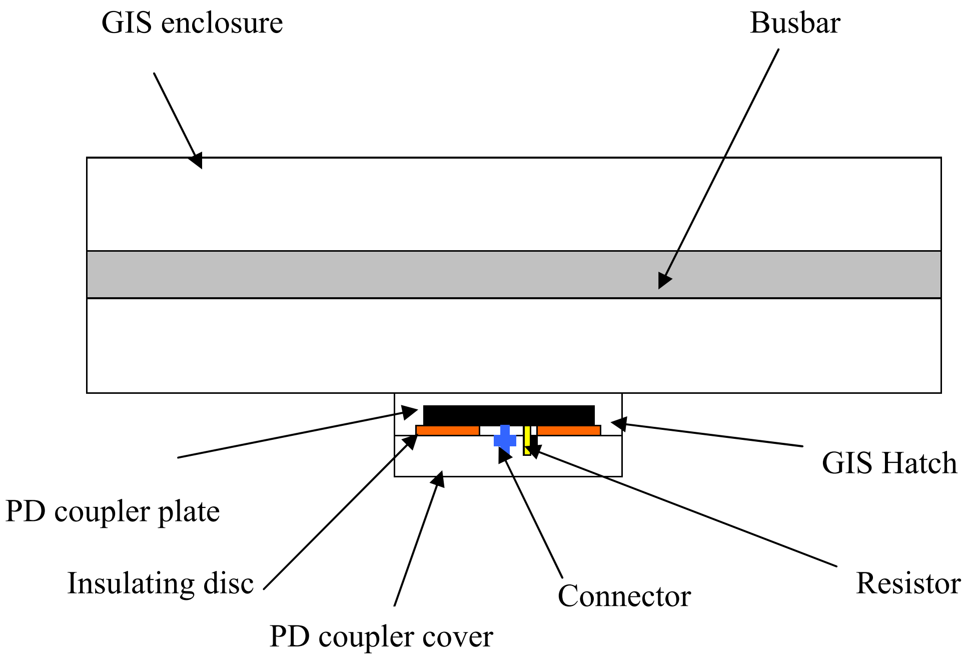


Figure 4.4: Diagram showing a typical PD coupler design

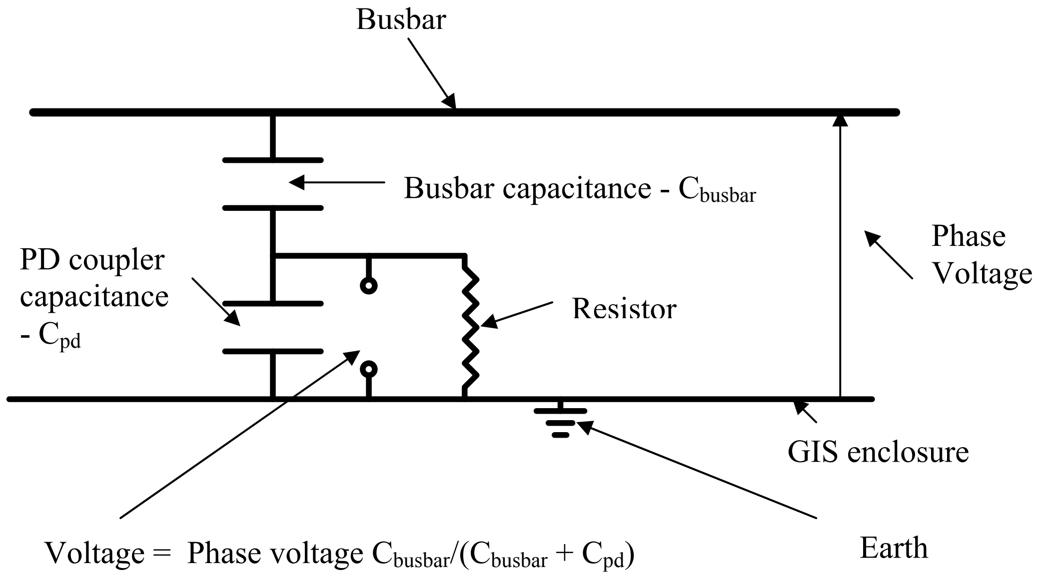


Figure 4.5: Diagram showing the PD coupler principle of operation

With regard to explosive failures, they have been excluded from the economic appraisal, as GIS is normally designed in accordance with [IEC 62271-203, 2003], which requires the enclosures to be designed to a strength that withstands an internal arc that is, at least, equal to the time of delay of the operation for the backup protection.

Therefore, the equations given for the modified synthesis approach for the corrective maintenance costs, with and without PDM, can be re-written as:

Minor Failures:

$$mf = mfr_{GIS}(mrc + (mrt \times poc \times \alpha)) \tag{4.21}$$

$$\begin{aligned} mf_{pdm} = {} & mfr_{GIS}(mrc + (mrt \times poc \times \alpha)) + \\ & P_d[MFR_{GIS}(mrc + (mrt \times poc \times \alpha)) + \\ & MFR_{pdm}(mrc + (mrt \times poc \times \alpha))] + \\ & mfr_{pdmo}(mrc + (mrt \times poc \times \alpha)) + mfr_{pdmn} \times mrc \end{aligned} \tag{4.22}$$

Major Failures:

$$MF = MFR_{GIS}(MRC + (MRT \times poc \times \alpha) + (P_t \times uoc)) \quad (4.23)$$

$$MF_{pdm} = (1- P_d)[MFR_{GIS}(MRC + (MRT \times poc \times \alpha) + (P_t \times uoc)) + MFR_{pdm}(MRC + (MRT \times poc \times \alpha) + (P_t \times uoc))] \quad (4.24)$$

where

MFR_{GIS}: the major failure rate of the GIS

mfr_{GIS}: the minor failure rate of the GIS

P_d: the probability that the PDM will detect a failure before it occurs

mfr_{pdmn}: the minor failure rate of the PDM system when it can be repaired without causing an outage of the GIS

mfr_{pdmo}: the minor failure rate of the PDM system that will cause an outage of the GIS to repair or re-commission it

MFR_{pdm}: the failure rate of the PDM system that will cause a major failure of the GIS

mf: the cost due to minor failures without PDM

mf_{pdm}: the cost due to minor failures with PDM

MF: the cost due to major failures without PDM

MF_{pdm}: the cost due to major failures with PDM

4.11.3 Case Studies

Using equations 4.21 to 4.24, this section presents the results from three case studies, where all examples use a one and a half switch GIS substation arrangement. For each case study, both a five and ten diameter configuration (with reference to Figure 4.2, a diameter consists of three circuit breakers and associated plant connecting one main busbar with the other) is considered to analyse the effect that the number of diameters has on the operating costs when applying PDM. The first considers a scenario where there is a high unplanned outage cost, such as a power station, and there are a low number (30 operations/year/GIS bay) of switching operations for the GIS. Namely, there are dedicated generator circuit breakers. The second example considers the scenario where there are a high number of switching operations (500 operations/year/GIS bay) but there is a negligible unplanned outage cost and the third example considers the case where there are a low number of switching operations and once again a negligible unplanned outage cost.

4.11.3.1 Preventive Maintenance

From [Cigré, 150, 2000] manufacturers normally recommend two major types of maintenance: A) Routine Maintenance (RM) - carried out regularly at intervals of five to ten years, where the circuit breaker bay outage time ranges from about several hours up to two days; and B) Major Preventive Maintenance (MPM) - carried out at intervals ranging from ten to twenty years or upon accumulating the permissible number of switching operations. In MPM, the circuit breaker bay outage time ranges from about five to fourteen days and only during this type of maintenance do some gas compartments have to be opened.

The formal definitions [Cigré, 150, 2000] of RM and MPM are given as:

"Routine Maintenance (Inspection): Periodical investigation of the principal features without dismantling. Investigation generally directed toward pressures and/or levels of fluids, tightness, position of relays, pollution of insulating parts. Includes actions such as lubricating, cleaning and washing, which can be carried out with the switchgear in service."

"Major Preventive Maintenance (Overhaul): Work done with the objective of repairing or replacing parts which are found to be out of tolerance by inspection and test, examination, or as required by the manufacturers maintenance manual to restore the equipment to a acceptable condition."

As mechanical wear and tear or routine internal inspections are the main causes of the need for MPM, it is believed that for the low switching substations on-line PDM would provide the evidence and confidence for utilities to extend the frequency of MPM. In this evaluation, on the advice of a domain expert, a conservative assumption has been made that the MPM frequency interval could be extended to 20 years from 10 years. There is the potential that the MPM frequency interval could be extended further, but until experience is gained it is recommended that a cautious approach be initially adopted. With regard to RM, it is believed that on-line PDM would have little effect on its frequency or scope.

As for the on-line PDM system, it is assumed that it has an asset life of twenty years [SP, 2005] and taking a forty year life for the GIS [NGTS 2.1, 2002], the costs of replacing the PDM system midway through the life of the GIS need to be considered in the evaluation. With the exception of the PD couplers, the evaluation assumes that the complete system, including cabling, needs to be replaced after twenty years. In addition, as it is recommended that an annual maintenance [DMS, 2003] of the PDM system be carried out, this has also been included in the economic appraisal.

4.11.3.2 Corrective Maintenance

Equations (4.21) to (4.24) were used to calculate the corrective maintenance costs for the three scenarios with and without on-line PDM. Reliability figures for a PDM system were obtained from a PDM manufacturer and figures from [SP, 2002a] were used for the PD couplers. Unfortunately, the PDM manufacturer cannot be identified as the figures were made available on the basis they remain anonymous.

The major failure rate for the GIS was taken from [Cigré, 150, 2000] and the minor failure rate was estimated based on data from a manufacturer. The GIS manufacturer also cannot be identified for confidentiality reasons. Major and minor failure costs were derived from the experience of [SP, 2002c] and also from data obtained from a manufacturer. With regard to the probability that the on-line PDM system will detect the signs that could lead to a major failure, reference was made to [Electra, 176, 1998].

Planned and unplanned outage costs were calculated by first determining the loss of capacity that would result when the GIS under question needs to be removed from service due to a major failure. By using average generation costs from [SP, 2002d] and the minimum time to restore capacity, the potential loss of profit and consequential loss was determined. Once again the figures are confidential and therefore cannot be published. However, as stated previously, a utility should be able to calculate their figures with relative ease.

4.11.4 Summary of Corrective and Preventive Maintenance Costs when PDM is applied to GIS

Table 4.6 summarises the cost returns when on-line PDM is applied based on the assumptions and data presented in the previous two sections. The values are presented as an NPV and are expressed as either a percentage increase or decrease of the costs for the GIS when on-line PDM is employed.

Table 4.6:Summary of percentage increase or decrease in preventive and corrective costs for GIS when on-line PDM is fitted.

	Number of Diameters	**Costs/Year (%) - Case 1**	**Costs/Year (%) - Case 2**	**Costs/Year (%) - Case 3**
Preventive Maintenance	5	1.98	-1.27	1.98
	10	2.78	-1.31	2.78
Corrective Maintenance	5	0.93	0.77	0.07
	10	1.17	0.96	0.09

where:

Case 1: High unplanned outage cost and low number of switching operations

Case 2: Low unplanned outage cost and high number of switching operations

Case 3: Low unplanned outage cost and low number of switching operations

4.11.5 Discussion of results

Examining Table 4.6, it is clear that when there is a high unplanned/planned outage cost, such as a loss of generation or there are a low number of switching operations, there is an argument to fit on-line PDM. However, when that is not the case, the savings decrease by a considerable amount and the argument for on-line PDM becomes more marginal. Consequently, as with the EHV circuit breaker case studies, a utility needs to use it own data in any investment appraisal and carry out its own sensitivity analysis, paying particular attention to the parameters that are the least known. In addition, the size of the substation to be monitored needs to be considered carefully, as there will be a threshold where a utility will need to consider an alternative solution such as off-line diagnostics or examine if there is any way that the on-line system can be simplified in order to reduce costs.

4.12 Chapter Conclusions

The application of the modified synthesis model for evaluating the economic worth of on-line condition monitoring to a GIS substation demonstrates that this approach can be used in other applications, because factors such as the reliability of the condition monitoring system are applicable regardless of the type of plant. However, it is still recommended that the model be reviewed each time it is applied to a new item of equipment, as slight modifications may be required, such as the different treatment of explosive failures for the GIS. Furthermore, it is important that each user carry out their own review, as depending on the standards they employ to specify plant, this may affect the final form of the model. For example, if a user does not specify that the GIS has to be able to withstand an internal arc, then explosive failure costs would need to be considered. Similarly, it is important to review the model for each type of condition monitoring system. Using the GIS example again, there are designs of PD couplers [DMS, 2006] that are non-intrusive and therefore there is no risk of them causing a major failure.

Through the development of the modified synthesis model for both the EHV circuit breaker and the GIS, unlike previous models, the reliability of the on-line condition monitoring system has been highlighted as a major influencing factor on the economic case for a utility to move to an on-line condition based strategy. Consequently, apart from improving the reliability of condition monitoring systems and giving careful consideration as to how they are applied, as is shown in the next chapter, it is essential to understand the failure modes of the plant that they are monitoring to allow the role of on-line condition monitoring to be indentified in any future maintenance strategy. With current reliability figures, it may be that for certain failure modes and applications, on-line condition monitoring is not the most efficient method, both technically and economically, of reducing operating costs.

Further factors that can have a significant influence on the economic case for on-line condition monitoring systems are the initial capital cost and the on-going maintenance commitments. For EHV circuit breakers in particular, the case studies question the number and type of parameters that need to be monitored, as well as challenging a utility to consider if there is a requirement for a dedicated stand-alone system. Namely, as is covered in more detail in Chapter 6, could existing substation control systems be utilised to fulfil the monitoring function?

4.13 Chapter Summary

This chapter reviewed various methods of examining the economic viability of applying an OLMS to EHV circuit breakers. The synthesis approach [Cigré, 167, 2000] proved the most promising both from an accuracy and ease of use point of view. However there were limitations, the main one being that it does not consider the reliability of an OLMS. Therefore, the synthesis model was modified to take cognizance of this factor and it was shown that even if an OLMS is completely non-intrusive, a failure of it may still lead to an outage of a circuit breaker in order to repair it.

The treatment of planned and unplanned outage costs was also examined. In particular, it was explained that the cost is not always directly proportional to the repair time. Based on the configuration of the substation, it may be possible to isolate a circuit breaker to allow any generation, interconnection or customers to be restored. Moreover, depending on the type of generation, there may be a minimum duration before it can be synchronised and returned to full load.

Case studies were then presented and using the modified synthesis model it was shown that for a new EHV SF_6 circuit breaker fitted with on-line condition monitoring, the initial perceived savings for the corrective maintenance costs can reduce by as much as 86% when the reliability of a condition monitoring system is taken into account. Similarly, when the maintenance requirements of a condition monitoring system are considered, the preventive maintenance costs can increase by as much as 17% per year. Consequently, despite many evaluation methods making the assumption that the reliability of a condition monitoring system can be ignored or it is more reliable than a circuit breaker, the results demonstrated that this is not always the case. If careful consideration is not given to the reliability of the condition monitoring transducers and how their effect on a circuit breaker's performance can be minimised, then the initial apparent economic justification for condition monitoring is greatly reduced.

The results of sensitivity studies undertaken to identify the critical parameters in the economic appraisal further reinforced this concern. The sensitivity studies covered the variables of both a circuit breaker and a condition monitoring system, and demonstrated that the critical and most sensitive parameters are the major failure rate for a circuit breaker, the probability to successfully detect the early signs of a major failure, the minor repair cost and finally, the minor failure rate of a condition monitoring system. Apart from demonstrating that it is important that a utility employ its own data in the appraisal and that a separate study should be conducted for each type of condition monitoring system, the results suggested that when the economic or system benefits are marginal, an OLMS should be kept as simple as possible.

Finally, it was shown that the modified economic viability model can be applied to other types of plant or a system as whole, in this case a GIS substation. It was recommended that the model be reviewed for each application and condition monitoring system, as there may be slight variations, such as the treatment of explosive failures for GIS. However, the principles adopted in the modified model, in particular the effect of the reliability of the condition monitoring equipment, are applicable regardless of the equipment being monitored.

Chapter 5

5 Reliability Centred Maintenance of EHV Switchgear

In this chapter, Reliability Centred Maintenance (RCM) is introduced in order to explore the practicalities of applying it to a circuit breaker and establish whether it changes the view on the role of on-line condition monitoring that was formed in the previous chapter when using it as part of on-line CBM strategy. More specifically, using the structured methodology of RCM and through case studies, the chapter considers if there is a more effective means, both technically and economically, of detecting an impending failure. From this analysis the aim is to ascertain whether the number of monitored parameters can be rationalised and if an OLMS for an EHV SF_6 circuit breaker can be simplified.

5.1 Introduction

As explained in the previous chapter, careful thought needs to be given to where and how an OLMS is used in an EHV circuit breaker maintenance strategy or indeed for any item of plant or system. Even in the applications where there appears to be a strong economic argument for using an OLMS, such as when there are high unplanned costs, an OLMS may not be the most efficient method of detecting an impending failure. Therefore, before deciding to apply an OLMS it is imperative to understand the maintenance requirements of a circuit breaker and to what extent an OLMS can reduce the overall operating costs. In summary, a maintenance scheduling technique is required that optimizes maintenance resources whilst ensuring the maximum equipment reliability; namely, a process such as RCM.

5.2 Reliability Centred Maintenance

As discussed in Chapter 2, RCM is more a process that determines the most appropriate maintenance policy for each individual component, taking into account its operating environment and regime, rather than a common maintenance procedure such as CBM. The procedures and principles of RCM can be expressed in many different ways [Nowlan et al, 1978; Smith, 1993; and Moubray, 1997], but in this chapter the widely accepted RCM methodology, RCM2 [Moubray, 1997], is employed to examine the practicalities surrounding the application of RCM to EHV circuit breakers and to what extent an OLMS figures in this strategy.

To recap, as shown in Figure 5.1, RCM consists of addressing seven key questions:

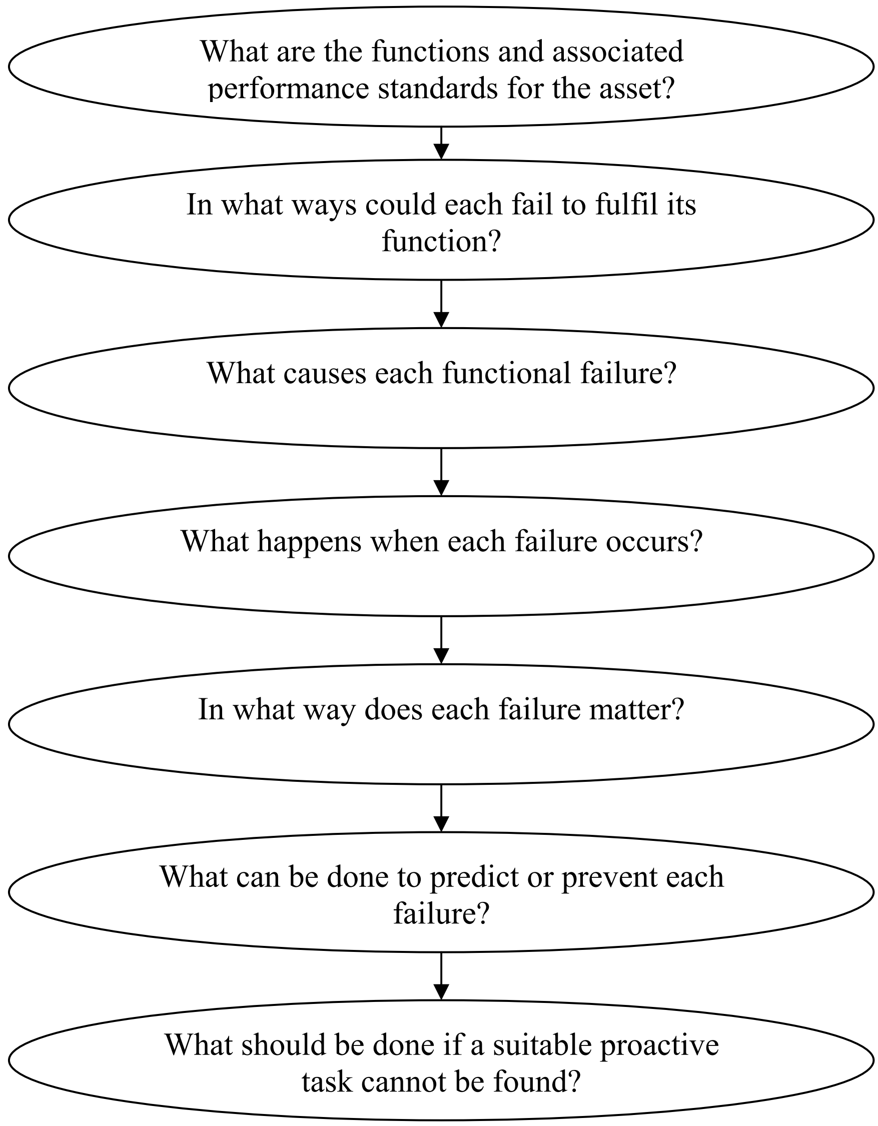


Figure 5.1: Diagram showing the seven steps to RCM

5.2.1 Functions and associated performance standards of the asset

The first step in the RCM process is to define the functions of each asset in its operating context, together with the associated desired standards of performance. The key point to remember is to define what the user requires it to do, whilst ensuring that it is capable of doing it in the first instance, rather than what it is designed to do. For example, if a pump is designed to supply hydraulic fluid at a rate of 25 litres/minute but is only required in practice to pump at 20 litres/minute then the latter figure should be selected. In addition, if there are any safety, environmental, or quality standards, etc. to be upheld, these secondary functions should also be specified. An easy way of ensuring that these functions are included is to use the acronym ESCAPES, which stands for:

- Environmental integrity;
- Safety/structural integrity;
- Control/containment/comfort;
- Appearance;
- Protection;
- Economy/Efficiency; and
- Superfluous functions.

5.2.2 Ways plant fails to fulfil its functions

The second step is to define what constitutes a failed state and the events that could lead to this failed state. As part of this exercise it is important to define any partial failures, which is when the item of plant may still be operating, but to an unacceptable standard. Care should also be taken to define exactly what constitutes a failure as different parts of an organisation could have a different view. For example, consider the various stages of an SF_6 gas leakage, as shown in Figure 5.2:

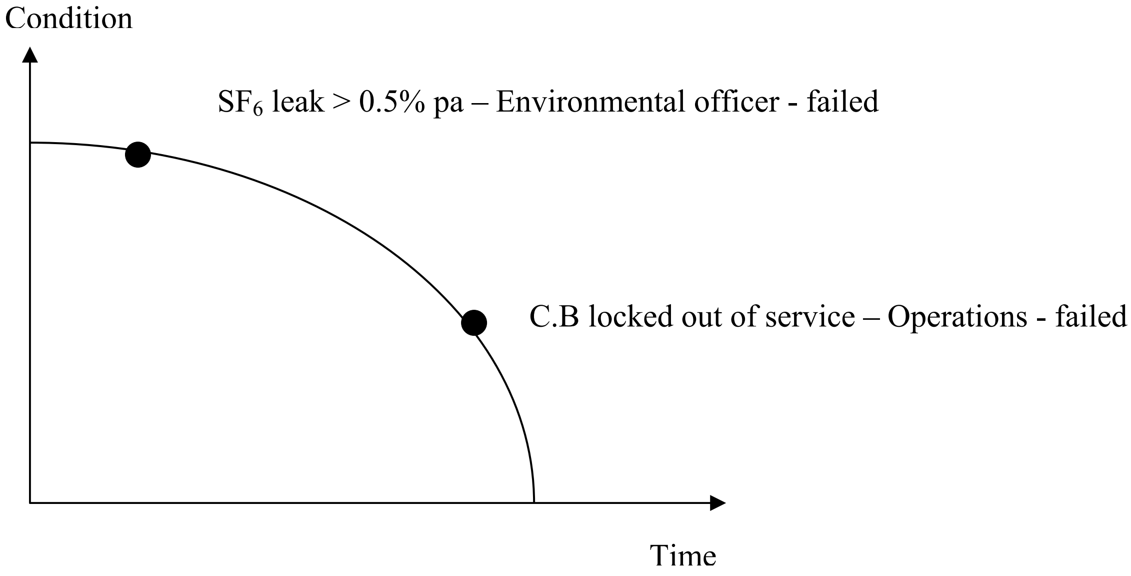


Figure 5.2: Diagram showing the different stages of failure recognition depending on user's perspective

5.2.3 Functional failure causes

Once the functional failures have been identified, the next step is to identify all the events that could have reasonably caused each failure state. These events are otherwise known as failure modes.

This is one of the most critical parts of the RCM analysis. If all failure modes can be identified at this stage then they can be addressed and eliminated in future steps. If failure modes are overlooked this will result in excessive reactive maintenance being carried out during the life of the equipment instead of proactive maintenance.

Failure modes can take various forms:

- Falling capability – This arises when the performance of the asset falls below a desired level during operational service; the five principal reasons being:
    - Deterioration due to wear and tear;
    - Lubrication failures;
    - Ingress of dirt;
    - Disassembly or parts coming adrift; and
    - Human error.
- Increase in applied stress – This arises when the desired performance from an asset is increased beyond its envelope of capability; the four reasons for this occurrence being:
    - Sustained, intentional overloading;
    - Sustained, unintentional overloading;
    - Sudden, unintentional overloading; and
    - Incorrect specification of parts or materials.
- Initial incapacity – this is where the capability of the asset never met the initial performance specification

The level of detail provided for each failure mode is also important and must be sufficient to allow a suitable maintenance task to be identified. Similarly, the phenomenon known as analysis paralysis must be avoided and is where too much detail is provided causing the RCM process to take much longer than is necessary.

5.2.4 What happens when each failure occurs?

This stage identifies what happens, or the effects, when each failure mode occurs. Unlike the next stage, it is quite different from the failure consequences, which identifies how each failure mode matters. When describing the failure effects the following information should be recorded:

- What evidence (if any) is there that the failure has occurred;
- In what ways (if any) it poses a threat to safety or the environment;
- In what ways (if any) it affects the system or the operation of the asset;
- What physical damage (if any) is caused by the failure; and
- What must be done to repair the failure?

5.2.5 In what ways does each failure matter?

Failures can be split into two categories – hidden and evident. As their names suggest, a hidden failure, if it occurs, will not become apparent to an operator under normal operating circumstances, whereas an evident failure will be noticeable.

An example of a hidden failure could be one that affects the selector switch to open a circuit breaker. Namely there would not be any indication that a fault has occurred until the circuit breaker is requested to open.

The consequences of evident failures can be split into three categories:

- Safety and environmental consequences – If the failure could kill or injure any person or breach any environmental standard, a proactive task must be found to reduce the probability of occurrence to an acceptable level; otherwise re-design will be required;
- Operational consequences – If the failure has a direct adverse effect on the operational capability of the asset, a proactive task should be employed if its

cost is less than the cost of the operational consequence plus the cost of the repair; and

- Non-operational consequences – This failure does not have any effect on the operational capability of the asset. Similar to a failure that has operational consequences, a proactive task should be employed if its cost is less than the cost of the repair.

5.2.6 What can be done to predict or prevent each failure?

RCM encourages the use of proactive maintenance (preventive and predictive methods) and tries to eliminate reactive maintenance, which is inherently unpredictable and inefficient.

Preventive maintenance is only feasible if an item has a definite age at which the probability of failure begins to increase rapidly, as indicated in failure patterns A and B shown in Figure 2.2. The two forms of preventive maintenance are:

- **Scheduled restoration** – which involves restoring the condition of a part or item to its original capability, at a specified interval, regardless of whether it needs to be restored or not; and
- **Scheduled discard –** which involves replacing a part or item, at a specified interval, regardless of whether it needs to be replaced or not.

Predictive maintenance is applicable when components do not have a definite age such as those that have failure patterns C to F shown in Figure 2.2. In order to detect these failures, the RCM process encourages the use of techniques that are called “on-condition tasks”. They are given this name as the components or parts are left in service *on the condition* they continue to meet the required performance standards. Another name for this type of maintenance activity is CBM and tasks include:

- Condition monitoring – both on and off-line;
- Primary effects monitoring –such as gauges; and
- Human senses – such as temperature, noise and smell.

Predictive maintenance relies on being able to recognise when a failure is about to occur and being able to carry out some action to prevent the failure occurring. Each failure will have an associated P-F curve and as described in Chapter 3, the on-condition task must be carried out at an interval less than the P-F interval, remembering to take into account the time required to carry out any failure avoiding action. On-condition tasks are appropriate:

- If they can be relied upon to give adequate warning of safety or environmental consequences; and
- If the cost of implementation is less than the operational or non-operational consequences.

5.2.7 What should be done if a suitable proactive task cannot be found?

If a proactive task cannot be found then one of the following default actions must be taken:

- A failure finding task would be required for hidden consequences;
- Re-design would be necessary for safety or environmental consequences; and
- No scheduled maintenance if the failure has operational and non-operational consequences. However, if the consequences for the former were still too high, re-design would be required. Similarly, if the repair costs for the non-operational consequences were still unacceptable, once again, re-design would be required.

5.3 Application of RCM to EHV Circuit Breakers

To allow a comparison between the potential change in operating costs when RCM is used to determine the maintenance strategy for plant, the same type of 300kV single pressure SF_6 circuit breaker used in the previous chapter for the on-line CBM feasibility studies was used for the RCM study. In addition, the same three case scenarios were employed; namely, the NSC, interconnector and generator circuit breaker applications.

As with the CBM examples, the RCM exercise was conducted using the experience of utility operational and maintenance personnel, and representatives from the manufacturer. This is an important aspect, as RCM should be carried out by a small team representing all the interested parties and specialists, as opposed to a single person, to ensure the process is as robust as possible.

5.3.1 Functions of an EHV SF_6 Circuit Breaker

As discussed previously, the first step in applying RCM to an EHV SF_6 circuit breaker is to list all the primary and secondary functions. The former are the main reasons why the asset exists and care must be taken to define the exact performance specification. In total, three were identified and are listed as follows:

- To interrupt current up to a value in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e] and International Standard (IEC) 62271-100 [IEC 62271-100, 2001];

- To make current up to a value in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e] and IEC 62271-100 [IEC 62271-100, 2001]; and

- To continuously carry load current up to a value in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e] and IEC 62271-100 [IEC 62271-100, 2001].

If the plant is used for different functions, such as a point of isolation, then some of the primary functions could be split into a number of functional statements. However to avoid many different maintenance programmes for the same asset, it is recommended that the worst case be specified. This may lead to some over maintenance, but it will ensure that the asset can handle the worst case condition and stresses.

In addition to the primary functions, most assets are expected to carry out additional functions, which in some cases are taken for granted. For example, when a circuit breaker opens to interrupt fault current or closes it is expected that the correct open or closed indication be displayed. As discussed previously, these requirements are called secondary functions and for the EHV SF_6 circuit breaker used in this study, these can be listed as follows:

- To ensure the gas leakage is no more than 0.5% per annum;
- To ensure safety of operation;
- To provide insulation in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e] and IEC 62271-100 [IEC 62271-100, 2001];
- To ensure the open/close indication reflects the actual position of the circuit breaker contacts in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e];
- To ensure the spring charged/discharged indication reflects the actual position of the circuit breaker close springs in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e];
- To prevent a closure when the circuit breaker is already closed;
- To indicate the gas density in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e] and IEC 62271-100 [IEC 62271-100, 2001];

- To charge the close springs in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e] and IEC 62271-100 [IEC 62271-100, 2001];

- To display the circuit breaker SF_6 lockout alarm in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e] and IEC 62271-100 [IEC 62271-100, 2001];

- To display the circuit breaker SF_6 falling alarm in compliance with ScottishPower specification for 300kV circuit breakers [SP, 2002e] and IEC 62271-100 [IEC 62271-100, 2001]; and

- To display the correct number of circuit breaker operations.

5.3.2 Failure Functions of an EHV Circuit Breaker

For each of the primary and secondary functions, the failure functions now need to be identified, where failure functions are defined [Moubray, 1997] as:

"the inability of any asset to fulfil a function to a standard of performance, which is acceptable to the user"

As a function can have different failure states, this step illustrates why it is important to accurately define each function and an appropriate performance standard. For example, the gauge that displays SF_6 gas density could fail altogether or it could display a gas density 3% below or above the actual gas density.

The failure functions for each function are listed in Appendix A1, but taking the primary function "*To interrupt current up to a value in compliance with ScottishPower specification for 300kV circuit breakers and IEC 62271-100"* as an example, the two functional failures identified can be listed as follows:

- Opens but fails to interrupt up to the specified value; and

- Fails to open on command.

5.3.3 Failure Modes of an EHV SF_6 Circuit Breaker

When listing the failure modes that could cause each of the functional failures, a pragmatic view must be taken. For example, when considering the functional failure 'Opens but fails to interrupt' twenty-four failure modes, as shown in Table 5.1, were initially identified. However, through operational experience, a view was taken that only eleven were probable of ever occurring. Although a failure mode such as 'lack of lubrication of the main drive shaft bearings' could lead to a failure to interrupt, if the bearing is a 'sealed' type [Shigley et al, 2004], it is believed that this is an unlikely event and therefore should not be included any further in the RCM process. Equally, the level of detail specified is important, as there must be enough to allow a suitable maintenance task to be identified. An example is the lack of lubrication of the trip latch assembly. For the purposes of this study, this level of detail was deemed sufficient. However, in other applications where the plant is more critical, it may be appropriate to consider what has led to the lack of lubrication.

Table 5.1: Example of EHV Circuit Breaker Failure Modes

Failure Function	**Failures Modes**
Opens but fails to interrupt up to specified value	Blast nozzle worn
	Piston valves - lack of lubrication*
	Blast cylinder damaged*
	Seal leakage - low gas density
	Over damping - damper corroded*
	Mechanism out of adjustment*
	Main drive bearings worn
	Trip spring bearings worn
	Trip spring beyond useful working life*
	Over damping - wrong fluid*
	Contacts worn
	Tulip contact worn
	Tulip contact springs broken *
	Contact rod worn
	Contact springs broken*
	Trip latch worn
	Trip latch assembly - lack of lubrication
	Trip spring broken*
	Trip bearings corroded*
	Main drive bearings corroded*
	Fault level above specified value*
	Loss of damper fluid - seal failure
	Latch hits backside of cam - cam in incorrect position
	Control voltage below 70% of nominal*

* Denotes failure modes not progressed due to low probability of occurring

Ultimately, the user must strike a balance between too much detail, where the process becomes unmanageable, and insufficient detail where an informed decision cannot be made.

Once again, the failure modes identified for each of the failure functions can be found in Appendix A1.

5.3.4 Failure Effects of an EHV SF_6 Circuit Breaker

When recording the effects of each failure mode, the study considered what evidence would be present from a control engineer's perspective as opposed to an operator visiting the site. An operator is normally visiting a site to either carry out maintenance or to respond to a fault and therefore there is not any guarantee they will detect the failure effects. On the other hand, the control engineer is monitoring the system continuously. In addition, the failure effects description considered the questions outlined in section 5.2.4, such as the effects on safety, the environment, the operation of the electrical network and how the fault could be repaired. The failure effects for each failure mode are listed in Appendix A1, however, Table 5.2 provides an example of how the failure effects were developed for two of the failure modes outlined in Table 5.1.

Table 5.2: Example of EHV Circuit Breaker Failure Effects

Failure mode	**Failure effects**
Blast nozzle worn	Circuit breaker opens. Attempt to interrupt current, but continues to flow. Grid operator can view current trace. CB fail protection will operate 300 ms later and remote feeds will be isolated. Site visit to repair fault.
Seal leakage - low gas density	Gas density falling alarm. Threat to environment due to leaking SF_6 gas. CB opens. Attempts to interrupt current, but continues to flow. Grid operator can view current trace. CB fail protection will operate 300 ms later and remote feeds will be isolated. Site visit to repair fault

5.3.5 Failure Consequence and Maintenance Task Selection

As outlined previously, the next stage is to consider the consequences of each failure mode and therefore the most effective method, both economically and technically, of handling them.

Using the procedure outlined in [Moubray, 1997], for each failure mode, it is necessary to initially establish if the associated consequences from the loss of a function will become evident under normal operating circumstances. On the assumption that the failure mode will manifest itself, the next step is to consider if the consequences can be described as belonging to one of the following categories:

- Safety – where the loss of function could cause damage, injury or death;
- Environmental – where there is the risk of a breach of an environmental standard or regulation; and
- Operational – where there is a direct impact on the performance.

The highest priority is naturally given to safety followed by environmental and then operational impacts. Once the consequences of a failure mode have been attributed to a particular category, a suitable maintenance task is identified. Even if the consequences of a failure mode spans more than one category, it is only assessed against the one that has the highest ranking in importance on the basis that this alone will provide the strongest justification for carrying out a particular maintenance task.

As for failure modes that will not be evident under normal operating circumstances, the RCM approach [Moubray, 1997] takes the view that these failure modes should be treated differently as they are normally associated with protective devices. However, similar to the safety, environmental and operational categories the maintenance task that is identified needs to be technically and economically viable.

With regard to determining a suitable maintenance task, the RCM approach establishes in descending order of importance if the following tasks are appropriate:

- An on-condition task, such as condition monitoring and visual inspections;
- A scheduled restoration task, such as carrying out refurbishment at a pre-determined interval; and
- A scheduled discard task, such as replacing a component regardless of its condition.

For failure modes that have safety and environmental consequences, if a suitable task or combination of tasks cannot be found or justified then re-design is compulsory. As for hidden failure modes, if a failure finding task cannot be justified and there are not any safety or environmental consequences, re-design may be appropriate or alternatively, it may be justifiable to not carry out any maintenance at all. Similarly, where a maintenance task for a failure mode with operational or non-operational consequences is not feasible, again it can be reasoned that not carrying out any maintenance is the most appropriate approach.

Once the type of task has been determined, the maintenance frequency and who will be responsible for carrying out the maintenance can be specified.

As three separate applications (NSC, interconnector and generator) were considered for the EHV SF_6 circuit breaker example, the aforementioned procedure had to be carried out for each case scenario to determine the required types of maintenance tasks. For each failure mode in each of the case scenarios, it was initially considered if it were technically and economically feasible of applying an on-line condition monitoring task. As discussed previously, it is essential that the reliability and lifetime costs of a condition monitoring system be considered in this exercise. As each additional on-line parameter is added, a continual check must be kept on the economic viability of the OLMS. In addition, an OLMS solution that may be suitable for one application may not be suitable for another. For example, with reference to [Cigré, 165, 2000; ETRA, 1996; Cigré, 262, 2004; and Bachiller et al, 1994], the effectiveness of an OLMS to detect the degradation of a circuit breaker interrupter is questionable for reactive switching as the degradation process occurs in a completely different manner to normal line switching. If an on-line monitoring solution was not viable, an off-line condition based task was then considered, such as diagnostics or simply an operator visiting site to carry out a visual inspection of the circuit breaker. If that was not feasible, preventive maintenance was considered. This took the form of either carrying out an overhaul or replacing a part at a pre-determined interval.

The work sheets for the three case scenarios can be found in Appendix A1 and an extract for the interconnector application is shown in Table 5.3.

Table 5.3: Sample of RCM failure consequence and task selection worksheet for an interconnector circuit breaker

Failure Mode Reference No.	**Failure Consequences**	**Maintenance Task**	**Maintenance Frequency**	**Responsibility for Task**
1A2	Hidden	Monitor trip coil current. Switch CB.	1 year	Grid Control Centre (GCC)
1A3	Hidden	Monitor trip coil current. Switch CB.	1 year	GCC
1A4	Operational	Trip circuit supervision.	Continuously	GCC
1A6	Environmental	Monitor gas density.	Continuously	GCC
1B1	Hidden	Monitor Isqt (square of primary current).	Continuously	GCC
1B4	Operational	Trip circuit supervision.	Continuously	GCC
1B7	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
1B8	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
1B11	Hidden	Monitor Isqt.	Continuously	GCC
1B12	Hidden	Monitor Isqt.	Continuously	GCC

1B14	Hidden	Monitor Isqt.	Continuously	GCC
1B16	Hidden	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
1B17	Hidden	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
1B22	Hidden	Monitor travel curve.	1 year	GCC
1B23	Hidden	Monitor travel curve.	1 year	GCC

5.4 Discussion of Results

With reference to Table 5.3 and Appendix A1, Table 5.4 summarises the maintenance schedule developed using the RCM process for the interconnector circuit breaker. This yields a strategy based mainly on a CBM approach and compared to the previous chapter, the main difference is that the RCM process has revealed that fewer parameters need to be monitored on–line (Refer to Table 5.5). Consequently, as shown in Table 5.6 there is a corresponding reduction in the annual operating costs. It is a similar scenario with the generator circuit breaker. However, unlike the interconnector circuit breaker, the RCM process has revealed that during the circuit breaker mid-life refurbishment, it is more economical to conduct an overhaul of the interrupters as opposed to using an on-line condition monitoring technique, such as monitoring the primary current to ascertain the contact and nozzle wear. This result is dependent on the planned outage cost and the substation configuration. For example, if it is a ‘one and a half switch’ substation configuration it may be possible to isolate the circuit breaker without causing any disruption to supplies and therefore significantly reduce the planned outage cost. Consequently, each user must consider their operating regime when applying RCM.

Table 5.4: Recommended RCM maintenance schedule for the interconnector circuit breaker application

Maintenance Frequency	**Main Tasks**
Annual	Operate circuit breaker remotely. Test result dependent.
10 years	Transducer calibration checks. Control scheme functional checks.
20 years	Replace absorber.

With regard to the NSC circuit breaker, through the FMECA, the RCM approach has given the user the ability to focus the OLMS on the critical failure modes, whilst at the same time ensuring that it is economically viable. For example, as with the generator circuit breaker, it has revealed that it is more economical to overhaul the interrupters as opposed to monitoring the primary current. Consequently, as shown in Table 5.6, the potential maintenance savings are now 15% per annum, compared to 6% when an RCM approach was not employed. However, as described in the previous chapter, there are a number of factors that can have a significant effect on this result and therefore it is still recommended that each user carry out the RCM process specific to their network.

Table 5.5: Recommended on-line condition monitoring parameters using RCM

Generator/NSC Circuit Breaker (CB)	**Interconnector CB**
Trip coil current	Trip coil current
Close coil current	Close coil current
Travel Curve	Travel curve
SF_6 gas density	SF_6 gas density
-	Primary current
Temperature	Temperature

Table 5.6: Comparison of operating costs when using an RCM approach

Maintenance Type		NSC Circuit Breaker (CB) Cost Savings/year (%)	Interconnector CB Cost Savings/Year (%)	Generator CB Cost Savings/Year (%)
RCM	Preventive	-12	60	-12
	Corrective	24	40	47
	Total	15	45	38
On-line CBM	Preventive	-3	59	-3
	Corrective	8	35	39
	Total	6	42	32

Note: A symbol (-) denotes a cost increase

5.5 Conclusions

Through the RCM process a maintenance programme has been developed, which gives best value for money. Although condition based or predictive maintenance tactics are favoured over traditional time based methods, in some cases RCM has shown that it may be more economical to carry out a scheduled refurbishment task. Moreover, it has identified the critical failure modes and allowed the number of monitored parameters to be rationalized. Overall, the results appear promising, however to validate them and show the real impact of RCM, long-term studies are required.

There are also other less obvious benefits of RCM. Namely, its structured methodology ensures an auditable maintenance needs analysis is carried out for each item of plant. Not only does this allow manufacturers' drawings and manuals to be checked and reviewed by the relevant representatives from the various parts of an organisation, it also allows the reasons for a particular maintenance task to be recorded. The former point is important as it is surprising how many errors or ambiguities this exercise reveals and the latter point reduces a company's risk should experienced staff leave. There are also other benefits in that it ensures a training plan is put together that covers the needs of all levels of an organisation and overall it encourages team working.

As discussed previously, in identifying the failure modes, a balance must be struck between the probability of occurrence and the number that are progressed to the next stage to ensure the RCM process is manageable and relatively straightforward to implement. However, the FMECA is very subjective and depending on the experience and knowledge of the team carrying out the exercise, there is a risk that some failure modes will be missed or their importance under or overestimated. What is clear is that understanding the failure modes of an asset is essential to determining its future maintenance requirements and the parameters that need to be monitored by an OLMS. Consequently, in the next chapter, a technique called Fault Tree Analysis (FTA) is used to analyse in more detail the failure modes of a single pressure SF_6 circuit breaker to determine how it compares to the FMECA technique.

5.6 Chapter Summary

In this chapter RCM, and in particular the RCMII technique, has been introduced and the practicalities surrounding its application were discussed in detail. It was explained that RCM is not a common maintenance procedure like TBM or CBM, but a process that produces a maintenance programme for an asset or system to ensure the designed-in levels of safety are protected whilst balancing reliability and availability versus cost.

The key to successfully implementing RCM is to commence with accurately specifying the functions of an asset against specific performance standards. Rather than what the asset can do, it was emphasised that a user should specify what is expected of it. This then allows the failure functions and ultimately the failure modes to be identified. Priority is given to safety and environmental consequences, and through a rigorous and logical process, maintenance tasks are selected for each failure mode. Preference is given to "on-condition" tasks and where this is either technically or economically not feasible, consideration is given to carrying out scheduled restoration or if that is not viable to replacing the item at a given frequency, regardless of it condition. Failing that it may not be worth carrying out any maintenance or alternatively, re-design may be required if the consequences are still considered unacceptable.

Finally, case studies were presented where the feasibility of applying a RCM programme to an EHV SF_6 circuit breaker was evaluated. To allow a comparison with the results from the previous chapter, the same 300kV single pressure SF_6 circuit breaker was employed, where similar to before, an NSC, interconnector and generator application was considered. The results demonstrated the potential economic benefits of moving to an RCM strategy and in particular emphasised the importance of the FMECA study to determine the maintenance needs of an asset and subsequently the parameters that should be monitored by an OLMS. In addition, the case studies highlighted the additional benefits of RCM, such as knowledge capture and having an auditable process that records why certain decisions were taken at the time.

Chapter 6

6 Failure Mode Analysis of High Voltage Circuit Breakers

This chapter uses the technique of Fault Tree Analysis (FTA) to develop a model for a 145 kV gas insulated circuit breaker to ascertain the accuracy of RCM in identifying failure modes and whether current thinking is correct in addressing the maintenance needs of modern SF_6 single pressure circuit breakers. The method adopts a top down approach and identifies how each component part quantifiably relates to the overall availability of the circuit breaker. In particular, the chapter examines the role of on-line condition monitoring by analysing the effect that each on-line parameter has on the availability of the circuit breaker. Namely, it compares the potential failure modes that could be detected versus the failures that may be introduced due to the unreliability of the OLMS to allow the number and type of on-line condition monitoring parameters to be further optimised.

6.1 Introduction

In the previous chapter it was demonstrated that the key to determining the most effective maintenance strategy for a circuit breaker, and with that the role of condition monitoring, is to identify the critical failure modes. There are two basic approaches that can be taken, namely:

- Failure mode, effects and criticality analysis (FMECA), and
- Fault Tree Analysis.

As discussed previously, the former takes each failure mode and analyses the consequences along with their significance with regard to the system's performance. The basic process of this technique is to identify a particular cause or failure mode within the system and trace forward the logical sequence of this condition through the system to the final effects.

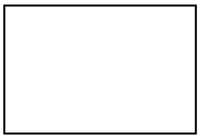
In contrast FTA identifies a particular effect or outcome from the system and traces backwards into the system the logical sequence to the prime cause(s) of this effect. It is a top down technique that starts with a system failure and then methodically breaks the system down, in increasingly hierarchical stages, until a level is reached where the basic system component parts are identified. Apart from being used as a qualitative evaluation method to assess the failure process of a complex system, unlike FMECA, it can also be used as a quantitative evaluation method to understand how each component part contributes to the overall availability of the system. When properly used, it is a powerful diagnostic tool that forces a user to understand a system thereby affording a high probability of identifying the critical failure modes.

FTA is a powerful design evaluation technique and was developed in 1961 to study a missile launch system for the US Air force [Lee et al, 1985]. Since then there has been extensive interest in using FTA and in particular to analyse the safety and reliability of nuclear plants. For example, in [Bagchi et al, 1981] FTA is used to examine the instrument and control system failures of a nuclear power plant containment isolation system. More specifically it is used to determine the potential combination of component and human failures that could lead to a release of radioactivity. Outside of the nuclear industry FTA has been used by the aerospace sector [Nyström et al, 2006] and the railway industry [Chen et al, 2007]. In the former it has been used to analyse an aircraft power supply system and in the latter it has been used to assess railway power systems and the impact of maintenance activities on the overall reliability. Within the power sector, the use of FTA is more limited, but it has been utilised by [Xu et al, 2006] to assess the reliability of power distribution systems and by [Beresh et al, 2008] to demonstrate how FTA could be applied to protection systems.

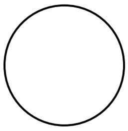
6.2 Fault Tree Analysis

To successfully conduct an FTA the first step is to obtain a detailed understanding of the system under analysis. This involves having knowledge of its design, its functional operation and maintenance requirements, and how it is used. In fact, as is shown in the next section, it is helpful to provide a system description, which should clearly define the undesired event or "top event" under consideration.

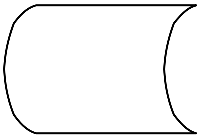
Using the symbols defined in Figure 6.1, the next step is to work logically and systematically through the system to determine how the top event can occur. One of the most important rules in FTA is to keep it simple. When an event statement is being developed down to its basic causes, it does not pay to advance too rapidly. In a complex system some of the combined fault events that could lead to a system failure can be easily identified, but there are usually many combined failure events that would be missed if the systematic approach to the fault tree logic is ignored. This simple approach also produces a fault tree, which can be easily modified when a system design is changed.



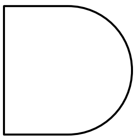
The rectangle describes a combination of fault events.



The circle identifies a basic fault event.



The OR gate defines the situation whereby the output will exist if one or more of the input events exist.



The AND gate defines the situation whereby the output event will exist only if all input events coexist.

Figure 6.1: Nomenclature used in FTA

To illustrate the application of FTA, consider the example shown in Figure 6.2.

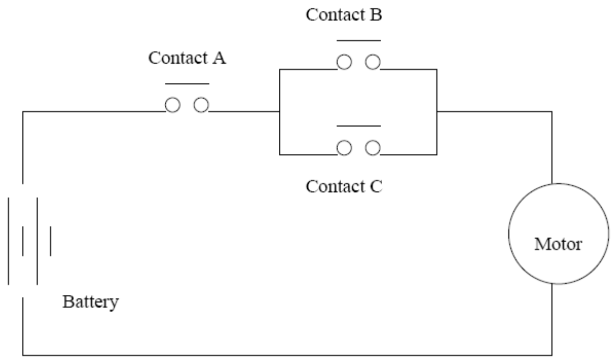


Figure 6.2: Electrical schematic for a motor circuit

Figure 6.2 depicts an electrical circuit to control an electrical motor. To turn the motor on, switch A and either switches B or C needs to be in the closed position. If the undesired or top event is "motor fails to start", the causes could be due to the following reasons:

- Failure of battery;
- Wiring failure;
- Faulty connection;
- Failure of switch A;
- Failure of switches B and C; or
- Failure of motor.

To construct the Fault Tree Diagram (FTD) for the motor circuit shown in Figure 6.2, a standard fault tree software package has been used. There are many software packages available for constructing and analysing the fault tree. In this instance, Faultree^{+} [Isograph, 2002] has been used, which provides a means to construct the fault tree simply by adding logic gates directly into the FTD edit area. Using the FTA symbols shown in Figure 6.1 and referring to the FTD for the motor circuit shown in

Figure 6.3, the first step is to enter the top event, which as described previously is “motor fails to start”. On entering the gate, the software package requires the user to select the gate type and to define the inputs or reasons for the top event to occur. In this case an OR gate has been selected and the inputs correspond to the seven possible reasons outlined previously. In addition, the gate requires a label, in this example ‘TOP1’, and for each of the inputs the user must define if they are a basic event or an event that can be developed further. In the case of the basic events, which are events that cannot be developed any further, such as “failure of switch A”, the user must enter the failure rate; this figure being denoted by ‘r’ in the FTD. Where events can be developed further, such as “failure of motor”, the user must repeat the process of selecting the appropriate logic gate and defining the inputs. In working towards the basic events, a balance needs to be struck between providing insufficient detail where the analysis becomes superficial and too much detail where the FTA becomes unmanageable. For example, one of the failure modes for the motor could be that the field coil has failed. At this stage it could be left as a basic event or alternatively it could be broken down further into failure causes such as the terminal voltage being too high or a manufacturing defect. The latter in turn could be split further into events such as an assembly error or material failure. However, as can be observed, although an event can usually be progressed to another level there comes a point where too much detail detracts from the original objective of the FTA.

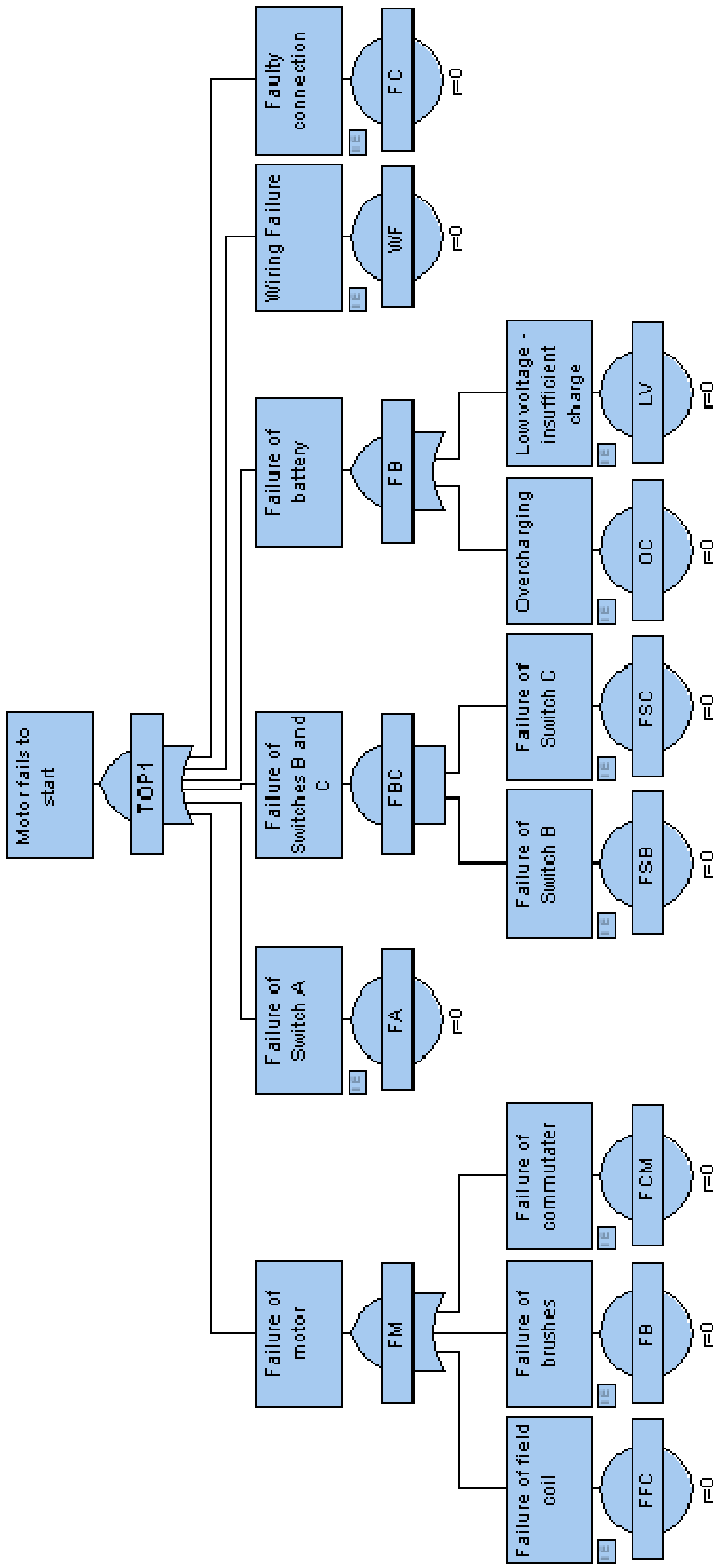


Figure 6.3: FTD for the motor circuit of Figure 6.2

6.3 Development of a Fault Tree Model for an SF_6 Circuit Breaker

In this section an FTD is developed for an SF_6 gas insulated single pressure circuit breaker using the fault tree software package, Faultree+ [Isograph, 2002]. The FTD is developed in the same manner as the motor circuit, where the first step is to identify the top event, which in this case is defined as a failure of one of the circuit breaker's primary or secondary functions; namely, corrective action is required to repair the fault. To create manageable segments against which the FTD could be constructed, the circuit breaker has been subdivided into the following functional groups:

- Operating Mechanism;
- Interrupting Chamber;
- Control Circuit; and
- Drive linkage and housings.

This approach also allows the sub-modules to be re-used for other types or models of circuit breakers. For example, for operating mechanisms, it is common for manufacturers to have a range of standard designs, which will be selected depending on the energy requirements of a circuit breaker. Similarly, due to the cost of developing an interrupter, it is not unusual to find a manufacturer using the same design in different models of circuit breakers.

The FTD for each functional group is developed to the point where all basic faults at the component level are identified, including inspection errors, controls and other areas where corrective action could be effected. This includes integrating into the diagrams basic component part failure modes as well as their significant life cycle failure influencing factors. In general, the FTDs address stress-strength related failure as well as wear out failure caused by operational aging.

The FTD that is presented in the following section is based on an SF_6 gas insulated, single pressure circuit breaker, rated at 145kV, employing a spring type mechanism. It was selected because the manufacturer kindly agreed to provide access to design and manufacturing drawings along with advising on potential failure modes and mechanisms. However, as this information is of a sensitive nature and as requested by the manufacturer, there are not any direct references to their name.

6.3.1 Selection and Refinement of Data Sources

As explained previously, as the FTDs are constructed, the user has to enter the basic component failure rates, as these are necessary inputs for determining occurrence probabilities and assessing criticality. The data consists of two general classes:

- Component failure rate data; and
- Human error rate data.

6.3.1.1 Component Failure Rates

Clearly, the accuracy of the fault tree method is highest when component failure rates are based on data obtained from failures in systems identical to the one under analysis.

However, unfortunately, many industries either do not have the data available or do not record in sufficient detail the level of information that is required by the analyst. For example, the Electricity Association [EA, 2001] each year collates fault statistics for the 132kV system in the United Kingdom and the 275/400kV system in Scotland. Whilst the reports provide general failure categories for circuit breakers, such as corrosion and age, they do not specify the part that has failed and the nature of the failure; for example is the circuit breaker located in a corrosive environment or has it ever been maintained? In addition, a large proportion, approximately 25%, of the faults are identified as unclassified or unknown. It could be that the operations engineer has been unable to diagnose the fault and allocate it to one of the categories provided or simply takes the easy option, as they do not understand the importance and reasons for recording accurate detail about the fault.

Therefore the problem is how to substitute for the lack of data. The possibilities include the use of data from other items of plant or from data banks. Neither of these methods is ideal, as data transferred from other sources may not be appropriate to the operating regime or the plant in question. In addition, the failure rates are affected by maintenance practices, measurement techniques and differences in the definition of a failure. This does not negate its value as a reliability engineering tool, but provided its limitations are recognised, it offers an initial estimate of the critical failure modes and a platform on which to build future maintenance and reliability studies upon. Namely, the data can be replaced when appropriate field data is available or the data can be refined using subjective estimates obtained by those knowledgeable in the area of study.

Consequently, the problem is now the identification and application of a suitable donor data bank. An extensive search has been made and each source [Cannon et al, 1991; Oreda, 2002; MIL217, 1992; and IEEE 500, 1983] investigated to determine its appropriateness for application to an SF_6 circuit breaker. The data source that has been selected for the component failures is from the Non-electronic Parts Reliability Data publication (NPRD) [NPRD, 1985]. This database provides failure rate and failure mode information for mechanical, electro-mechanical, electrical, pneumatic, hydraulic and rotating parts. The data represents a compilation of field experience in military, commercial and industrial applications, and covers a wide range of equipment, including circuit breakers. Unlike some of the other databases, it provides a minimum of five environments for each component type, such as within a closed environment or where the plant has lain dormant for long periods of time.

It is organised into four distinct sections. Section one contains background information, data limitations, assumptions and data analysis procedures. Section two provides generic field failure rates for numerous component types in a variety of operating environments. Section three provides detailed failure rates for selected part types and section four outlines the failure modes and mechanisms for the various mechanical and electro-mechanical devices.

Data Assumptions

Unfortunately there is a virtual absence of field data containing individual time to failures. Consequently, the exponential distribution, with its underlying constant failure rate assumption, has been used for the component part failure rate. For many complex non-electronic parts the exponential distribution is a reasonable assumption [NPRD, 1985], provided installation problems are disregarded in the analysis and parts are considered to be in the useful phase of their cycle. The former can be justified as circuit breakers undergo rigorous type and routine tests [IEC 62271-100, 2001] before entering service. As for the latter point, these same tests provide reliable upper limits beyond which the parts have entered their wear out phase and consideration needs to be given to their replacement or refurbishment.

As discussed previously, it is inevitable when analysing large samples of data, there will be variability in the failure rate between each of the data samples. Consequently, the failure rate should be expressed with some associated measure of confidence.

If the failure rate is defined as:

$$\lambda = f / t \qquad (6.1)$$

where

t: is the total number of part hours

f: is the number of failures observed in the sample

λ: is the failure rate expressed in terms of failures per million hours

then 60% confidence intervals can be calculated using the chi-square distribution [Chatfield, 1996], using 2f and 2(f+1) degrees of freedom, such that the upper and lower limits are given by:

$$\lambda_{80} = \chi^2 (2(f+1)Z_{20})/2t \quad (6.2)$$

$$\lambda_{20} = \chi^2 (2fZ_{80})/2t \quad (6.3)$$

where

Z_{20} and Z_{80} denote the 20% and 80% percentiles of the χ^2 distribution, respectively.

The fault tree allows for any on-line condition monitoring that is invasive to the circuit breaker and has already been installed for a future OLMS, such as the gas density transducer. However, all other transducers that can be retrospectively fitted have been excluded from the FTA, as the main objective of this analysis to establish the critical failure modes of the circuit breaker and therefore the monitoring that should be applied.

6.3.1.2 Human Error Rates

Human error rates mean the expected rate at which a failure caused by operating or maintenance personnel takes place, whether intentionally or unintentionally. Unfortunately, there are few sources for this type of data and in some cases [Anderson et al, 1990] subjective techniques are used based on discussions with personnel familiar with the operation and maintenance of the plant. However, for this analysis, [Swain et al, 1983] has been used, as it will provide a guide on how human error could affect the availability of a circuit breaker. The database has been developed from the nuclear industry and as the operating regime is similar to a transmission network, the data is deemed adequate for the purposes of this analysis.

6.3.2 Operating Mechanism

Referring to the typical spring type mechanism described in section 2.4.5, the operating mechanism can cause a failure of the circuit breaker through the following modes:

- Opens, but mechanism is not in the correct position;
- Closes, but rebounds;
- Fails to open on command;
- Fails to close on command;
- Closes without command;
- Fails to provide safety in operation;
- Attempts to close while closed;
- Failure to indicate correct status of circuit breaker;
- Circuit breaker closes, but fails to latch;
- Opens without command;
- Circuit breaker opening time incorrect; or
- Circuit breaker closing time incorrect.

To illustrate how each of these failure modes were developed, consider the failure mode where the circuit breaker opens, but is not in the correct position.

As indicated in Figure 6.4, when a circuit breaker opens, the trip latch is released by an electrical command to the trip magnet or by operating a mechanical manual release. The main shaft, which is directly coupled to the circuit breaker poles is accelerated in the open direction by the charged trip spring with the trip damper coming into action towards the end of the tripping process, to slow the moving mass of the circuit breaker and operating mechanism to a standstill.

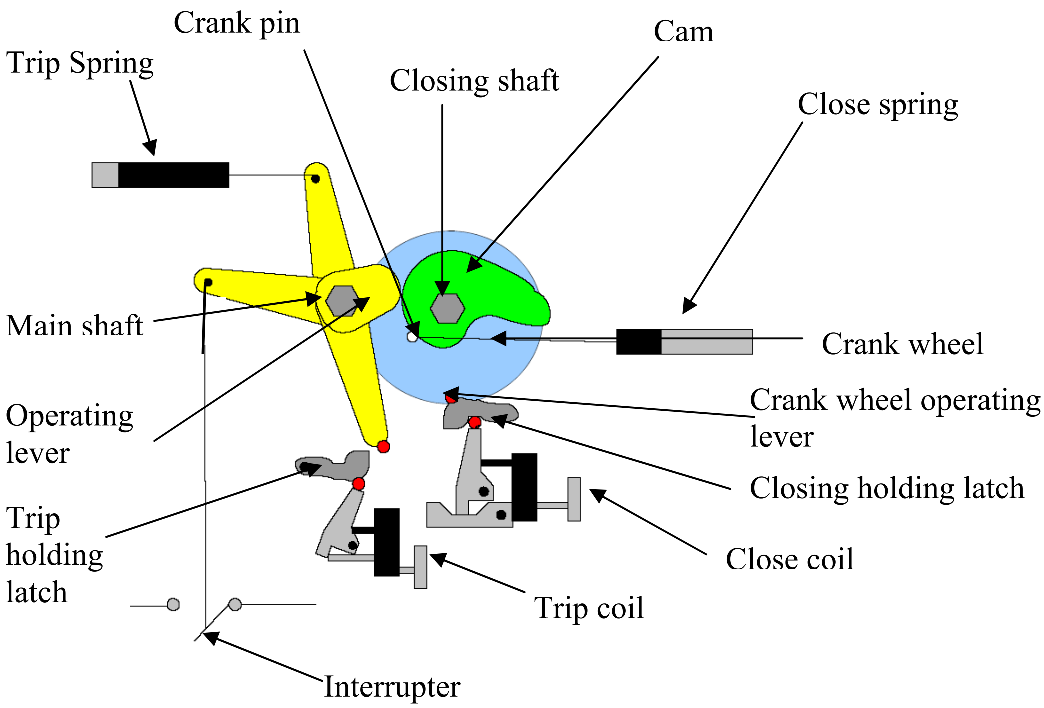


Figure 6.4: Diagram of a spring type operating mechanism

Therefore, as shown in Figure 6.5, if the circuit breaker fails to open, but is not in the correct position, the failure could be due to overdamping, the trip latch hitting the closing cam, friction with the main shaft assembly during opening, failure of the trip spring assembly or the circuit breaker being out of alignment.

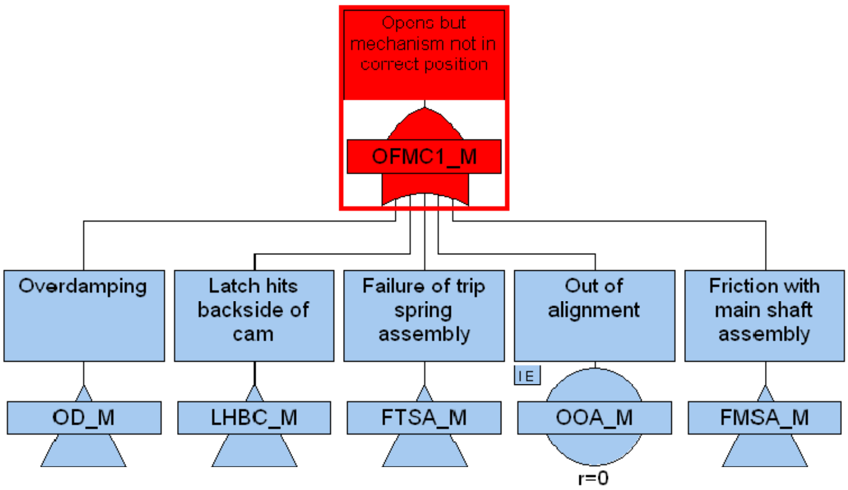


Figure 6.5: Top level FTD for failure mode 'opens but mechanism not in the correct position'

6.3.2.1 Overdamping

Damping of the tripping process is controlled via the trip damper, which is a hydraulic cylinder containing a piston and silicon oil. As the circuit breaker accelerates, the oil is expelled through an orifice, producing a damping force approximately proportional to the speed. Therefore, as shown in Figure 6.6, overdamping could be due to the trip damper being seized or the viscosity of the fluid being higher than required. The former could be due to corrosion of the trip damper and the latter could be due to the wrong fluid being used or the temperature being below the minimum service level.

With regard to the temperature being below the minimum service level it could be due to a failure of the mechanism cabinet and the heaters. As shown in Figure 6.7, the former could be due to a failure of the cabinet door seal or the cabinet may have corroded, and the latter could be due to a defective heater or a failure to energise the heater circuit. Corrosion of the cabinet could be developed further, examining failure mechanisms such as paint specification, environmental conditions and damage to the cabinet. However, as discussed previously, a balance must be struck between providing insufficient detail and too much where the process becomes unmanageable.

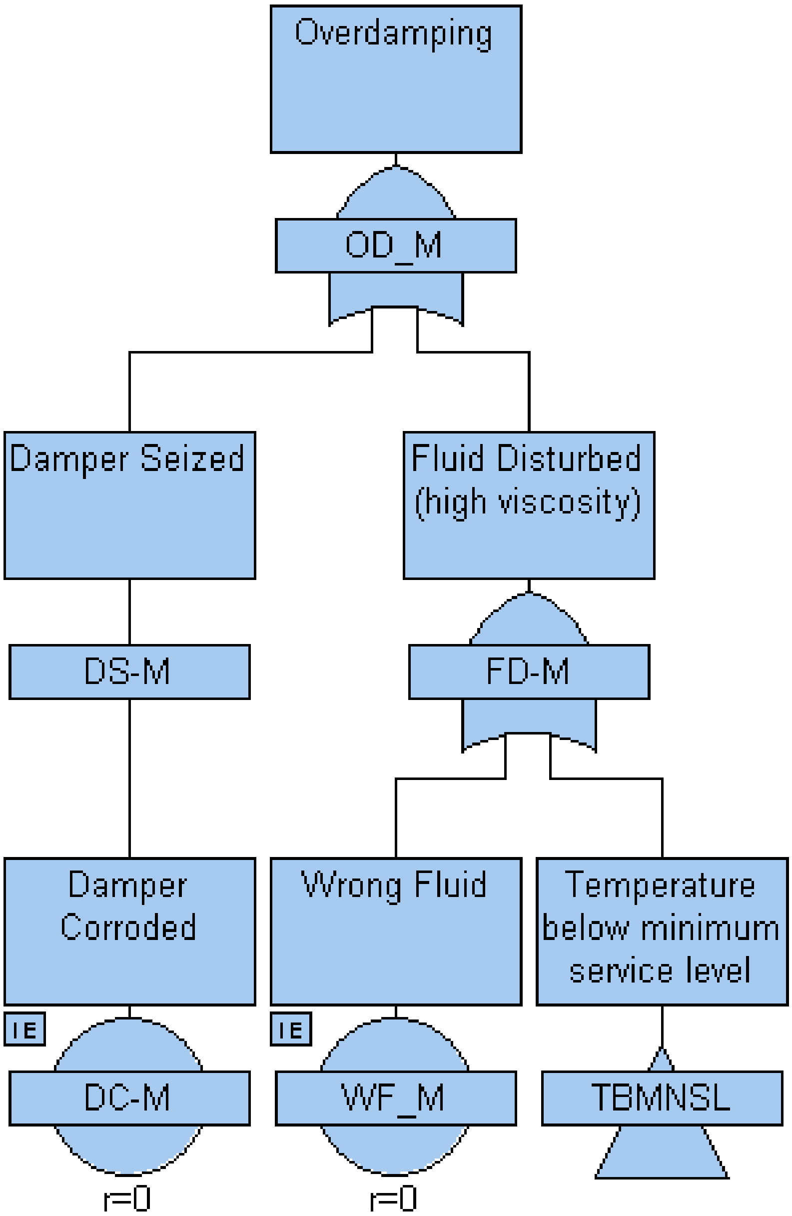


Figure 6.6: FTD for overdamping

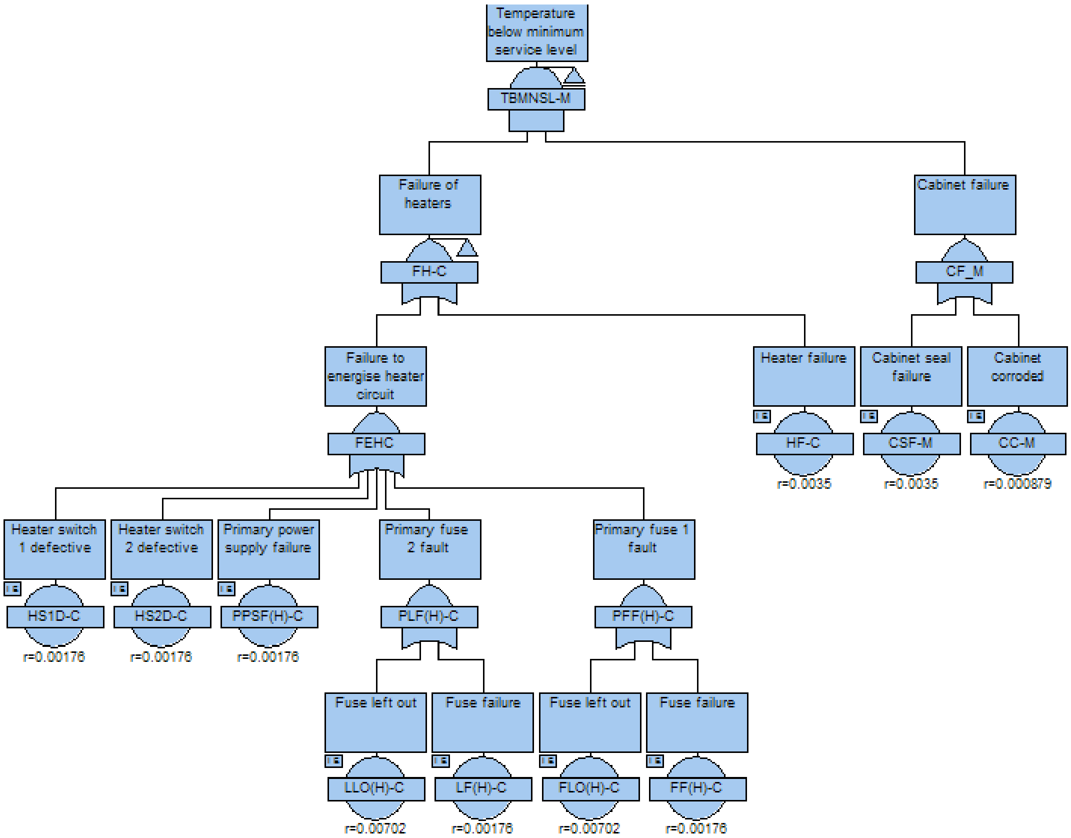


Figure 6.7: FTD for temperature below minimum service level

6.3.2.2 Trip Latch hits the closing cam

As shown in Figure 6.8, the trip latch hitting the closing cam could be due to a failure with the previous closing operation, as under normal circumstances the closing cam should have rotated to a position that does not impede the subsequent tripping operation. Consequently, the failure could be due to friction in the closing operation, the closing springs not being fully charged or the circuit breaker being requested to operate outside its functional limits.

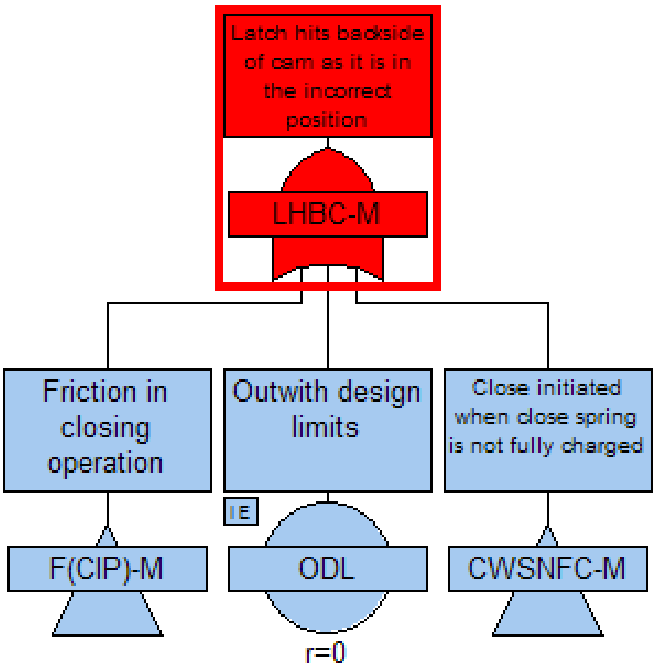


Figure 6.8: FTD for latch hits backside of cam

6.3.2.2.1 Friction in the closing operation

With reference to Figure 6.9, friction in the closing operation could be due to the closing shaft or the main shaft. In the closing operation, the closing latch is released by an electrical command to the closing magnet or by actuation of a mechanical manual release. The closing shaft is accelerated by the closing spring, which is attached to a crank wheel. The cam disc turns an operating lever, which in turn closes the circuit breaker via the main shaft. At the end of the closing movement the specially designed cam disc [Barkan et al, 1965] brings the main shaft to a safe, low-impact stop against the trip latch via the lever arm of an operating lever. At the same time, the cam disc should have moved away from the operating lever to allow a subsequent unimpeded trip of the circuit breaker. Therefore, any friction in the closing shaft will be due to the closing shaft bearings or the closing shaft bearing (closing spool) associated with the closing spring. If there is bearing friction it is likely to be due to a broken bearing, a worn bearing assembly, inadequate lubrication or the temperature being below a minimum level where it affects the bearing lubricant. As the closing shaft bearing is a 'ball bearing' type [Shigley et al, 2004] it is assembled during manufacture and would not normally be overhauled or replaced within the 'field' environment; namely the mechanism would be returned to the manufacturer for repair or overhaul. Consequently, inadequate lubrication is more likely to be due to the wrong lubrication being applied during assembly. With regard to a worn bearing, this failure mechanism is related to the number of close operations and the reasons for the temperature being below the minimum service level is the same as discussed previously.

With regard to friction associated with the main shaft assembly, as shown in Figure 6.9, this could be due to the main shaft bearings. In addition, as the trip spring is re-charged during a closing operation via the main shaft, any friction associated with the trip spring shaft bearings (note that there are two bearings associated with the trip spring) could also inhibit the closing operation. Like the closing shaft and closing spring bearings, the failure modes for the main shaft and trip spring bearings are likely to be due to a broken bearing, a worn bearing assembly, inadequate lubrication or the temperature being below a minimum level where it affects the bearing lubricant.

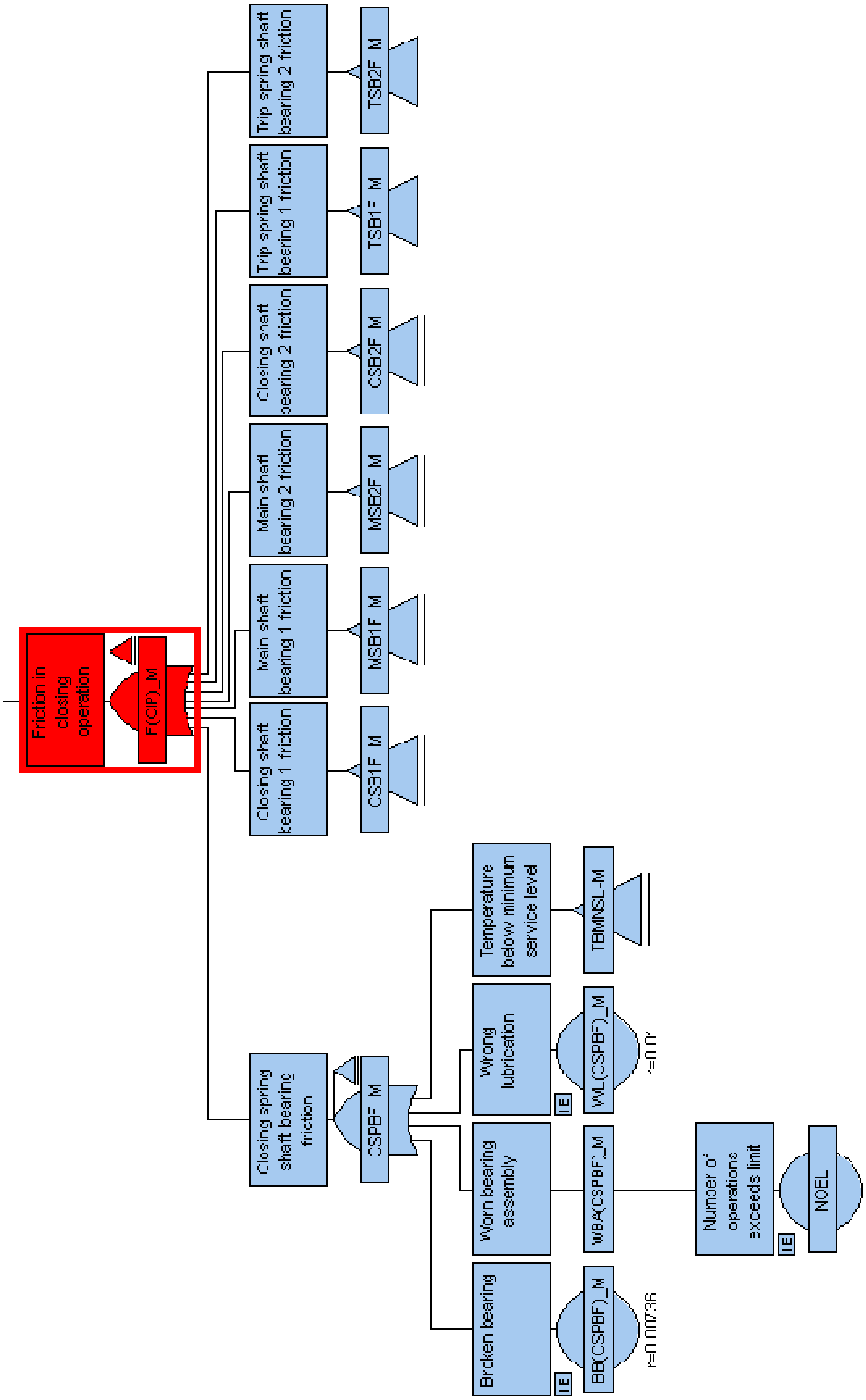


Figure 6.9: FTD for friction in the closing operation

6.3.2.2.2 Close spring not fully charged

At the end of the closing movement, the motor to re-charge the closing spring is energised via a motor limit switch, which in turn is operated by a motor limit switch actuating cam that is attached to the closing shaft.

On energisation of the spring charging motor, the closing spring is charged via gears, the crank wheel and the closing spring chain, where the latter is attached to the crank wheel through a crank pin. This spring charging process comes to an end when the crank wheel has rotated to a position where the operating lever of the crank wheel rests against the closing shaft. The spring charging motor is also de-energised via the aforementioned limit switch thereby allowing the gearing to run freely without imposing any load on the closing latch. At the same time the motor limit switch also primes the closing circuit.

Therefore considering this description and as shown in Figure 6.10, the close being initiated when the close spring is not fully charged could be due to the closing spring being not charged and a failure of the motor limit switch.

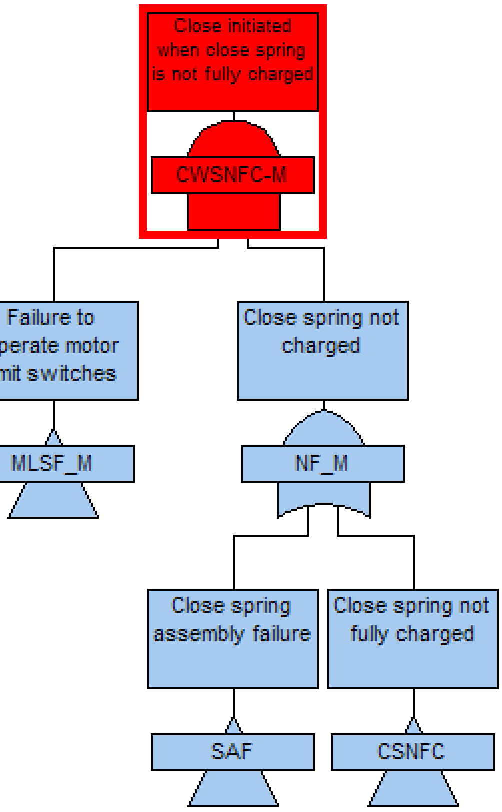


Figure 6.10: FTD for close operation initiated when spring is not fully charged

6.3.2.2.2.1 Close Spring Assembly Failure

For the closing spring to be not charged there would have to be either a failure of the closing spring assembly or a failure in fully charging the spring. As shown in Figure 6.11, the former could be caused by a deterioration of the bearing or a failure of the chain assembly. Deterioration of a bearing is either due to friction or it has seized. The reasons for friction in a bearing are the same as described previously and as shown in Figure 6.11, a seized bearing could be due to either there being a complete lack of lubrication or the temperature being so high that the lubricant becomes ineffective. Once again, referring to Figure 6.11, failure of the chain assembly could be due either to a failure of the close chain operating lever, a failure of the close chain/attachment, a catastrophic failure of the close spring, the close spring being overstressed or a failure of the shaft where the bearing is mounted for the closing spring chain.

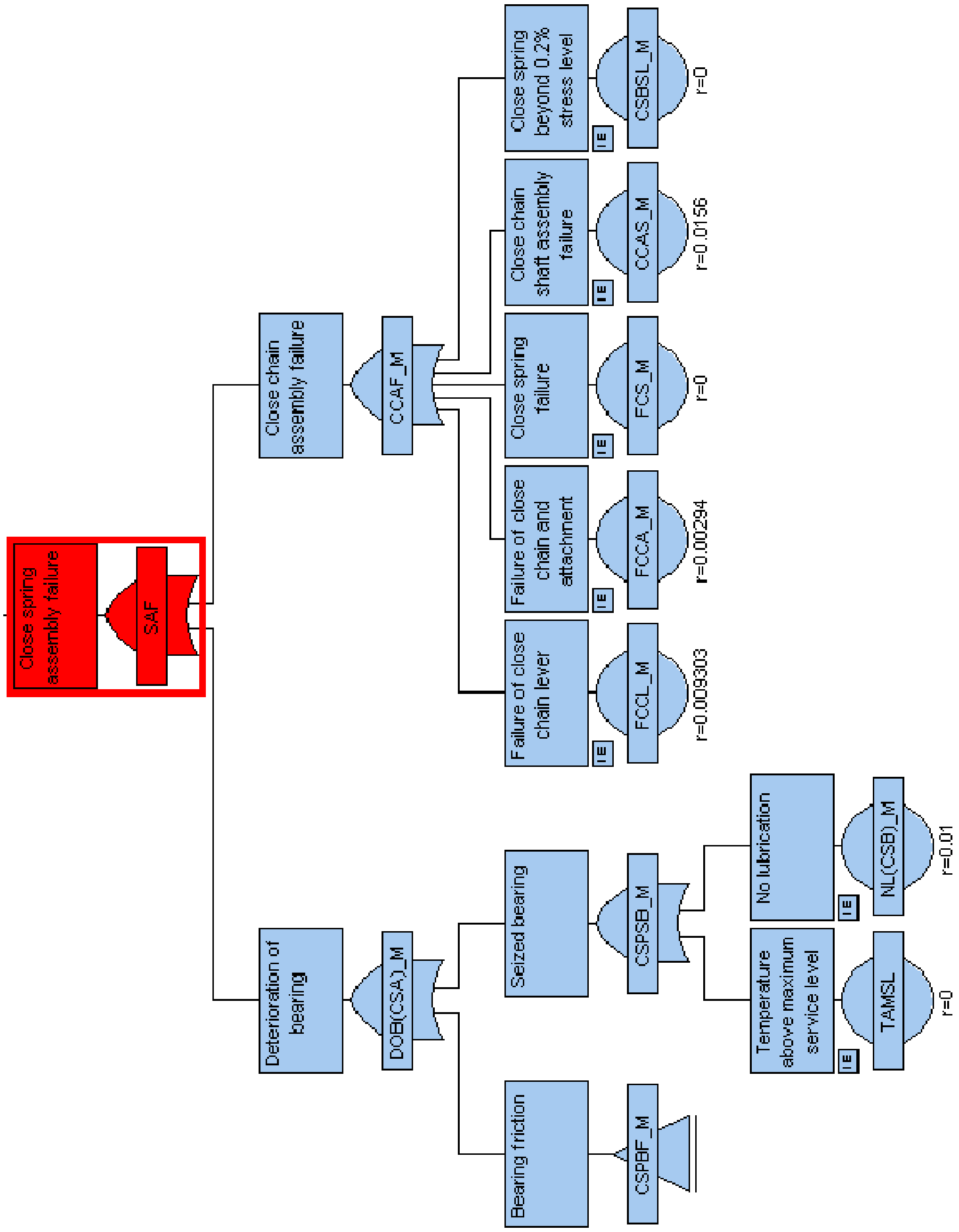


Figure 6.11: FTD for close spring assembly failure

6.3.2.2.2.2 Close Spring Not Fully Charged

As described previously, the closing spring is charged via a motor and gearing. There is also a manual means to charge the closing spring via a hand crank and worm gear assembly, but it has been excluded from the FTA as it is only used for maintenance purposes or for emergency purposes when there has been a failure of the motor.

For the circuit breaker used in the FTA, excluding the motor and crank wheel, there are a total of six gears mounted on three parallel shafts where an idler gear incorporates a freewheel to prevent the fast gearing stages from tracking the motion during the closing operation. In addition, the gearing includes a backstop, which in the event of the motor supply failing during the charging process prevents the crank wheel from reversing and thereby discharging the closing spring. Consequently, unlike the other gears, which are metallic, the gear associated with the backstop is made from an injection moulded thermoplastic due to its ability to deflect and absorb high impact loads.

Therefore, for there to be a failure to fully charge the close spring, as shown in Figure 6.12, there would need to be either a failure of one or more of the three reduction gear shaft assemblies, the motor or the crank wheel assembly.

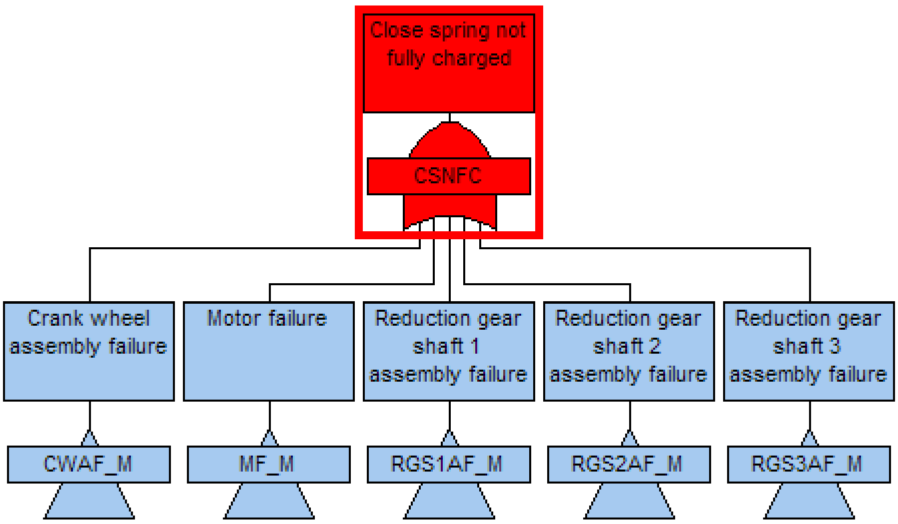


Figure 6.12: FTD for close spring not fully charged

Failure of Reduction Gears and Spring Charging Motor

There are two principal wear and tear types of gear failure: tooth breakage from bending stresses and pitting from surface stresses. Both modes of failure are fatigue failures due to the repeated stressing of individual teeth as they come in and out of mesh [Norton, 1998]. In addition, the gear wheel could be loose, which is more likely to happen after maintenance has been carried out. Similarly, there could be an obstruction preventing the gear wheels from meshing, such as a tool or screw being left over from the previous maintenance or it could be a part that has become detached from elsewhere in the mechanism. For metal-to-metal gears, the wrong lubrication may have been used, which can lead to a heavy build up of gum and cause the gears to seize. The final failure mode could be deterioration of the bearing supporting the gear wheel or wheels, which as described previously (Refer to Figures 6.9 and 6.11), could be due to either friction or the bearing being seized. Note, the fault tree for the reduction gear shaft 3 assembly also considers a failure of the freewheel device, as this could interfere with charging of the close spring.

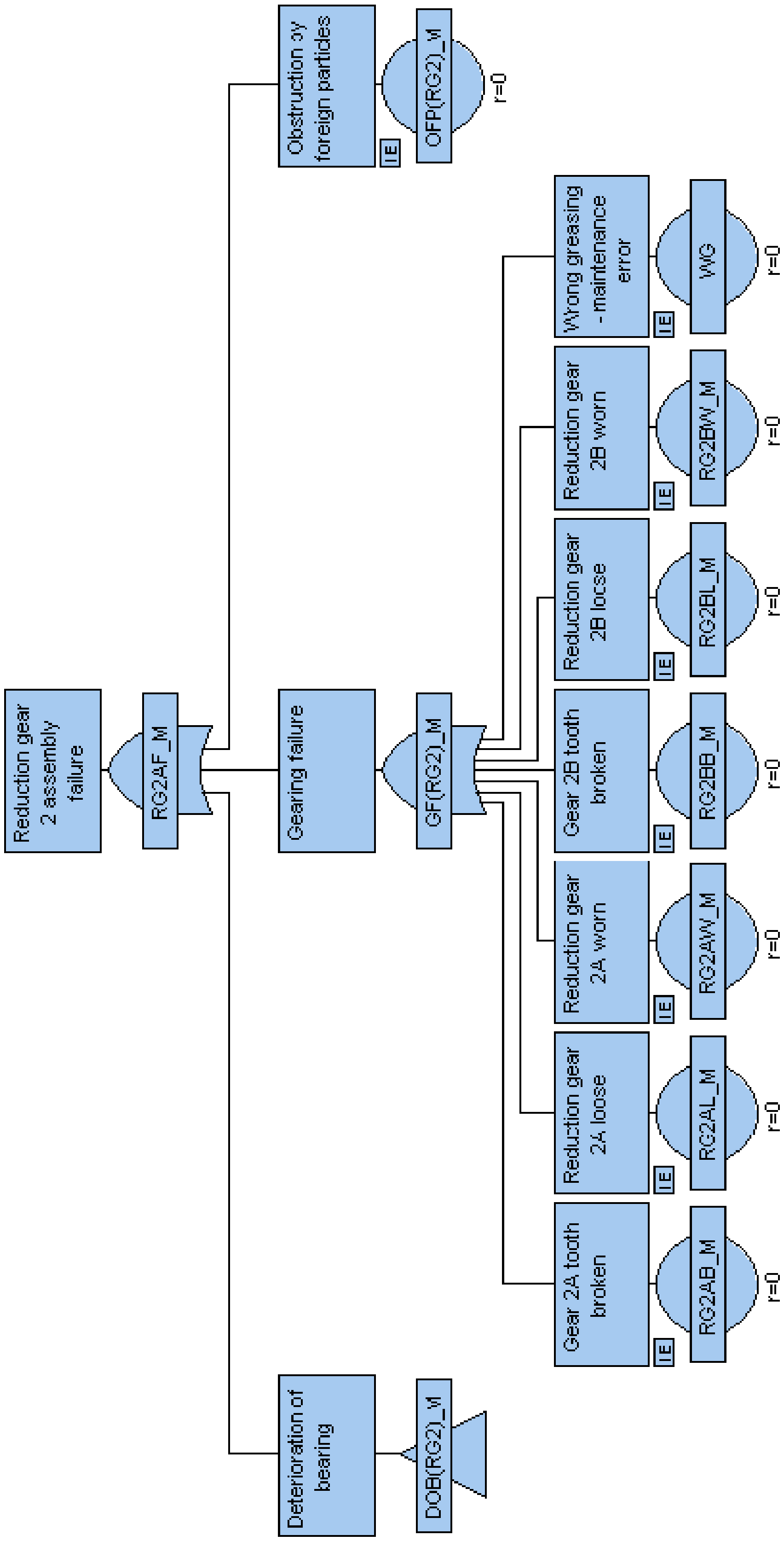


Figure 6.13: FTD for reduction gear shaft 2 assembly failure

Associated with the spring charging motor there is also a pinion gear, which naturally has the same failure modes as the other gears described previously (Refer to Figure 6.13). In addition, the motor itself could fail, which, as shown in Figure 6.14, could be due to either it being burnt out or a failure to energise the motor. The former could be broken down further, but as discussed previously, a balance must be struck between providing insufficient detail and too much where the process becomes unmanageable. Although the latter is strictly a control circuit failure, it is shown for information purposes in Figure 6.15.

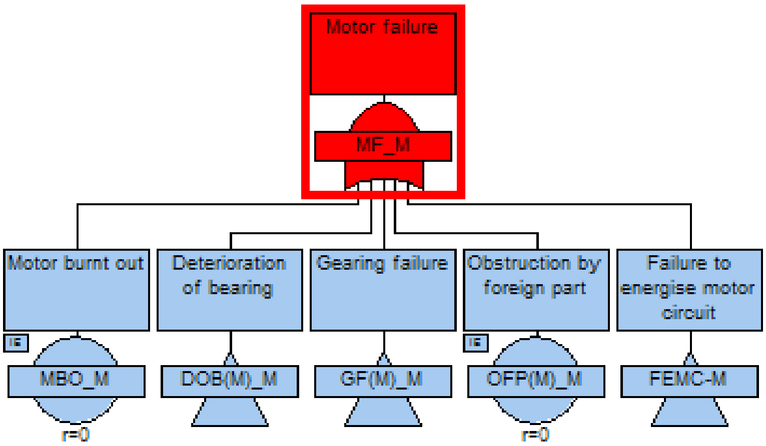


Figure 6.14: FTD for the motor failure

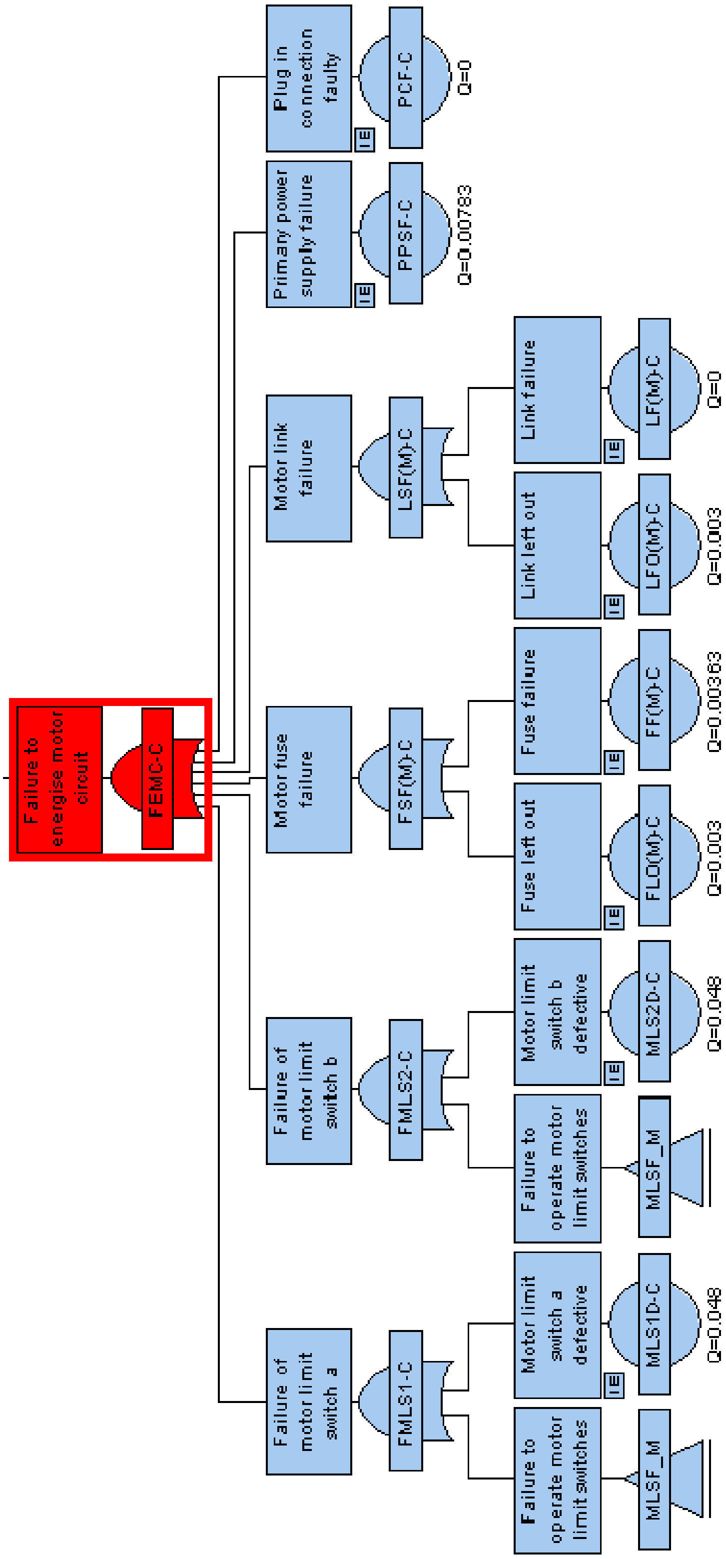


Figure 6.15: FTD for failure to energise motor

Many of the failure modes associated with the crank wheel are similar to the reduction gearing assembly described previously. However, as shown in Figure 6.16, there is one additional failure mode, which needs to be considered; namely, a failure of the crank pin, which is used to attach the close spring chain and attachment to the crank wheel.

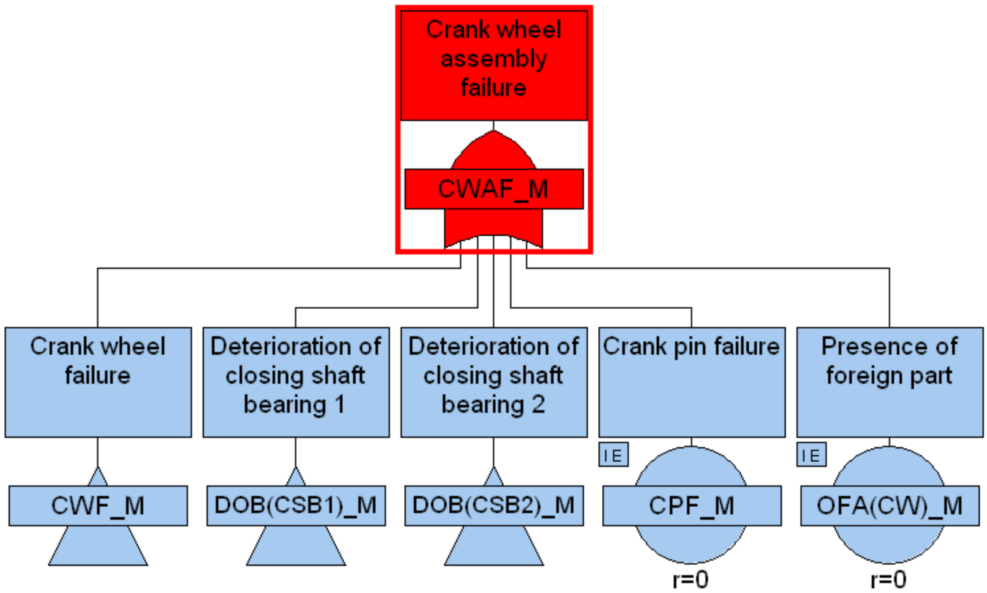


Figure 6.16: FTD for failure of the crank wheel assembly

6.3.2.3 Friction with the main shaft assembly during opening

As described in the previous section, friction with the main shaft assembly during opening could be due to the main shaft or trip spring shaft bearings.

6.3.2.4 Failure of trip spring assembly

The failure of the trip spring assembly is similar to the close spring assembly (Refer to Figure 6.11) in that there could be a failure of the trip spring chain assembly or deterioration of the bearings that are mounted on the trip spring shaft. Once again, the former could be due to friction or a seized bearing and the latter could be due to a failure of the trip chain operating lever, failure of the trip chain/attachment, catastrophic failure of the trip spring, the trip spring being overstressed or a failure of the shaft where the bearings are mounted for the trip spring chain.

6.3.3 Interrupting Chamber

The circuit breaker used in this analysis was a single pressure self blast or auto puffer type with one breaking point per pole with the three horizontal interrupters contained within a single enclosure and driven by a common mechanism.

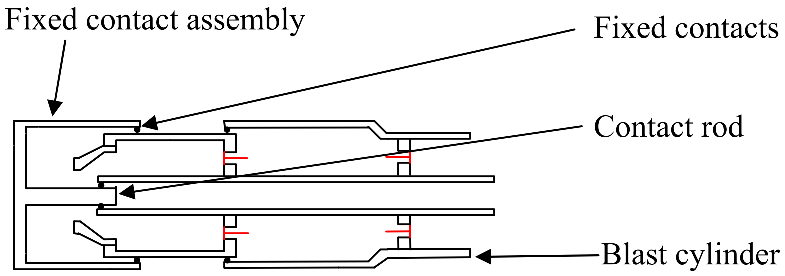
The interrupting chamber can cause a failure of the circuit breaker through the following modes:

- Fails to open on command;
- Fails to close on command;
- Failure to indicate correct status of circuit breaker;
- Circuit breaker opening time incorrect;
- Circuit breaker closing time incorrect;
- Fails to provide insulation;
- Opens but fails to interrupt current;
- Closes but fails to make current; or
- Fails to conduct current.

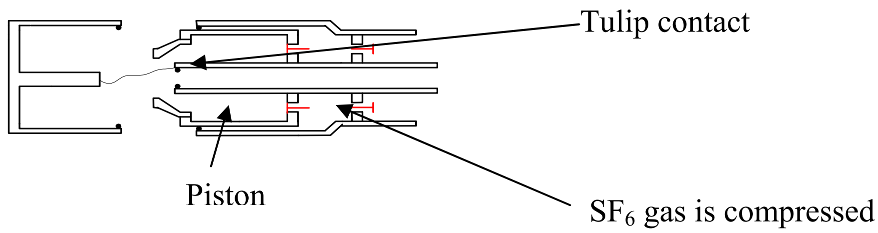
To illustrate how each of these failure modes were developed, consider the failure mode where the circuit breaker opens, but fails to interrupt the current. It should be noted that the following explanation has been restricted to one interrupter on the basis that all three interrupters are constructed and operate in the same manner. However, when carrying out the FTA to identify the critical failure modes, all three interrupters need to be considered.

As explained previously, the circuit breaker used in the FTA must remain confidential, but using a typical self blast interrupter, shown in Figure 6.17, the development of the FTD for the interrupter opens, but fails to interrupt can be explained.

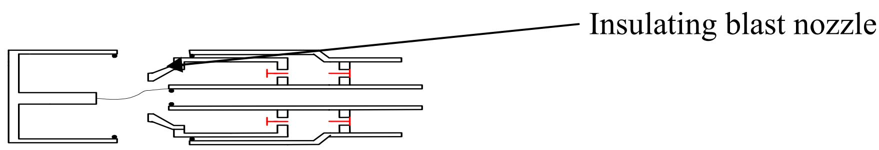
As shown in Figure 6.17, when the opening operation is triggered, the blast cylinder leaves the fixed contacts and the SF_6 gas between the blast cylinder and the piston is compressed. After the contacts are electrically separated, an electrical arc burns between the tulip contact and contact rod until it is extinguished by the blast of SF_6 gas passing through the insulated blast nozzle, the tulip contact and the contact rod. After the arc has been extinguished, the gas continues to flow until the pressure in the blast cylinder is equalized when the open position is attained. The open gap between tulip contact and contact rod effectively insulates the two electrodes in the open position.



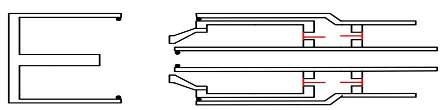
a – Blast cylinder leaves contact crown



b - Arc burn between contact rod and tulip contact



c – Arc is extinguished



d – Pressure in blast cylinder equalised and interrupter open

Figure 6.17: Diagram showing interrupter opening sequence

Therefore, when the interrupter opens but fails to interrupt, as shown in Figure 6.18, it could be due to either a failure of the auto-puffer, failure of the gas system, slow operation, the contacts parting too quickly, the contacts failing to open sufficiently or the circuit breaker has tried to interrupt a current beyond its design capability [IEEE C37.10, 1995 and IEEE C37.10.1, 2000].

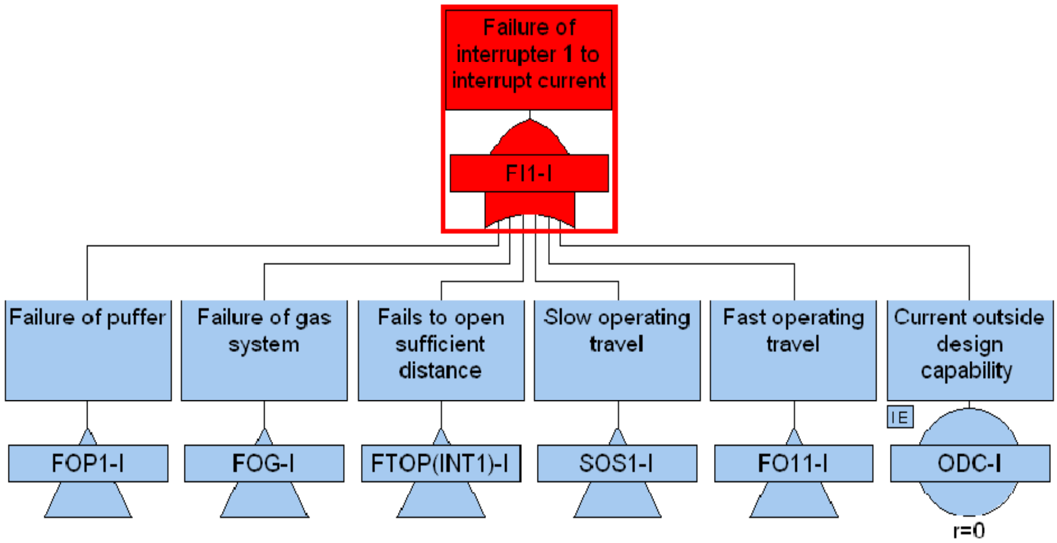


Figure 6.18: FTD for failure of interrupter chamber

6.3.3.1 Failure of auto-puffer

Referring to the previous description of the auto-puffer and Figure 6.19, the failure could be due either to the blast cylinder assembly or the fixed contact assembly unit. The analysis needs to consider the components involved in the interrupting process and not be confused with items that are performing a different function, such as the main contacts of the blast cylinder and the fixed contact assembly unit, which are utilised to conduct the primary current and not to interrupt it. Consequently, the failure of the blast cylinder assembly can be subdivided into a failure of the blast nozzle, the operating rod, the piston, the tulip contact or the auxiliary blast nozzle. Similarly, for the fixed contact assembly unit, the main component influencing the interruption process is the contact rod.

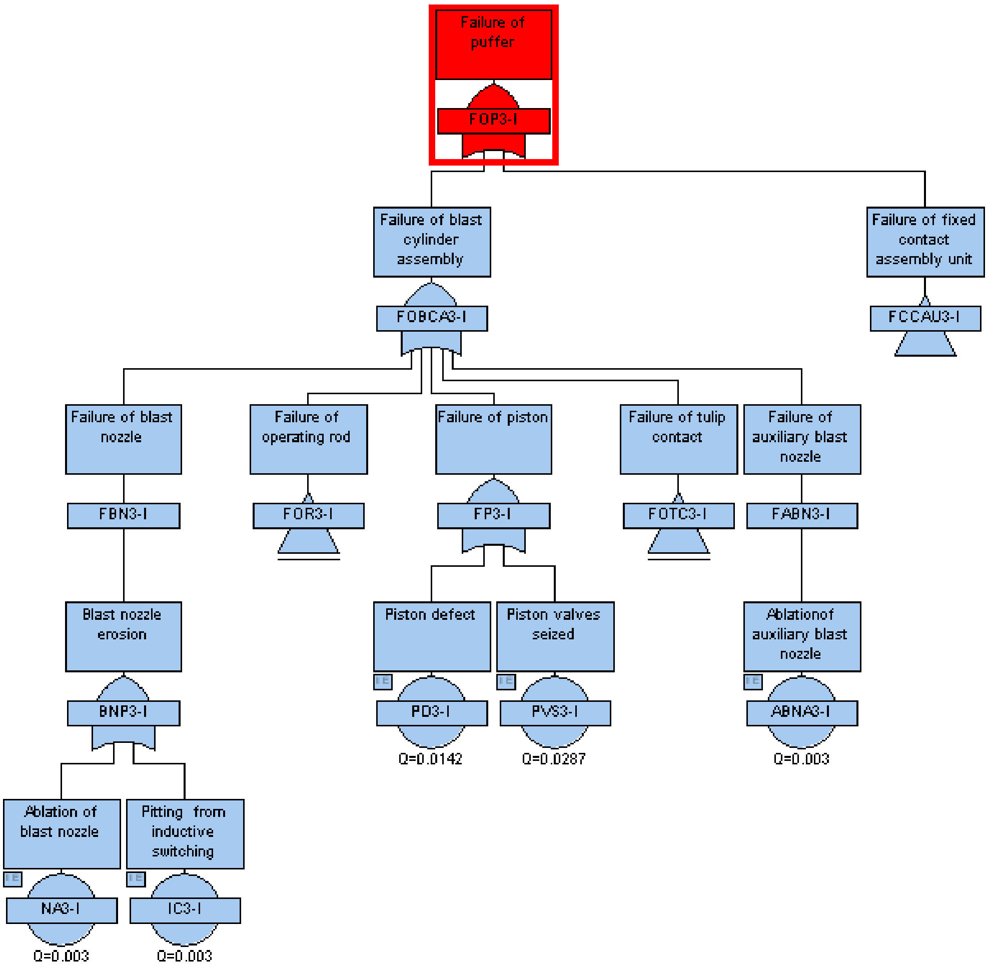


Figure 6.19: FTD for failure of the blast cylinder assembly and fixed contact assembly unit.

The expanded fault tree for a failure of the blast cylinder assembly and fixed contact assembly unit are shown in Figures 6.19 and 6.20, respectively, and the following notes describe the associated failure modes.

As explained in [Holaus et al, 2003 and Cigré, 262, 2004] and as shown in Figure 6.21, the electrical arcing that occurs during current interruption causes erosion of the contacts and ablation of the nozzles. In the case of the former, the presence of a burning electrical arc across the contact gap causes loss of material by vaporization, melting and burn-off. This leads to contact shape distortion and increase in surface roughness both of which influence the dielectric withstand characteristics of the gap and the co-ordination between main and arcing contacts. As for the latter, the inside wall surface experiences flaking, burn-off and vaporization.

Consequently, the nozzle ablation changes the gas flow dynamics during interruption and in turn leads to reduced gas density across the contact gap, which degrades the performance of the circuit breaker. Switching inductive circuits such as reactors can also be particularly onerous for the main blast nozzle [Cigré, 262, 2004; Bachiller et al, 1994; and ETRA, 1996]. Even in well-designed interrupters, there is a risk that re-ignitions will occur, which will cause damage and in the more severe cases, result in puncturing of the nozzle.

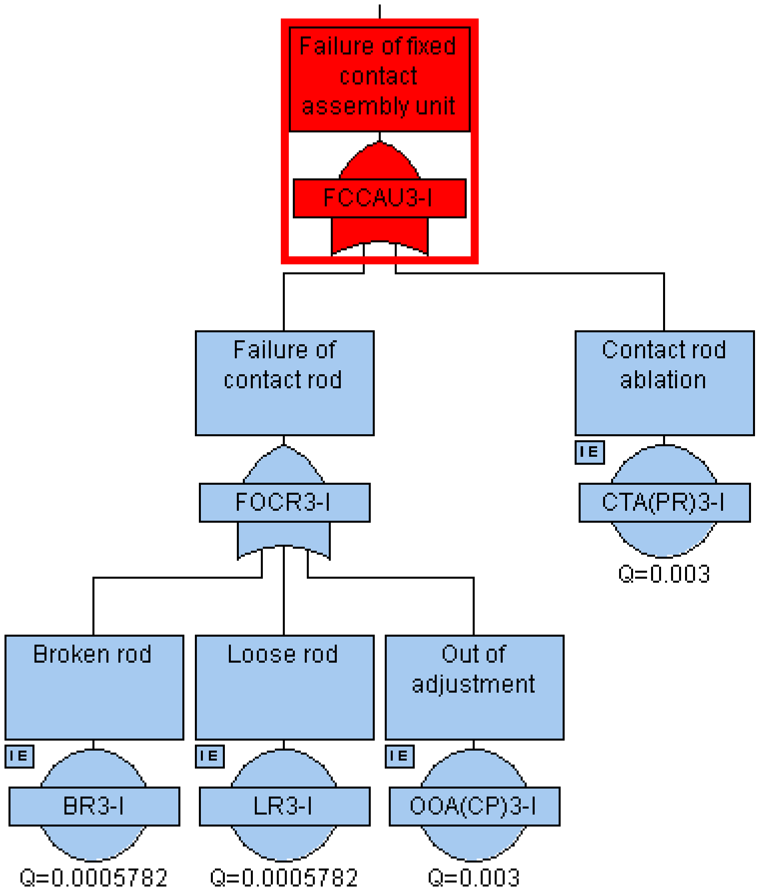


Figure 6.20: FTD for the fixed contact assembly unit

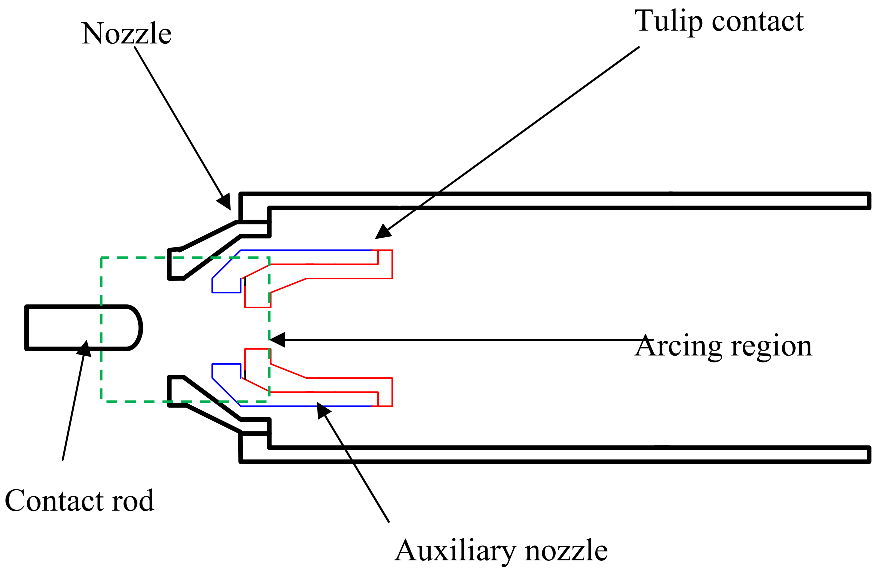


Figure 6.21: Diagram showing electrical arcing within the interruption chamber

Therefore, for the main blast nozzle and the auxiliary blast nozzle, the failure modes can be expanded as shown in Figure 6.19. For the tulip contact (Refer to Figure 6.22) and the contact rod of the fixed contact assembly unit (Refer to Figure 6.20), there are additional failure modes that need to be considered. Namely, the tulip contact fingers could fail due to either loose contact pressure or being broken due to hydrogen embrittlement and the contact rod of the fixed contact assembly unit could be broken or loose or it may be out of alignment due to an assembly or maintenance error. It should be noted that the subject of hydrogen embrittlement is covered in more detail later in this chapter when discussing the failure of the gas system.

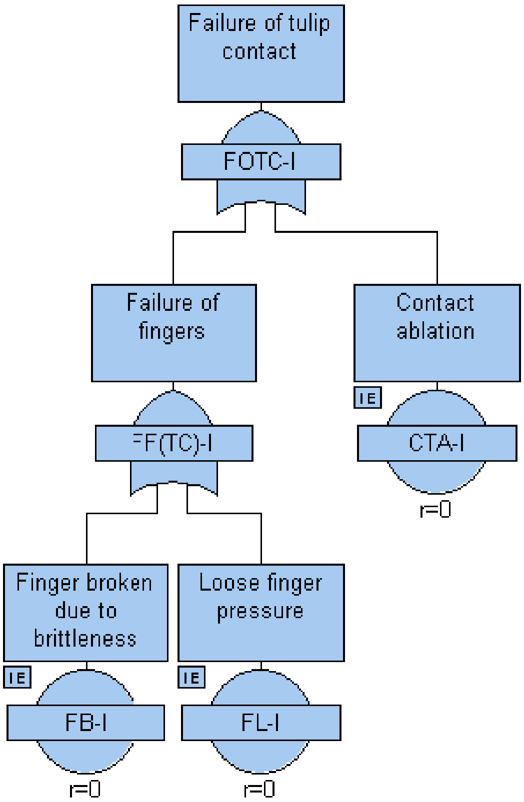


Figure 6.22: FTD for failure of tulip contact

With regard to the piston and as shown in Figure 6.19, the two main failure modes are either the valves being seized or there is a defect with the piston, such as a crack.

Finally, as shown in Figure 6.23, the operating rod comprises of an insulating component and a metallic connecting component, which is used to move the blast cylinder. Apart from being out of alignment, the other failure modes could be that it has sheared due to excessive force or the connecting pins that attach the two components together and to the blast cylinder are loose.

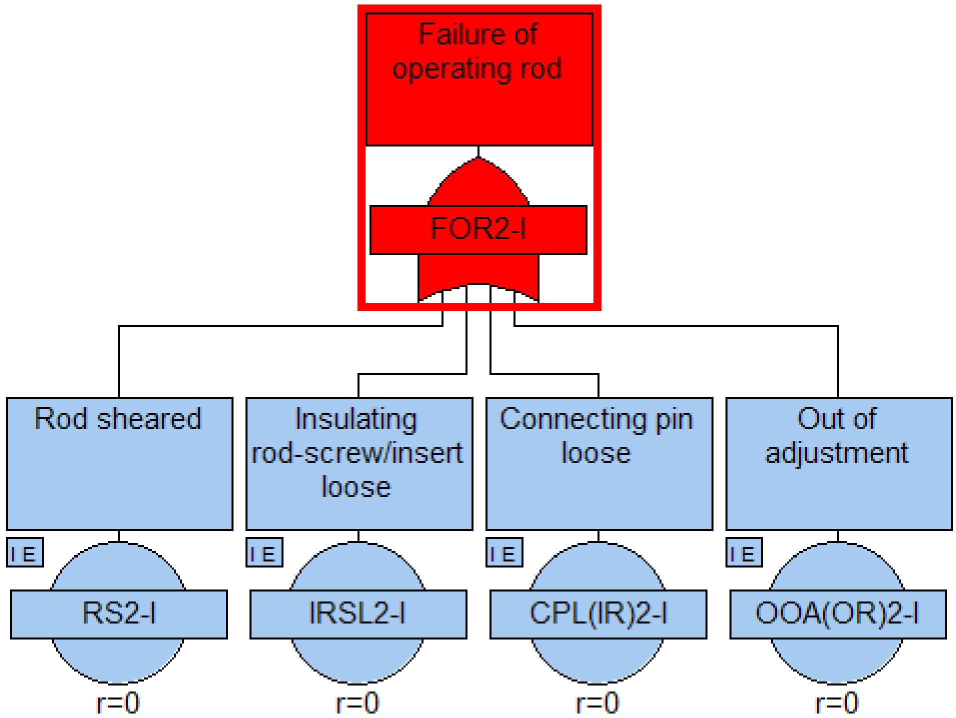


Figure 6.23: FTD for failure of operating rod

6.3.3.2 Failure of gas system

As explained previously, SF_6 has outstanding insulating and arc quenching characteristics. However, as shown in Figure 6.24, the two potential failure modes that can occur are either the interrupter operates at low pressure or there is liquefaction of the gas.

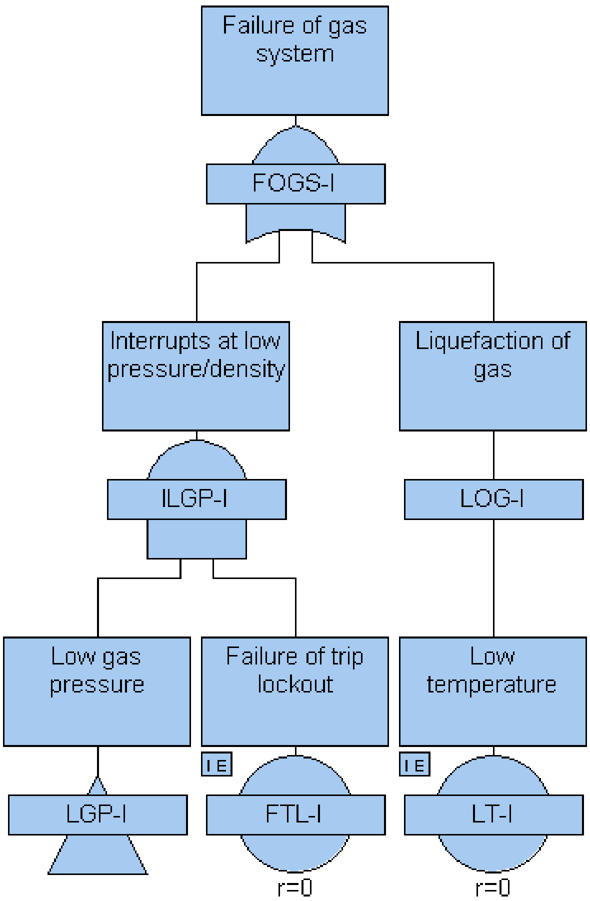


Figure 6.24: FTD for failure of the gas system

Depending on the performance standards specified for the GIS, if [NGTS 3.2.1, 1999] is used as in this case and as shown in Figure 6.24, the circuit breaker should remain inoperable (locked out) if the gas density/pressure is below its design criteria.

With regard to liquefaction, as shown in Figure 6.24 and reported in [Boggs, 1989] there is a significant decrease in the dielectric performance of SF_6 if the temperature falls to a level whereby the gas turns from a gaseous to a liquid state. As shown in [Stewart, 2004], this is due to the pressure falling in response to the temperature decrease, causing the gas density to remain constant.

For the gas pressure/density to fall below its specified performance limit, there would need to be a failure of the enclosure or at one of the apertures used for either the gas density monitoring transducers, pressure relief device, the gas connection point or where the operating rod enters the enclosure.

In the case of the gas density monitoring transducers, there are two sensors, one for on-line monitoring and one to ensure that the circuit breaker does not operate when the gas density/pressure falls below a specified limit. For there to be a leakage of SF_6 there would have to be either a failure of a gas seal or the self sealing valve that is used to prevent gas leakage if the gas density transducer has been removed for some reason. This latter failure would only apply to the gas density on-line monitoring transducer, as it would be normal to take the circuit breaker out of service if there were a failure of the other transducer. For there to be a seal failure, as shown in Figure 6.25, the main causes would be due to an assembly, manufacturing or maintenance error. Namely, 'O' ring manufacturing defect, 'O' ring installation error, and roughness of the sealing surface or the sealing surface has not been cleaned properly. However, there are two other failure modes; the first being that the seal has deteriorated due to the arcing products. As explained in [Chu et al, 1984] during the arc discharge, SF_6 dissociates at temperatures higher than 3000 Kelvin (K). Most of the decomposition products recombine quickly to reform SF_6 gas, but some gas remains dissociated and will react with other gas impurities to attack surrounding materials and metal surfaces. Unless the materials within the GIS have been specially selected to resist these aggressive products, they will be damaged.

Materials most at risk are:

- Silica, SiO_2, filled epoxy insulators (most manufactures have now adopted Alumina (Al_2O_3), which is not damaged by decomposition products);

- Non-acid resistant paints, which will blister or peel off when the decomposition acids diffuse through the paint causing hydrogen gas to form on the aluminum surface and lift the paint off;

- Steel springs as used in contact fingers due to hydrogen embrittlement;

- Silver plated contact surfaces - these can be damaged to the degree that the contact resistance becomes unacceptably high; and
- Silicone grease, silicone rubber and ‘O’ rings - these are degraded by the corrosive Hydrogen Fluoride (HF), which cannot be captured by filters.

The second potential failure mode for the seal is deterioration through environmental corrosion. As shown in Figure 6.25 and reported in [Porter et al, 1990], for this to happen there would need to be a combination of the following events occurring simultaneously:

- water being trapped between the flange surfaces;
- the silicone grease, used to prevent water penetration, being applied incorrectly; and
- the presence of a corrosive environment.

For the gas connection to fail, as shown in Figure 6.26, the failure mechanisms are the same as the gas density transducer, with the exception that the securing screws are an additional failure mode due to a corrosive environment attacking them in a similar manner to the flange sealing surfaces.

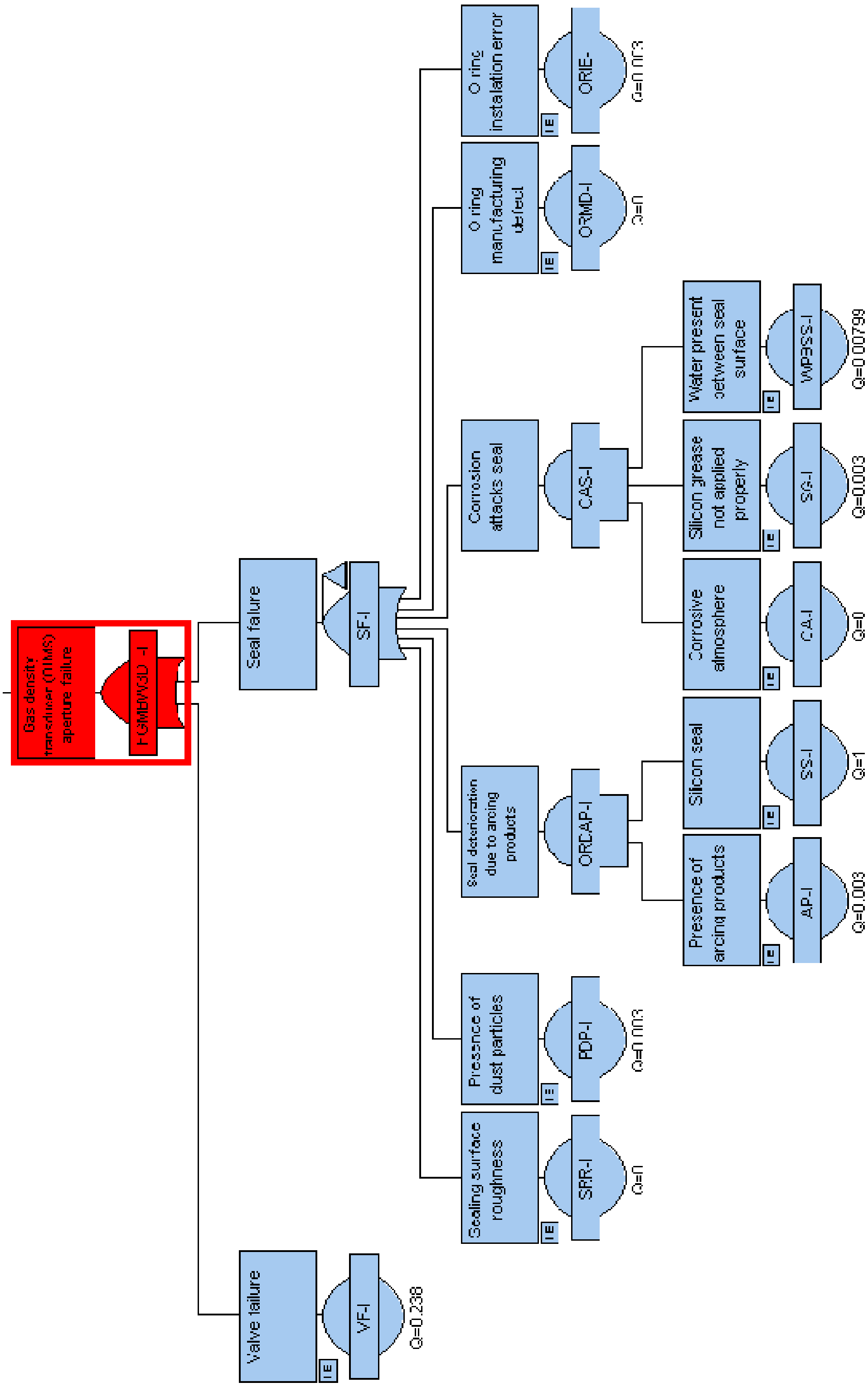


Figure 6.25: FTD for failure at aperture for gas density on-line condition monitoring transducer

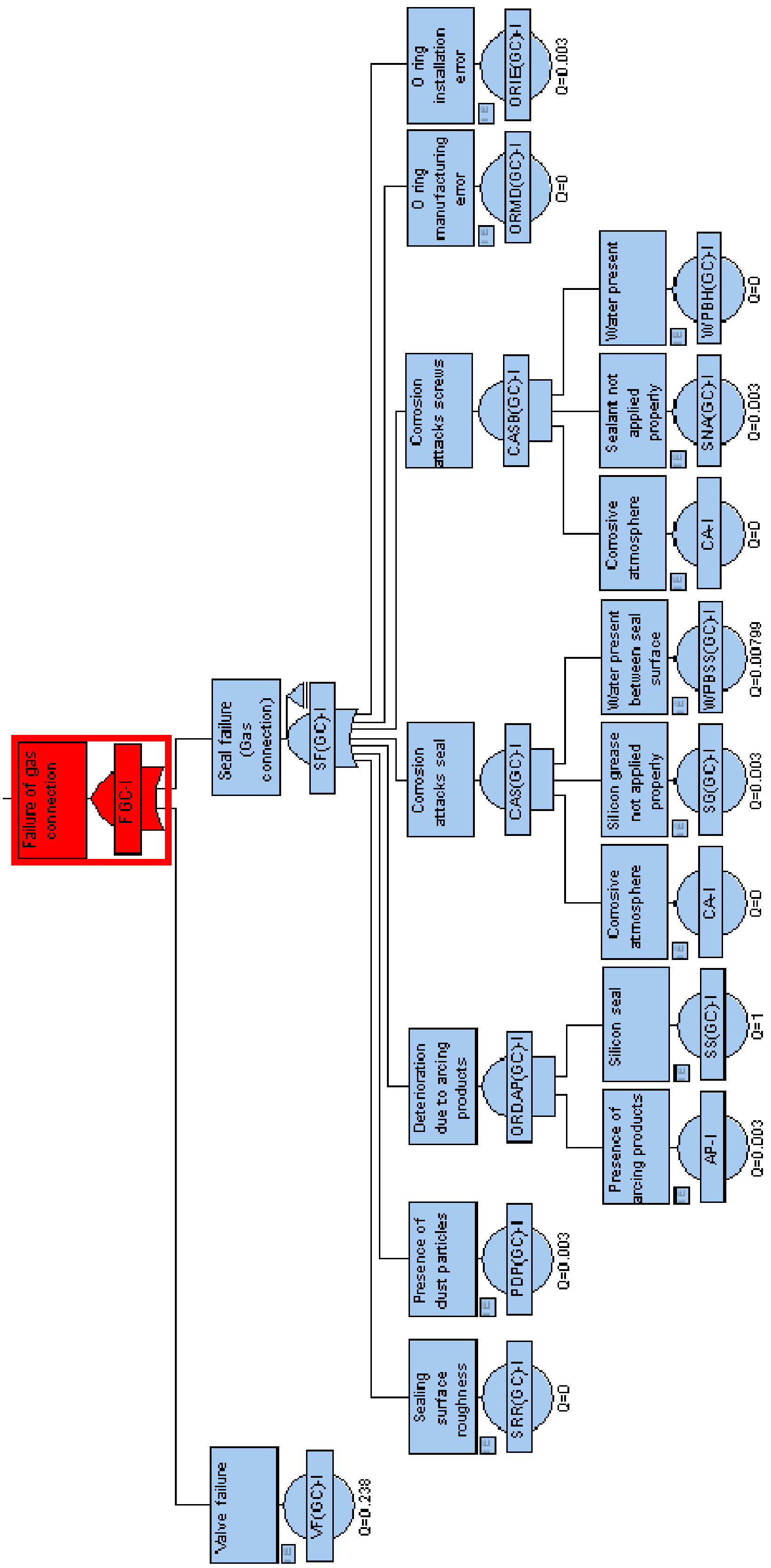


Figure 6.26: FTD for failure of gas connection

The Pressure Relief Device (PRD) and seal where the operating rod enters the enclosure are similar to the gas connection, with the exception that they do not contain a self-sealing valve.

Finally, for the enclosure to suffer a gas leakage, there would need to be a leak at the flange surfaces where it adjoins the adjacent enclosures. Once again the failure modes are similar to the PRD and the seal where the operating rod enters the enclosure.

6.3.3.3 Slow operating travel results in failure to interrupt

Slow operation that results in a failure to interrupt could be due to a failure of the mechanism/ drive linkage or the failure could be within the interrupter chamber. For the purposes of this description, the following explanation is restricted to developing the fault tree for the latter.

As shown in Figure 6.27, the failure mechanisms could lie with the fixed contacts, blast cylinder assembly, contact rod, piston valves or the tulip contact fingers.

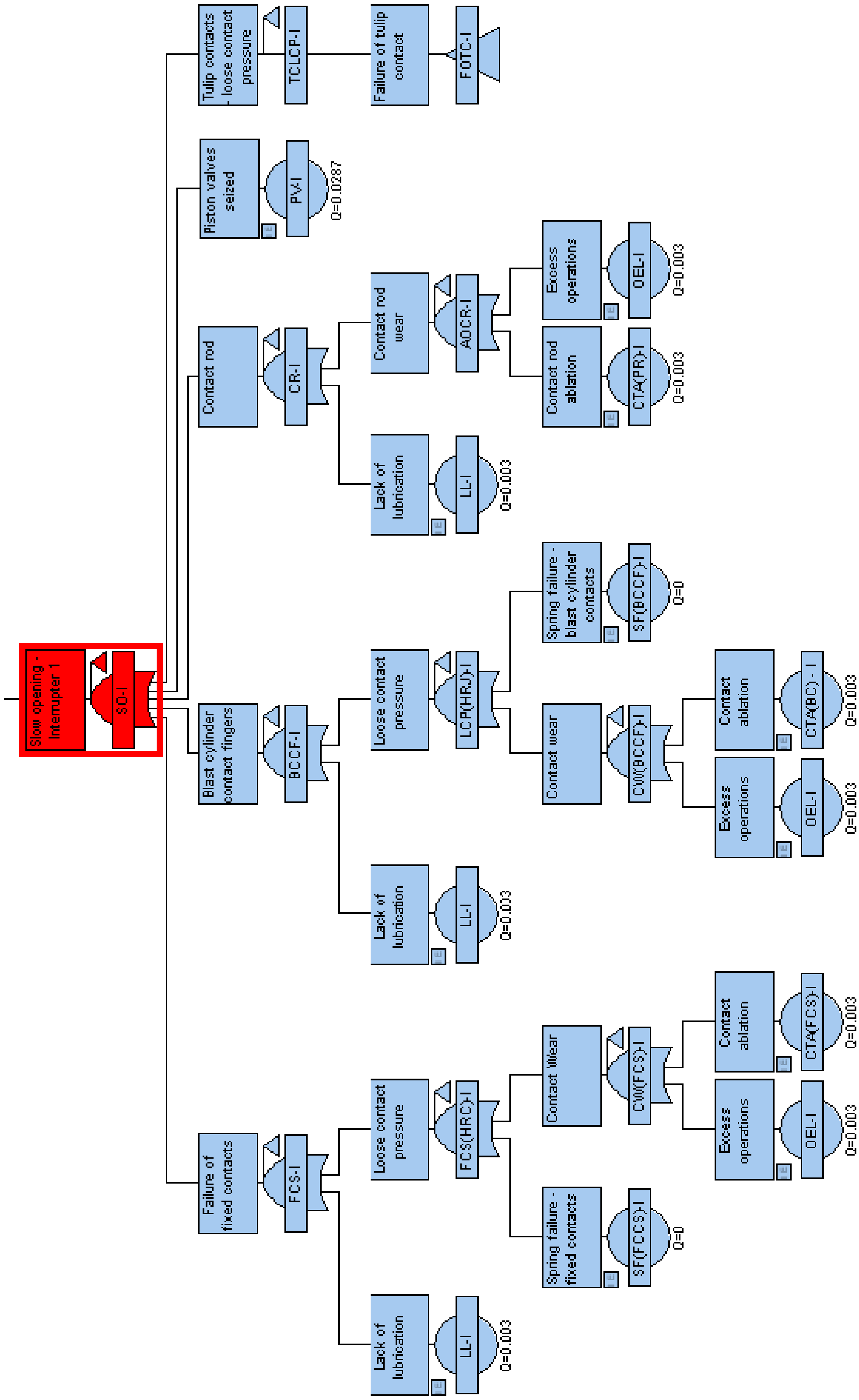


Figure 6.27: FTD for slow operating travel resulting in failure to interrupt

For the contact rod, the failure modes could be due to either a lack of lubrication (most likely a maintenance error) or as described previously a failure due to excessive wear or exceeding the recommended number of switching operations. In the case of the fixed contacts and blast cylinder assembly, once again the failure mechanism could be lack of lubrication and similar to the tulip contact, loose contact pressure or a broken spring due to hydrogen embrittlement.

6.3.3.4 Fast operating travel results in failure to interrupt

In the case of the circuit breaker opening too fast to allow successful interruption, the failure modes could be due to the circuit breaker being set up incorrectly (out of adjustment) or a failure of the trip damper or mechanical delay device, the latter being used to control the opening speed of the mechanism. Although these failure modes are associated with mechanism, the fault tree is shown in Figure 6.28 for information purposes.

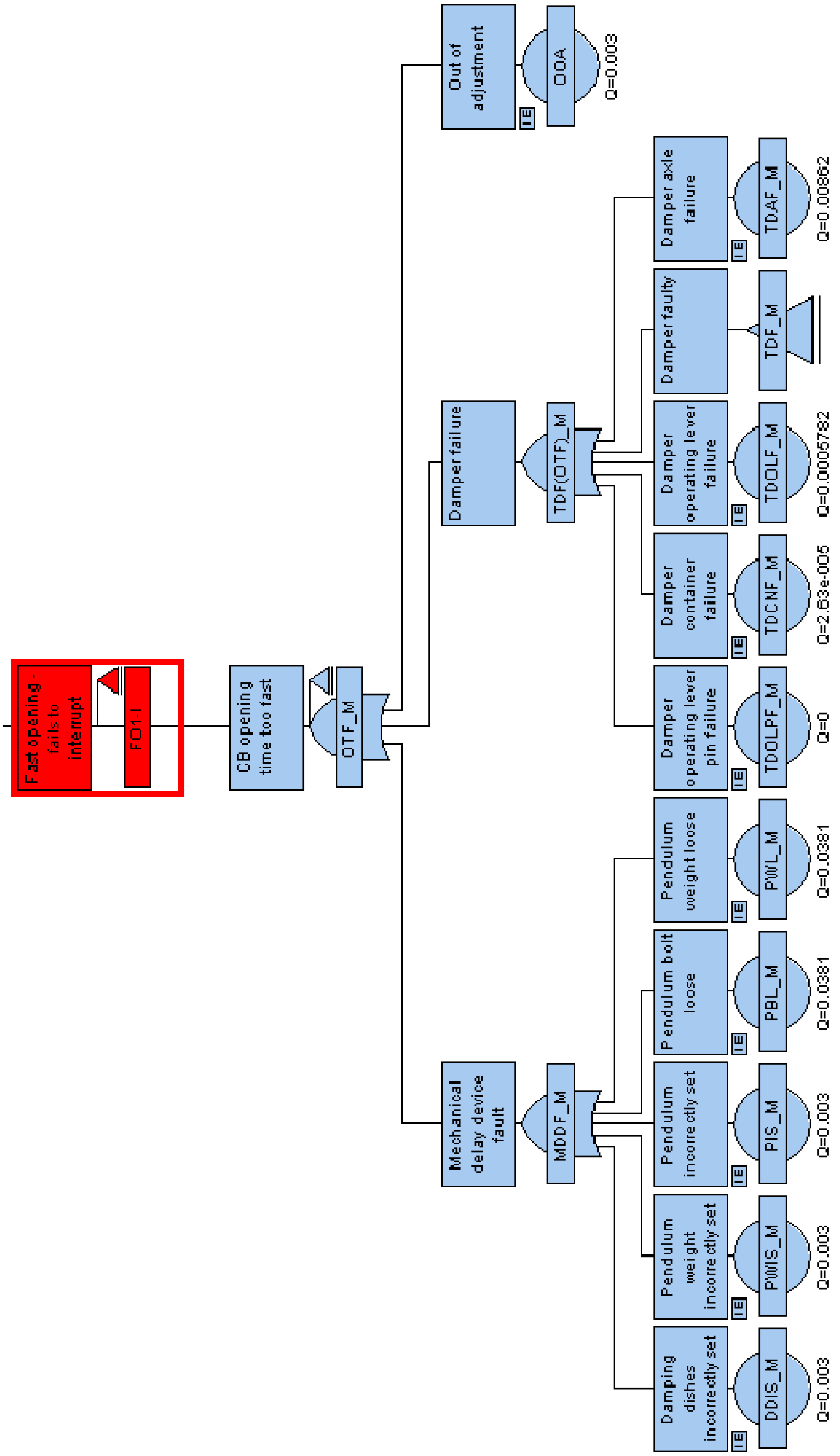


Figure 6.28: FTD for fast operating travel resulting in failure to interrupt

6.3.3.5 Interrupter fails to open sufficiently

Similarly, if the circuit breaker fails to open sufficient distance to allow successful interruption, the failure modes could be due to the mechanism or drive linkage. Once again for information purposes, the fault tree diagram has been included in Figure 6.29. The drive linkage failure modes are covered in the next section, but it is worth noting that the mechanism failure modes have been explored earlier in the chapter. This example illustrates the point of sub-dividing the circuit breaker into functional groups to enable the fault trees to be re-used for another type of circuit breaker that has the same interrupter chamber, but a different mechanism to the one being currently studied.

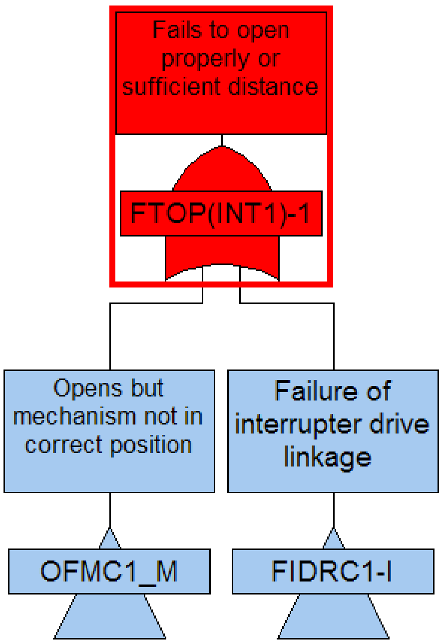


Figure 6.29: FTD for interrupter fails to open sufficiently

6.3.4 The Drive Linkage

The drive linkage connects the mechanism to the operating rod of each interrupter where the opening and closing force is transmitted from the operating mechanism lever, via a linkage to a lever located externally on the side of the interrupter chamber. This in turn drives a shaft and linkage assembly, located inside the enclosure housing. From the shaft and linkage assembly, levers connect to each of the interrupter operating rods, which as described previously are used to operate each of the interrupters.

The drive linkage can cause a failure of the circuit breaker through the following modes:

- Opens, but mechanism not in the correct position;
- Fails to open on command;
- Fails to close on command;
- Circuit breaker opening time incorrect; or
- Circuit breaker closing time incorrect.

To illustrate how each of these failure modes were developed for the drive linkage, consider the failure mode where the circuit breaker opens, but the contacts are not in the correct position.

Clearly, the failure modes will be due to a failure of one of the drive linkages, shafts or levers described previously. However, to simplify the following description, the explanation has been restricted to one interrupter linkage and where devices have similar failure modes one device is selected for the purposes of explaining how the FTD can be developed. For example, although the drive linkage comprises of a number of levers, only one lever is described in detail, as each lever fails in exactly the same manner.

Therefore, referring to Figure 6.30, if the failure occurs with the linkage driving the first interrupter in the enclosure, it could be due to the external linkage between the operating mechanism and interrupter enclosure, the external drive lever on the side of the enclosure, the internal operating shaft or the lever that is connected to the operating rod. One other possibility that needs to be considered is that if the shaft driving the other interrupters is seized, it could also affect the operation of the first interrupter, as the shafts are linked together.

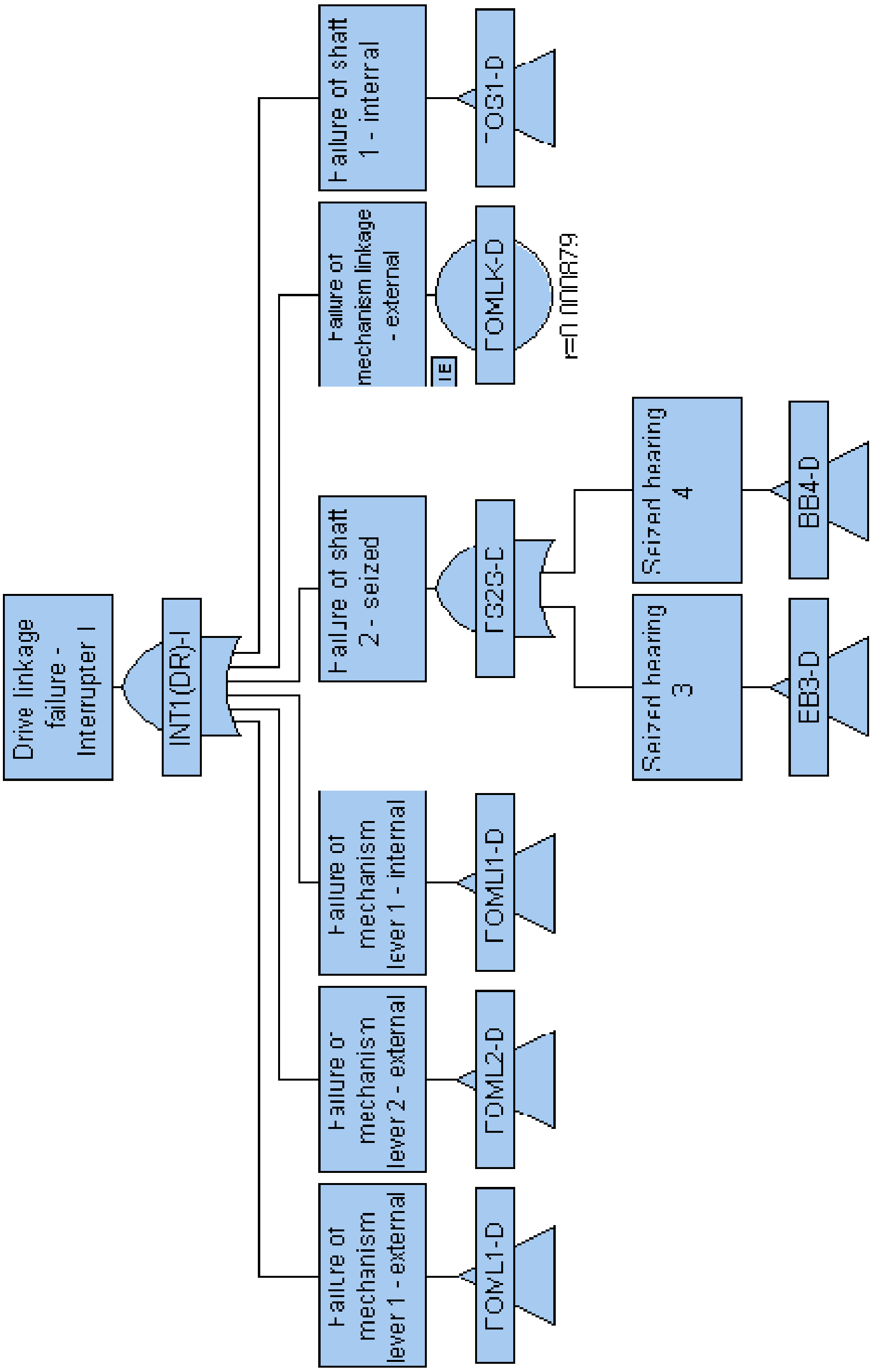


Figure 6.30: FTD for failure of drive linkage to be in correct open position

If it is a failure of a lever, referring to Figure 6.31, it can fail in three ways. Namely, the lever itself is broken or the pins securing it to the interrupting operating rod and operating shaft have failed.

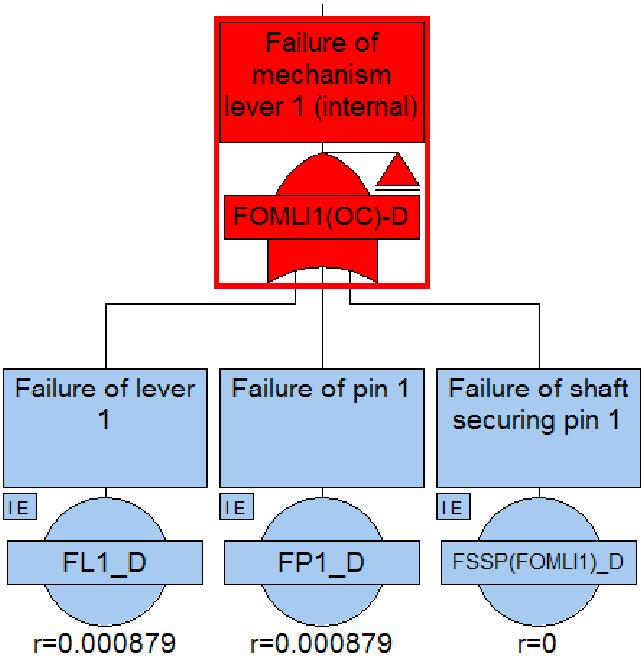


Figure 6.31: FTD for failure of drive linkage lever

On the other hand if the failure is attributable to the operating shaft, as shown in Figure 6.32, the shaft may be fractured or one or both of the bearings have seized.

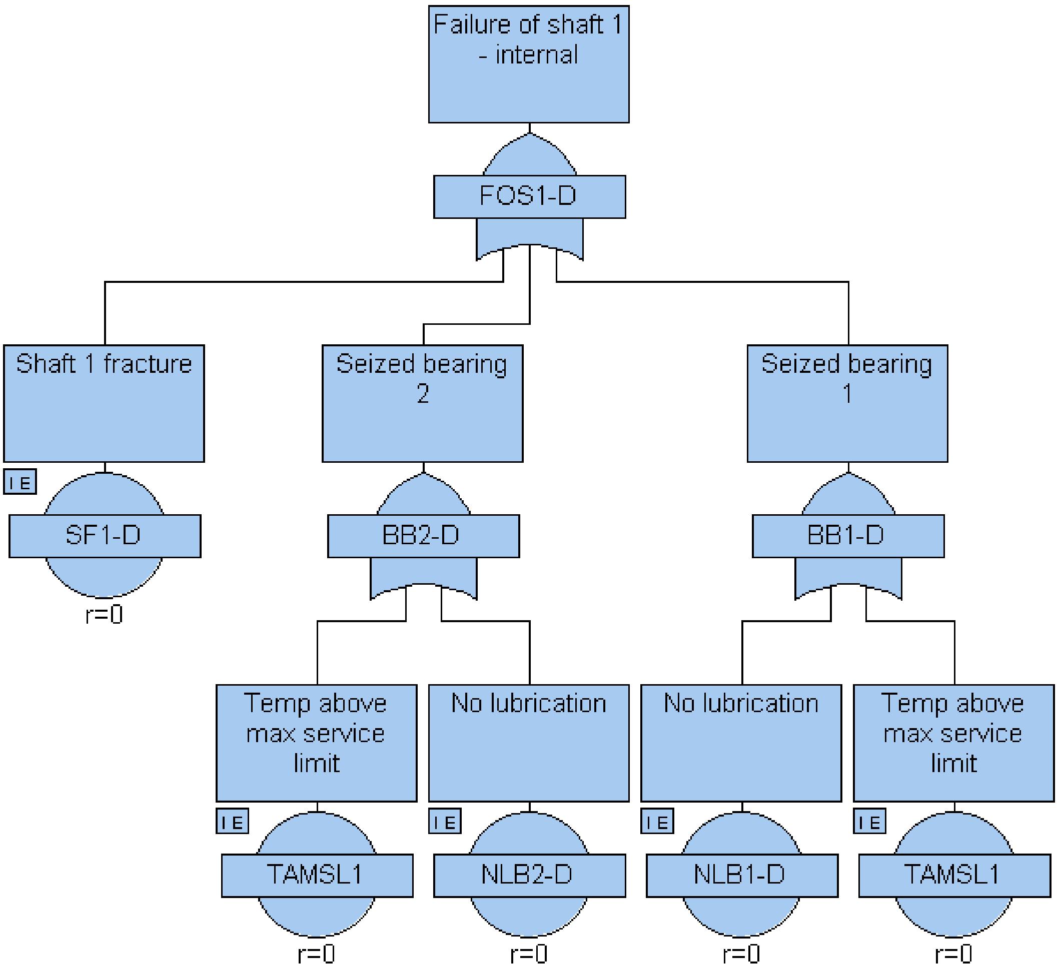


Figure 6.32: FTD for failure of drive shaft operating shaft

6.3.5 Circuit Breaker Control System

As described in [Cigré, 259, 2004] the circuit breaker control circuit is the electrical system required to ensure that the circuit breaker responds correctly, safely and reliably to external commands. This includes operating facilities such as operating coils, as well as monitoring facilities such as condition and position indications.

The control system can cause a failure of the circuit breaker through the following modes:

- Repeated close while previous close signal is applied;
- Fails to open on command;
- Fails to close on command;
- Opens without command;
- Closes without command;
- Failure to indicate correct status of circuit breaker; or
- Attempts to close while closed.

To illustrate how each of these failure modes were developed for the control system, consider the failure mode where the circuit breaker fails to open on command or more specifically, there is a failure to energise the trip coil.

As shown in Figure 6.33, the trip coil will either be initiated by the protection scheme, or by an operator, whether that is remotely or locally. For this example consider a failure of the remote operation, as the other opening methods have similar failure mechanisms.

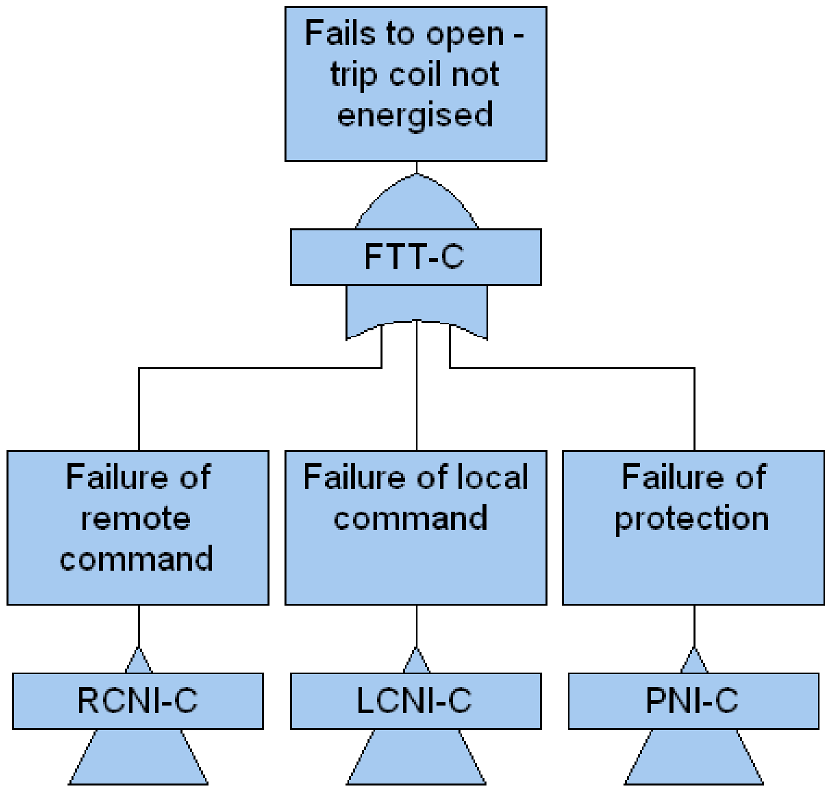


Figure 6.33: FTD for fails to open – trip coil not energized

For a remote operation to be unsuccessful, the failure could be due to one of the following reasons (Refer to Figure 6.34):

- The open command has not been received by the control system;
- The local/remote contact is in the incorrect position. e.g. for the remote operation circuit to be activated an operator must physically move a selector switch on the Local Control Cubicle (LCC), thereby closing a contact in the remote opening circuit;
- The trip coil isolation links are faulty. These links are located, electrically, either side of the trip coil and allow it to be isolated when carrying out maintenance checks on the protection and control scheme;

- The plug in connection on the cable between the circuit breaker mechanism housing and LCC is faulty;
- The circuit breaker auxiliary switch, which is used to indicate that the circuit breaker is closed, is in the incorrect position;
- There has been a failure of the trip coil;
- The contact that is used to lockout or disable the trip circuit, if the circuit breaker gas density is low, is in the open position; and
- The 110 volt DC supply, which is used to energise the trip coil, is faulty.

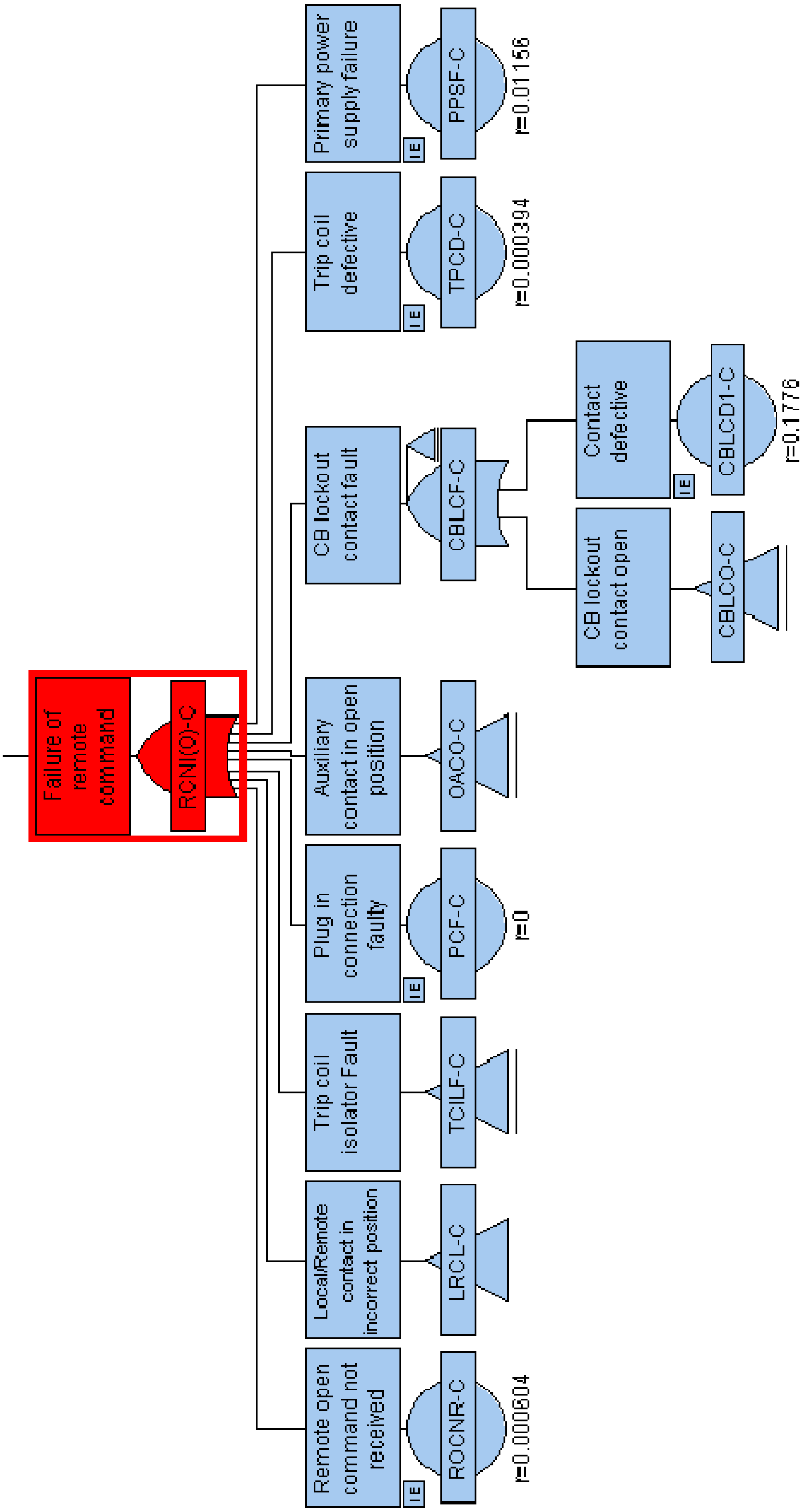


Figure 6.34: FTD for failure of remote command

As shown in Figure 6.35, some of these failure modes need further expansion. Namely, for the local/remote switch to be in the incorrect position the contact could either be defective or there has been a failure to prime the remote operation circuit. Referring to Figure 6.35, the latter could be due to either the remote relay coil being defective, a failure of the 48 volt DC power supply used to energise the remote operation circuit, a failure of the 48 volt DC fuse /link assembly for the remote circuit, the local/remote contact is defective or the operator has simply not selected remote operation. As for the trip coil isolation links, as shown in Figure 6.36, either link could be have been left out (maintenance error) or they have failed.

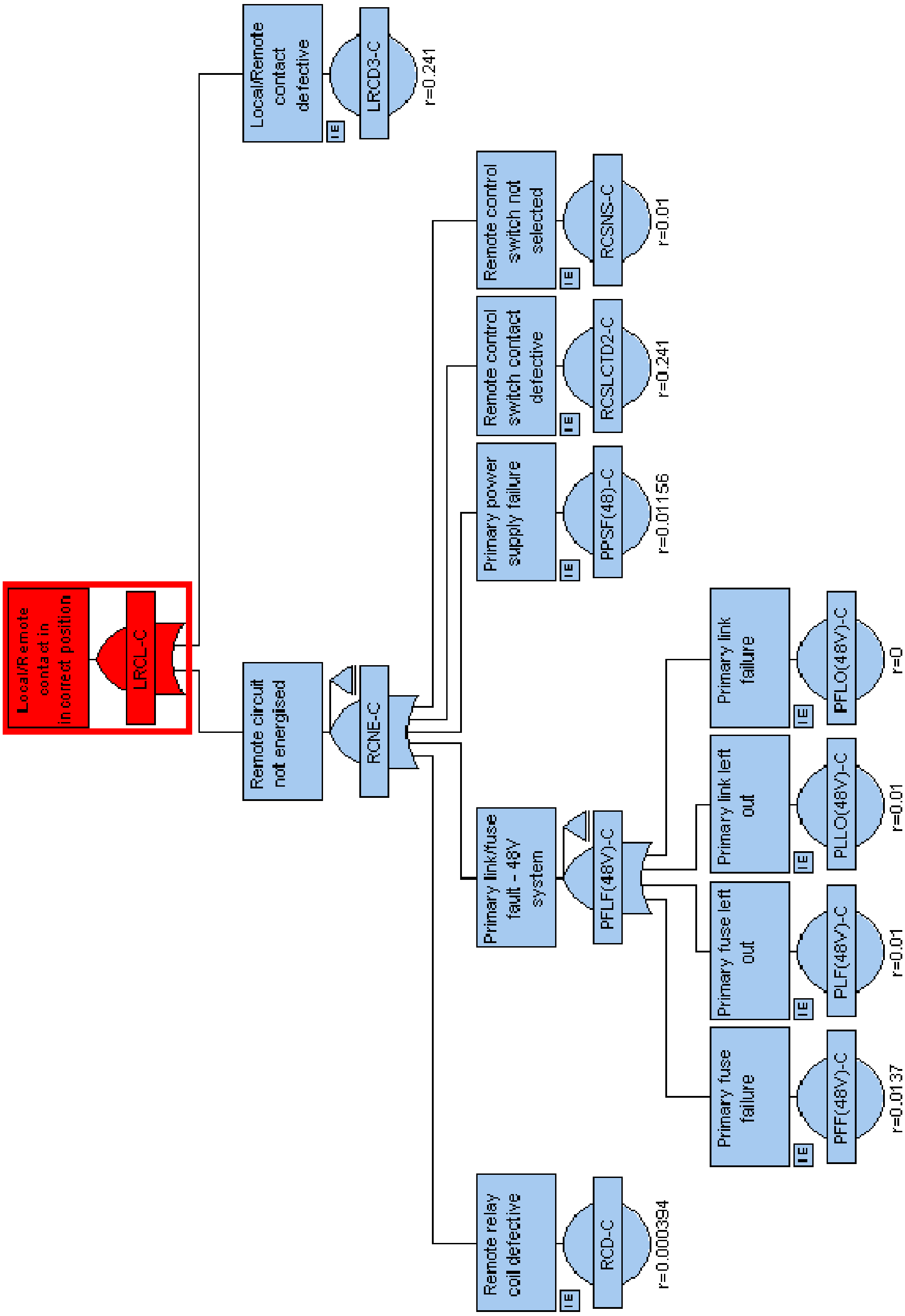


Figure 6.35: FTD for local/remote contact in incorrect position

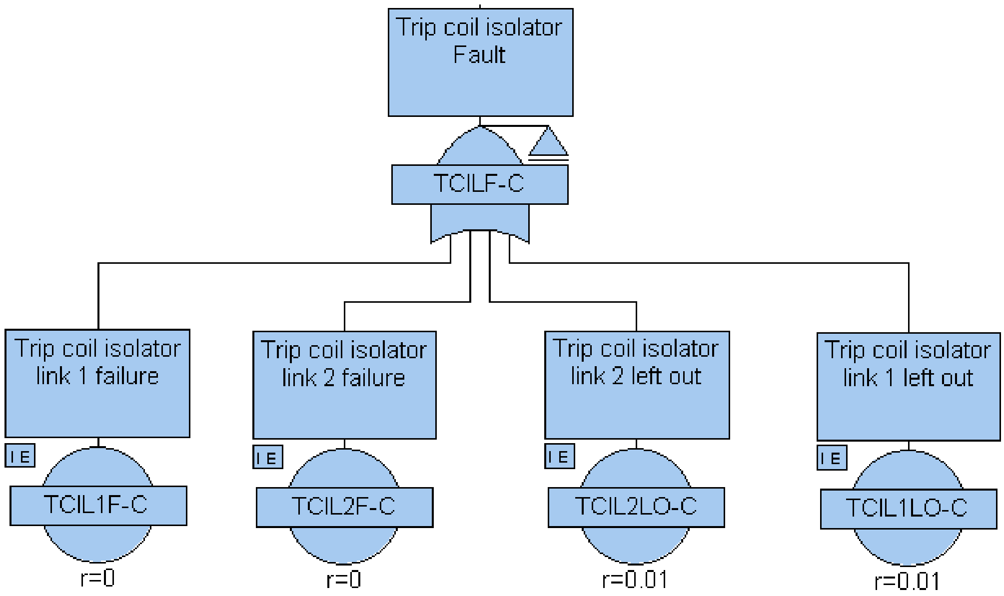


Figure 6.36: FTD for trip coil isolation fault

As shown in Figure 6.37, for the auxiliary contact to be in the incorrect position, it could either be defective or there has been a failure in the mechanism to operate the auxiliary switches or more simply, the circuit breaker is already in the open position – it does happen, although a good control room engineer will claim that they are just testing!

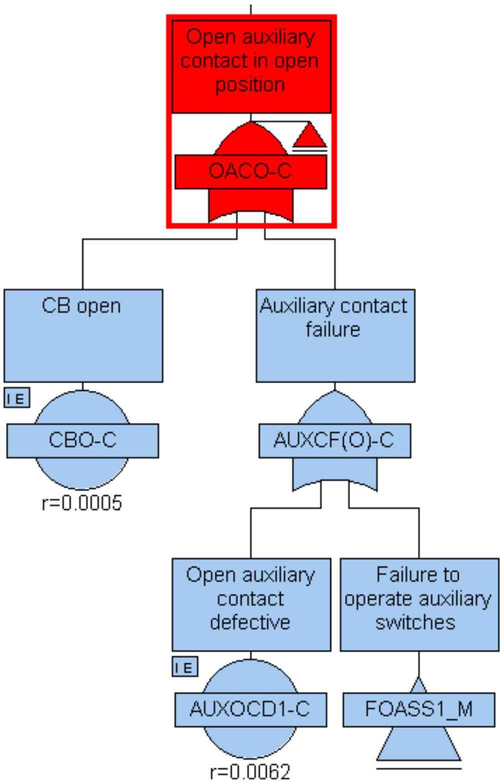


Figure 6.37: FTD for auxiliary switch contact failure

Finally, as shown in Figure 6.38, the circuit breaker SF_6 gas density lockout contact could be open due to the gas density transducer being defective, a failure of the gas monitoring equipment, the gas density being genuinely low (refer to section 6.3.3.2), or there has been a failure to prime the circuit breaker gas density lockout circuit. The latter could be due to either the relay coil being defective, a failure of the power supply used to energise the circuit breaker lockout circuit or a failure of the fuse /link assembly (either they have failed or have been left out by an operator).

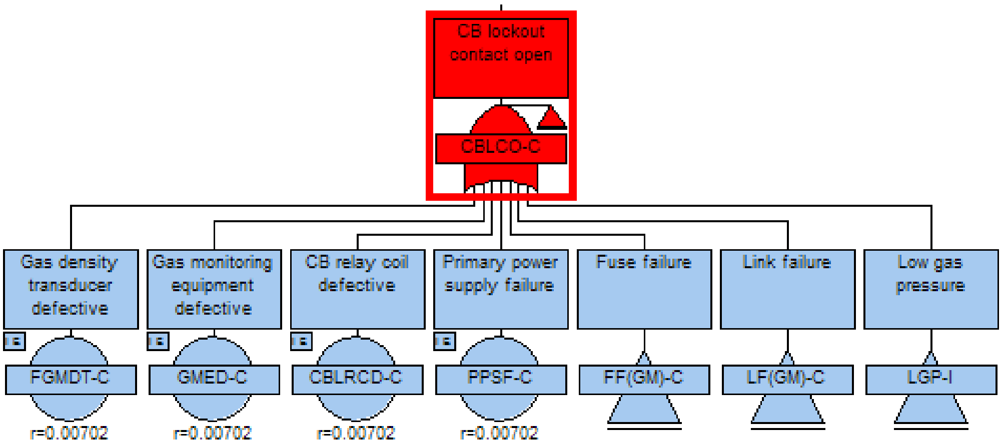


Figure 6.38: FTD for CB lockout contact open

6.4 Analysis and identification of critical parts that could result in a failure

After the fault tree has been constructed and the fault data has been entered, the software determines the minimum combination of component failures and subsets that will cause a system failure; otherwise known as the minimal cut sets. For a system failure to occur, all components of a minimal cut set must be in the failure state.

In carrying out the analysis, an important feature of the software is that it is able to determine a component's contribution to the circuit breakers unavailability. As outlined previously, this is invaluable information as it highlights the parts that have the most significant effect on the circuit breaker availability; namely, it identifies the critical failure modes.

Using the Faultree$^+$ software, the minimal cut sets are calculated for the Z_{20} (lower limit), Z_{80} (upper limit) and mean failure rates. The analysis reveals that in total there are four hundred and thirty minimal cut sets and using the mean failure rates, 72.2% of the circuit breaker's unavailability is attributable to fifty events. Similarly, using the lower and upper limits for the failure rates, the top fifty failure events represent 76.6% and 72.1% of the circuit breakers unavailability, respectively. On the other hand, if the number of minimal cut sets is increased to one hundred and fifty, this accounts for 90.1% of the circuit breaker's unavailability when considering the mean failure data set.

For illustration purposes, the top fifty events for the lower limit, mean and upper limit failure rates, along with their contribution to the circuit breaker's unavailability are shown in Tables 6.1, 6.2 and 6.3, respectively. Where a minimal cut set occurs in the top fifty events for the lower limit, mean and upper limit failure rates, it has been marked with an asterisk.

Table 6.1: Top fifty minimal cut sets for the lower limit failure rates

Minimal Cut Set Number	**Description**	**Minimal Cut Set ratio of overall circuit breaker unavailability**
1	Condition monitoring gas density transducer valve failure*	0.0949
2	Control scheme gas density transducer valve failure*	0.0949
3	Display supply switch failure*	0.0377
4	Local control switch contact 'a' defective*	0.0374
5	Local control switch contact 'b' defective*	0.0374
6	Local/Remote contact 'd' defective*	0.0191
7	Local/Remote contact 'e' defective*	0.0191
8	Local/Remote contact 'a' defective*	0.0191
9	Remote control switch contact defective*	0.0191
10	Local/Remote contact 'b' defective*	0.0191
11	Local/Remote contact 'c' defective*	0.0191
12	Local/Remote contact 'f' defective*	0.0191
13	Failure of interrupter 1 piston*	0.0169

14	Failure of interrupter 2 piston*	0.0169
15	Failure of interrupter 3 piston*	0.0169
16	Circuit breaker timing damping dishes loose*	0.0152
17	Circuit breaker timing damping dish support bracket loose*	0.0152
18	Circuit breaker timing pendulum bolt loose*	0.0152
19	Circuit breaker timing pendulum loose*	0.0152
20	Gas density transducer defective*	0.014
21	Circuit breaker gas density low contact 1 defective*	0.014
22	Circuit breaker gas density low contact 2 defective*	0.014
23	Circuit breaker gas density low contact 3 defective*	0.014
24	Failure to indicate open close position*	0.014
25	Adhesion of interrupter 1 piston valves*	0.0114
26	Adhesion of interrupter 2 piston valves*	0.0114
27	Adhesion of interrupter 3 piston valves*	0.0114
28	Close latch assembly slow to release	0.00583
29	Primary fuse fault – 48V system*	0.00383
30	Trip damper seal failure	0.00382
31	Spring indicator plate loose	0.00371
32	Trip damper axle failure*	0.00344
33	Primary power supply failure (trip) – 110V system	0.00312
34	Primary power supply failure – 48V system	0.00312
35	Primary power supply failure (close) – 110V system	0.00312
36	Drive linkage 2 failure	0.00283
37	Drive lever 3 loose	0.00283
38	Drive lever 3 failure	0.00283

39	Drive lever 4 loose	0.00283
40	Drive lever 4 failure	0.00283
41	Trip latch lever axle pin loose	0.00283
42	Intermediate trip latch lever axle pin loose	0.00283
43	Trip axle support pin loose	0.00283
44	Failure of mechanism linkage (external)	0.00283
45	Drive lever 2 loose	0.00283
46	Drive lever 2 failure	0.00283
47	Drive linkage 2 loose	0.00283
48	Drive linkage 2 failure	0.00283
49	Closing pin axle loose	0.00283
50	Drive linkage 1 loose	0.00283

Table 6.2: Top fifty minimal cut sets for the mean failure rates

Minimal Cut Set Number	**Description**	**Minimal Cut Set ratio of overall circuit breaker unavailability**
1	Condition monitoring gas density transducer valve failure*	0.0784
2	Control scheme gas density transducer valve failure*	0.0784
3	Display supply switch failure*	0.057
4	Local control switch contact ‘a’ defective*	0.0569
5	Local control switch contact ‘b’ defective*	0.0569
6	Local/Remote contact ‘d’ defective*	0.0323
7	Local/Remote contact ’e’ defective*	0.0323
8	Local/Remote contact ‘a’ defective*	0.0323

9	Remote control switch contact defective*	0.0323
10	Local/Remote contact ‘b’ defective*	0.0323
11	Local/Remote contact ‘c’ defective*	0.0323
12	Local/Remote contact ‘f’ defective*	0.0323
13	Circuit breaker gas density low contact 1 defective*	0.0238
14	Circuit breaker gas density low contact 2 defective*	0.0238
15	Circuit breaker gas density low contact 3 defective*	0.0238
16	Gas density transducer defective*	0.0238
17	Failure of interrupter 1 piston*	0.00764
18	Failure of interrupter 2 piston*	0.00764
19	Failure of interrupter 3 piston*	0.00764
20	Circuit breaker timing damping dishes loose*	0.00684
21	Circuit breaker timing damping dish support bracket loose*	0.00684
22	Circuit breaker timing pendulum bolt loose*	0.00684
23	Circuit breaker timing pendulum loose*	0.00684
24	Failure to indicate open close position*	0.00613
25	Adhesion of interrupter 1 piston valves*	0.00568
26	Adhesion of interrupter 2 piston valves*	0.00568
27	Adhesion of interrupter 3 piston valves*	0.00568
28	Primary fuse fault – 48V system*	0.00447
29	Close latch assembly slow to release	0.00413
30	Close switches defective	0.0033
31	Display fuse failure	0.00316
32	Gas monitoring fuse failure	0.00316
33	Trip damper axle failure*	0.00284

34	Trip coil isolator fault	0.00267
35	Failure of heaters/cabinet seal failure	0.00232
36	Trip chain assembly spool 2 failure	0.00209
37	Trip chain assembly spool 1 failure	0.00209
38	Trip damper seal failure	0.00186
39	Primary power supply failure (trip) – 110V system	0.00155
40	Primary power supply failure – 48V system	0.00155
41	Trip magnet faulty	0.00155
42	Primary power supply failure – 110V close system	0.00155
43	Failure of trip magnet	0.00155
44	Lack of lubrication – closing shaft bearing 1	0.00134
45	Trip latch seized	0.00134
46	Intermediate trip latch seized	0.00134
47	Lack of lubrication – closing shaft bearing 2	0.00134
48	Protection error	0.00134
49	Presence of foreign particles	0.00134
50	Presence of voids	0.00134

Table 6.3: Top fifty minimal cut sets for the upper limit failure rates

Minimal Cut Set Number	**Description**	**Minimal Cut Set ratio of overall circuit breaker unavailability**
1	Condition monitoring gas density transducer valve failure*	0.0645
2	Control scheme gas density transducer valve failure*	0.0645
3	Display supply switch failure*	0.0478
4	Local control switch contact 'a' defective*	0.0475

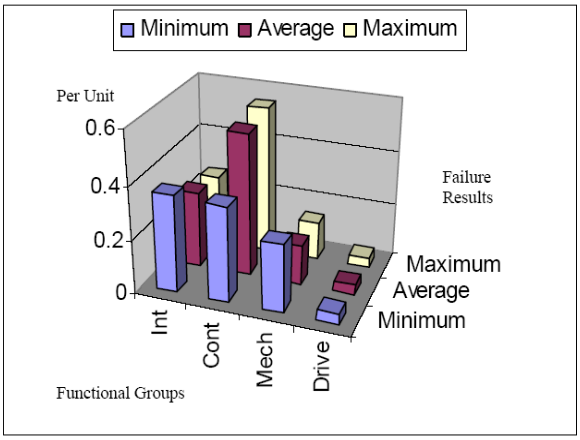
5	Local control switch contact ‘b’ defective*	0.0475
6	Local/Remote contact ‘d’ defective*	0.0375
7	Local/Remote contact ‘e’ defective*	0.0375
8	Local/Remote contact ‘a’ defective*	0.0375
9	Remote control switch contact defective*	0.0375
10	Local/Remote contact ‘b’ defective*	0.0375
11	Local/Remote contact ‘c’ defective*	0.0375
12	Local/Remote contact ‘f’ defective*	0.0375
13	Circuit breaker gas density low contact 1 defective*	0.0276
14	Circuit breaker gas density low contact 2 defective*	0.0276
15	Circuit breaker gas density low contact 3 defective*	0.0276
16	Gas density transducer defective*	0.0276
17	Close spring corrosion	0.00746
18	Trip spring corroded	0.00746
19	Trip solenoid failure	0.00746
20	Trip spring failure	0.00746
21	Close spring beyond 0.2% stress level	0.00746
22	Failure of trip spring assembly	0.00746
23	Trip spring beyond 0.2% stress level	0.00746
24	Local control not selected – human error	0.00511
25	Failure of interrupter 1 piston*	0.00396
26	Failure of interrupter 2 piston*	0.00396
27	Failure of interrupter 3 piston*	0.00396
28	Close switches defective	0.0037
29	Circuit breaker timing damping dishes loose*	0.00343

30	Circuit breaker timing damping dish support bracket loose*	0.00343
31	Circuit breaker timing pendulum bolt loose*	0.00343
32	Circuit breaker timing pendulum loose*	0.00343
33	Primary fuse fault – 48V system*	0.0034
34	Trip coil isolator fault	0.00336
35	Adhesion of interrupter 1 piston valves*	0.00317
36	Adhesion of interrupter 2 piston valves*	0.00317
37	Adhesion of interrupter 3 piston valves*	0.00317
38	Failure to indicate open close position*	0.00304
39	Failure of heaters/cabinet seal failure	0.00287
40	Trip damper axle failure*	0.00235
41	Gas monitoring fuse failure	0.00175
42	Gas monitoring link failure	0.00171
43	Display link failure	0.00171
44	Failure of conductor arm 1	0.0017
45	Failure of conductor arm 2	0.0017
46	Failure of conductor arm 3	0.0017
47	Crank wheel loose	0.00153
48	Presence of voids – gas barrier	0.00153
49	Presence of voids – insulting rod	0.00153
50	Presence of voids – gas barrier 2	0.00153

6.5 Analysis and Validation of model

To establish the contribution of each of the circuit breaker's functional groups (the control circuit, the mechanism, the drive linkage and the interrupter chamber) towards the overall unavailability of the circuit breaker, the total percentage contribution has been calculated for each group and plotted in Figure 6.39.

The results show that for the average and upper limit failure data sets, control circuit type failures account for more than 50% of the circuit breaker's unavailability. This is followed by the interrupter chamber (26-28%), the mechanism (14-15%) and finally, the drive linkage (4%). When the lower limit failure data set is used, the control circuit is less dominant, but still accounts for just over a third (35%) of the circuit breaker's unavailability. However, the influence of the interrupter chamber and the mechanism has increased to 36% and 25%, respectively, whilst the contribution from the drive linkage has remained the same.



where

Int: Interrupter Chamber

Cont: Control Circuit

Mech: Operating Mechanism

Drive: Drive Linkage

Figure 6.39: Diagram showing how each circuit breaker functional group contributes towards the overall unavailability of the circuit breaker

Cigré has carried out two international studies on circuit breaker failures [Mazza et al, 1981; Beierer et al, 1985; Michaca, 1985; and Cigré, 83, 1994], where the second study [Cigré, 83, 1994] concentrated on single pressure SF_6 circuit breakers. The second survey also applied to circuit breakers in service between the 1st January 1978 and 1st January 1992, with a rated voltage of 72.5kV and above, and covered a population of 70,708 circuit breaker service years. A total of 461 major failures and 3,239 failures were recorded, with the origin of the failure being determined as shown in Figure 6.40.

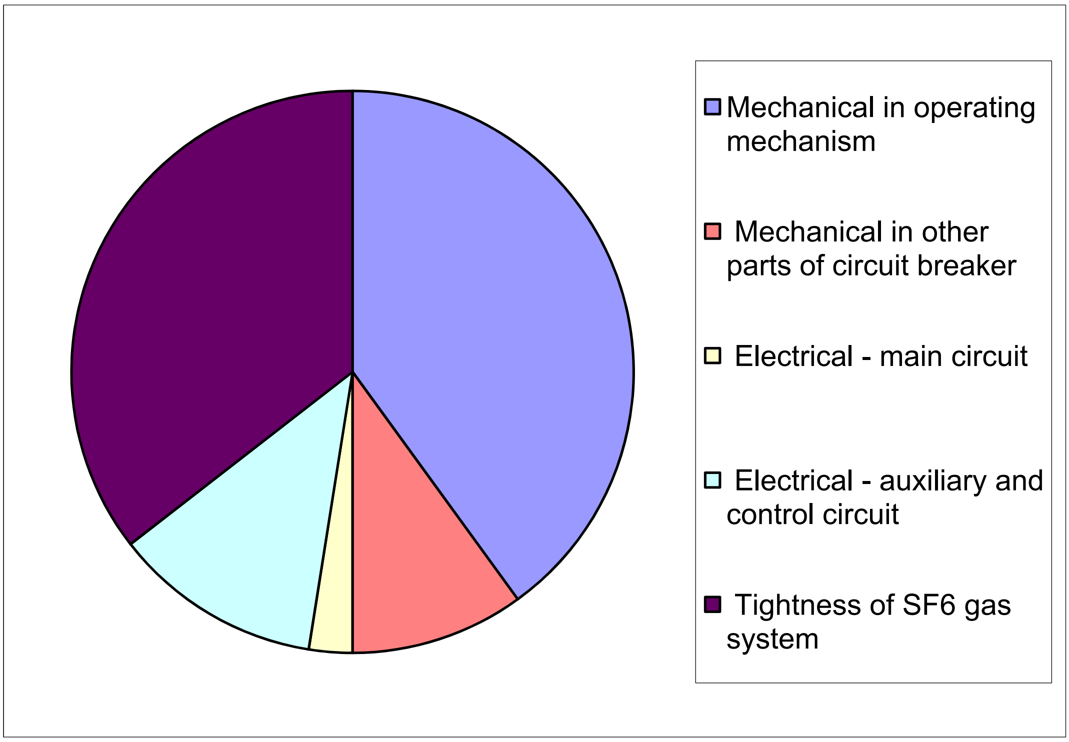


Figure 6.40: Diagram showing the origin of circuit breaker failures from an international survey[19]

As Figure 6.40 covers all types of single pressure SF_6 circuit breakers, the failure statistics have been filtered to be specific towards a spring type metal enclosed circuit breaker, similar to the circuit breaker type used in the FTA. As can be observed in Figure 6.41, the dominance of mechanical faults in the operating mechanism reduces significantly. Although it is not clear from Figure 6.41, there is

[19] Derived from [Cigré, 83, 1994].

also a dramatic reduction in the number of SF_6 leakage faults. Namely, the number of major failures reduces from 33 to 3 and the number of minor failures reduces from 1,280 to 162. The reason for this reduction is due to the exclusion of Non-Metal Enclosed (NME) type circuit breakers.

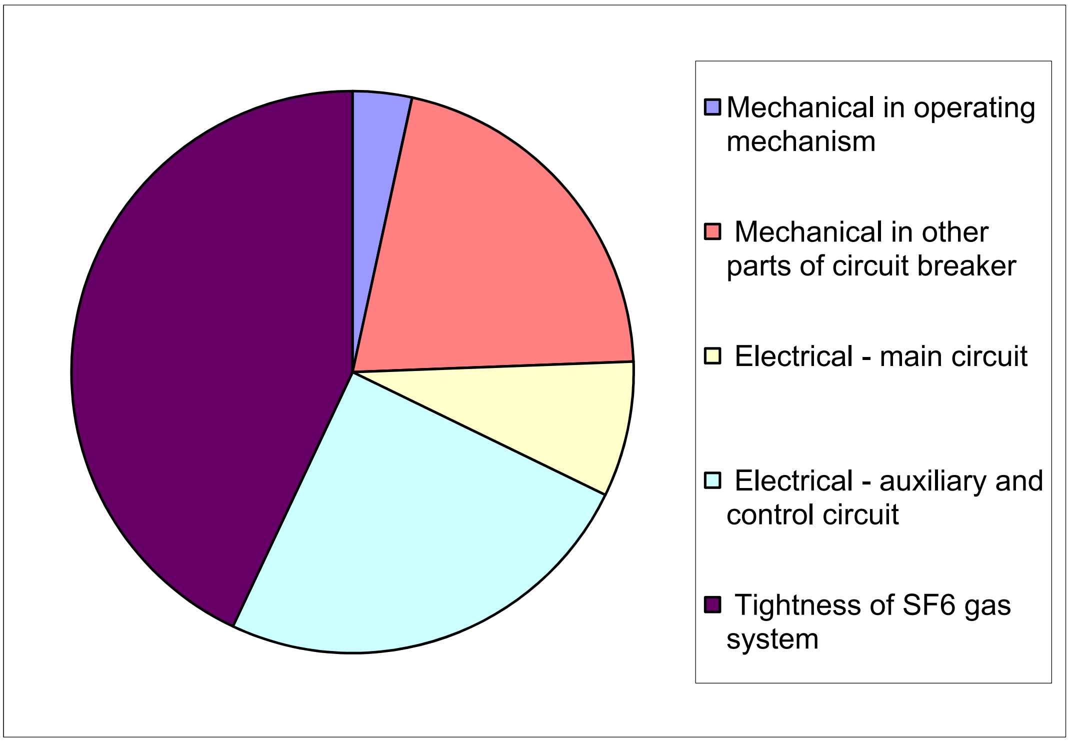


Figure 6.41: Diagram showing the origin of metal enclosed circuit breaker failures, utilizing a spring mechanism, from an international survey[20]

Comparing the Cigré figures [Cigré, 83, 1994] with the FTA results, Figure 6.42 indicates that there is still a marked difference in the origin of the failures. In particular, the number of SF_6 leakage failures, which has been grouped in the interrupter chamber category in Figure 6.42 still accounts for a significant proportion of the failures in the Cigré figures. As highlighted previously, the limitations of using a donor source for the FTA need to be recognised, but similarly the Cigré figures need to be treated with caution as well. For example, the statistics are dependent on the accuracy of the individuals responsible for filling out the failure records. In some cases, the Cigré questionnaire itself may cause difficulties and lead to errors in categorising faults. For example, is an auxiliary switch failure classified as an

[20] Derived from [Cigré, 83, 1994].

electrical or mechanism fault. The figures can also be heavily influenced by a particular country or utility. It is pointed out by [Cigré, 83, 1994] that the ratio of minor failures to major failures varies considerably between each country and if the two extreme cases are excluded from the figures, the major failure rate changes from 0.32 to 1.04 failures per hundred circuit breaker years for metal enclosed circuit breakers. Similarly, the minor failure rate changes from 2.18 to 6.44 failures per hundred circuit breaker years.

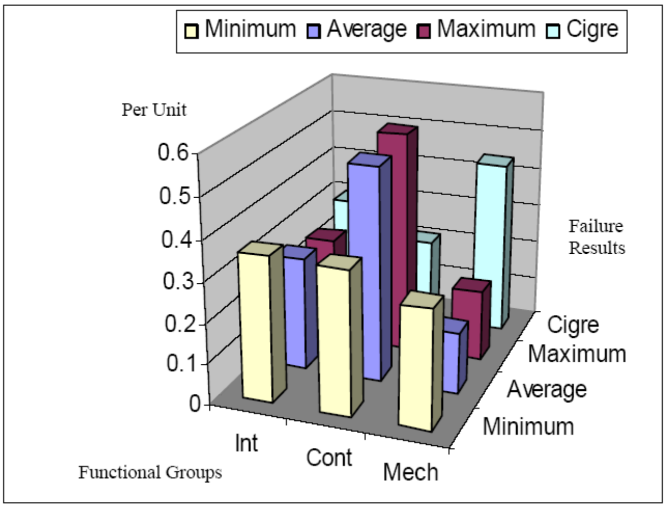


Figure 6.42: Comparison of FTA results with the results from an international survey for metal enclosed circuit breaker failures, utilizing a spring mechanism[21]

With specific reference to the number of SF_6 leakage failures, it is worth noting that the statistics used in Figures 6.40 and 6.41 include the early designs of circuit breakers in which, as shown in [Cigré, 83, 1994], SF_6 leakages were significantly higher than circuit breakers placed in service after January 1983. Namely, for outdoor circuit breakers, the SF_6 tightness failure rate reduced from 3.03 failures per hundred circuit breaker years to 1.64 failures per hundred circuit breaker years. The progress in design and manufacturing is one possible reason for this change, which has seen further advancement since the Cigré survey was completed. Namely, [IEC 62271-203, 2003] now specifies a maximum leakage rate of 0.5% per annum for gas-

[21] Derived from [Cigré, 83, 1994].

insulated equipment instead of the previous figure of 1% per annum [BSEN 60517, 1997]. However, some manufacturers have being going one step further and achieving a level of less than 0.3% per annum [Pohlink et al, 2006].

The other factor to consider is that more than 40% of the small SF_6 leakage failures in the Cigré survey were due to corrosion, which is not such a significant risk with an indoor circuit breaker as used in this study. Interestingly, SF_6 density monitoring equipment was a significant failure mode, and accounted for 4% of major failures and 11% of minor failures or 10% of the total failures. Examining the top fifty minimal cut sets in Tables 6.1 to 6.3, the significance of this type of failure is again highlighted with a figure of 25% or 15% to 17% if the on-line condition monitoring transducer is excluded.

The final validation of the FTA and whether the donor data is an appropriate selection will occur when the circuit breaker has been in service for a number of years and there is accurate data about its performance and failure mechanisms. However, there is some confidence in the FTA when a sensitivity analysis is carried out on the number of SF_6 leakage failures reported in the Cigré study [Cigré, 83, 1994]. If the aforementioned points are accepted and the Cigré results filtered further to reduce the number of SF_6 leakage failures, as shown in Figure 6.43, when the number approaches 40% (which is not an unreasonable assumption given that 40% of SF_6 leakages are attributable to corrosion and also when it is considered that there has been significant improvement in the design of SF_6 circuit breakers since the Cigré study was undertaken) of the original value, the proportion of auxiliary and control circuit failures increase to such an extent that the trend in the origin of the failures is similar to the lower limit failure data set. Admittedly, further reductions in the number of SF_6 leakage failures would never result in the control circuit category becoming the dominant source of failures, due to the number of failures in the category 'mechanical failures in other parts of the circuit breaker'. Once again, a potential reason could be incorrect or inconsistent categorisation of the fault. For example, there are many mechanical parts within the interrupting chamber, which could be allocated to either the failure category for the 'electrical main circuit' or the category for 'other mechanical failures in the circuit breaker'.

Due to the numerous uncertainties surrounding the Cigré results, it cannot be claimed there is an exact match with the FTA results. However, when sensitivity studies are carried out and the results are analysed to understand the potential reasons for some of the differences, there is some confidence that a common trend is emerging. The results need to be treated with caution, but provided that is understood, they provide a foundation upon which to develop and refine a future maintenance strategy.

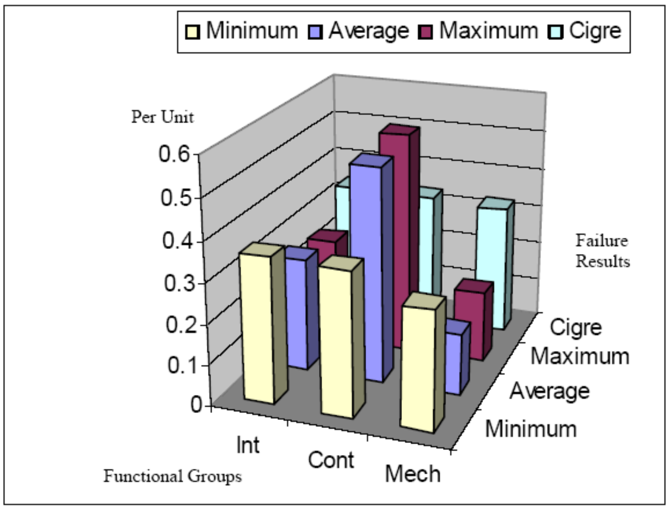


Figure 6.43: Comparison of FTA circuit breaker functional group failure contributions with the results from an international survey for metal enclosed circuit breaker spring mechanism failures when filtered to reduce the number of SF_6 leakage failures[22]

6.6 Identification of an appropriate maintenance strategy

To determine the appropriate maintenance task for each of the minimal cut sets or failure modes, the same method was adopted as used in the previous chapter for the RCM methodology. Namely, to consider the consequences of each failure mode and therefore the most effective maintenance method, both economically and technically, of handling them.

[22] Derived from [Cigré, 83, 1994].

A decision must be made as to whether to analyse all the failure modes or to identify and consider only the critical items. This is a balance between the consequence of the failure and the probability of the event. If the circuit breaker is being used in an interconnector or generator application it may be more appropriate to consider more failure modes than an NSC application due to the higher planned and unplanned outage costs. Each user will have a different opinion, which will depend on a number of factors such as their commercial arrangements with generators and neighbouring utilities, regulatory constraints and system configuration. In this exercise all the failure modes were considered, as it may be justified in carrying out a maintenance task to cover a group of similar failure modes, where as it may not be viable to do this for each failure mode on its own.

Referring to the case studies presented in Chapters 2, 4 and 5 for a 300kV single pressure SF_6 circuit breaker, the same three circuit breaker application scenarios could have been used for the 145kV rated circuit breaker in the FTA; namely the NSC, interconnector and generator applications. However, for the purposes of this exercise, only the generator and NSC case scenarios were considered as the unplanned and planned outage costs for an interconnector circuit do not have the same significance as they do at 300kV. This assumption may not be valid for other users and in some cases it may be more appropriate to study other application scenarios, such as customer circuit breakers.

Similar to the RCM methodology in Chapter 5 and using the worksheet as shown in Table 5.3, consideration was first given to applying an on-line condition monitoring task to each failure mode. If that was not technically or economically feasible, an off-line condition monitoring task was then examined. Failing that, consideration was given to preventive maintenance and if that was not viable the final alternatives were either to re-design or to not undertake any scheduled maintenance.

Although the circuit breaker in the FTA is a different type of circuit breaker to that used in the TBM, CBM and RCM case studies, a comparison can be made as the spring mechanism is common to both types and a common logic is used for the control circuits. In addition, both use a self blast or auto-puffer interrupter, where again there is close synergy between the functional parts; namely, the blast cylinder, the tulip contacts, the main contacts, the blast nozzle, the operating rod, etc.

Examining Table 6.4, for the recommended preventive maintenance strategy, the first noticeable difference, compared to the RCM analysis, is that apart from switching the circuit breaker remotely, there is also a need to switch the circuit breaker locally. Referring to Tables 6.1 to 6.3, out of the top fifty minimal cut sets, it can be observed that there are eight minimal cut sets or failure modes that are common to the lower limit, mean and upper limit failure data sets, where the circuit breaker needs to be switched locally to identify the failure. This represents 19.3%, 30.4% and 29.6% of the total failures of each data set, respectively. It will depend on the importance that a utility places on operating a circuit breaker locally, but as a minimum it is recommended that it be carried out every five years.

One other difference is that due to the failure rate of the gas density monitoring equipment, it is recommended that a calibration check be carried out every five years instead of at ten-year intervals.

Similar to the RCM recommendations in Chapter 5, it is also more economical to conduct an overhaul of the interrupters as opposed to using an on-line condition monitoring technique, such as monitoring primary current, to ascertain the contact and nozzle wear. However, as highlighted previously, this will be dependent on the substation layout and the planned outage cost.

With regard to the on-line condition monitoring parameters, the reliability of the OLMS is once again highlighted when it is considered that the failure mode that contributes the most to the overall circuit breaker failure rate is a failure of the gas density transducer. When it is considered that SF_6 leakages account for 2.8% to 5.9% of the total circuit breaker failures, depending on the failure data set used, it cannot be justified to have a separate OLMS SF_6 gas density transducer. Namely, it introduces more failures than it would prevent. Consequently, a more sensible solution would be to use the same transducer for the normal circuit breaker and OLMS requirements. However, some users would argue that this would then necessitate more frequent calibration checks of the transducer until confidence was gained in the failure figures.

Another difference is that for both the NSC and generator circuit breaker applications, there is not any economic benefit in monitoring the full travel curve if the trip coil current profile and external temperature are recorded. As discussed in Chapter 3, the trip coil current can provide invaluable information about the circuit breaker timing as well as the trip latch assembly. To measure the travel curve would give the added benefit of calculating the acceleration and deceleration of the main contacts. However, its measurement would only account for the detection of a further 6.9% to 10.3% of the failures. Although the corrective and preventive maintenance costs increase (3.1% per year for the NSC circuit breaker and 4.9% per year for the generator circuit breaker) with its exclusion, the saving is not high enough to justify the inclusion of a travel transducer. Consequently, it is recommended that a timing curve be obtained off-line every five years. Likewise with the close coil current, its inclusion in the OLMS cannot be justified as it only accounts for the potential detection of 2.2% to 3.3% of the failures. Once again, it is more cost effective to check the close latch assembly and circuit breaker timing off-line every five years.

Similar to the RCM methodology, the FTA did not justify the on-line measurement of the primary current and motor spring charging current for the generator circuit breaker application. The former accounts for between 5.6% and 11.1% of the failures, but since a CT is required for each phase, the perceived cost benefits (4.8% per year for the NSC circuit breaker and 5.1% per year for the generator circuit breaker) are negated.

As before, parameters that are already monitored by existing substation control and protection systems, such as the trip coil supervision and 48V DC power supply, have not been duplicated and included in the list of parameters for the OLMS.

Table 6.4: Recommended FTA maintenance schedule for generator and NSC application circuit breakers

Maintenance Frequency	Main Tasks
Annual	Operate circuit breaker remotely. Test result dependent.
5 years	Transducer calibration checks. Control circuit checks & indications, obtain timing curve of CB, check close coil and latch assembly and spring charging time.
20 years	Replace absorber/desiccater, overhaul interrupters.

6.7 Comparison with RCM, CBM and TBM methods

It has already been shown in the previous chapter that compared to a purely TBM or CBM approach, the RCM methodology has the ability to offer a more effective maintenance strategy by giving a user the opportunity to focus the OLMS on the critical failure modes where it is appropriate to use it both technically and economically. Therefore, to understand how the FTA approach compares with the previous methods, the simplest way is to compare it against RCM, which means that the RCM process will have to be applied to the 145kV circuit breaker used in this chapter.

As discussed previously, there are a number of similarities between the two types of circuit breaker and consequently there are not any differences in either the preventive maintenance strategy or the parameters to be monitored. However, the number of OLMS transducers will be less, as the 300kV circuit breaker has three separate enclosures and mechanisms as opposed to a single enclosure and mechanism for the 145kV circuit breaker. In addition, the failure rates, and planned and unplanned outage cost will be different for the 145kV circuit breaker.

Once again, apart from using [Cigré, 83, 1994] for the minor and explosive failure rates, figures from ScottishPower [SP, 2002a; SP, 2002b; SP 2002c; and SP 2002d] were used for the other factors. As shown in Table 6.5 the corrective maintenance savings from using an OLMS have increased for the RCM process mainly due to the increased reliability of the OLMS; namely, there are less transducers to fail. On the other hand, as expected, the preventive maintenance savings have remained constant.

When the preventive and corrective maintenance costs are calculated for the strategy recommended using the FTA, the first noticeable difference is that although the preventive maintenance cost has increased compared to TBM strategy, it has decreased compared to the RCM methodology. Despite there being more frequent off-line checks, as shown in Table 6.6, this decrease is due to a reduced OLMS capital cost that is a consequence of monitoring less parameters. This same reason results in a saving in the corrective maintenance costs as well. Namely, the reliability of the OLMS has effectively increased, which means that the costs to repair it or the consequential costs from its failure have reduced.

The overall result is that there has been a further reduction in the maintenance costs when using the FTA technique. However, as highlighted in Chapter 4 with the sensitivity studies, each utility needs to conduct its own case studies, as one factor such as the unplanned outage cost or major failure rate could make it viable to monitor more or even less parameters.

Table 6.5: Comparison of maintenance operating costs when using the FTA approach

Maintenance Type		NSC Circuit Breaker (CB) Cost Savings/Year (%)	Generator CB Cost Savings/Year (%)
RCM	Preventive	-12	-12
	Corrective	50	51
	Total	34	35
FTA	Preventive	-2	-2
	Corrective	59	60
	Total	45	46

Note: A symbol (-) denotes a cost increase and costs are compared to a TBM strategy

Table 6.6: Comparison of FTA with RCM for recommended on-line condition monitoring parameters for a generator and NSC circuit breaker application

FTA Recommended OLMS Parameters	RCM Recommended OLMS Parameters
Trip coil current	Trip coil current
	Close coil current
	Travel curve
	SF6 gas density
Temperature	Temperature

6.8 Conclusions

It can be seen that the RCM and FTA approaches are very similar and in fact it could be argued that as FTA is a substitute for the FMECA stage, it is a more sophisticated form of RCM. Namely, it is a refinement of the RCM process that allows a more accurate balance to be struck between time and condition based maintenance tasks.

Its main disadvantage is that it is very time and resource consuming. Moreover, it requires co-operation from the manufactures and access to their design drawings. In addition, for its results to be meaningful, an accurate source of data is required, which needs to be kept up to date. Although in the interim period, to make up for the lack of a potentially accurate data set, there is an opportunity to undertake further research by carrying out sensitivity studies on the current data to understand how this could influence the results.

FTA is also a powerful tool that allows a user a more detailed understanding of the failures modes and the ability to quantify their effects. Assuming that appropriate and experienced personnel are used, the FMECA approach is quick and easy to apply to a circuit breaker. However, unlike FTA, it is very subjective and as highlighted by the number of local control failures, can miss or underestimate the criticality of some of the failure modes. It is accepted that there could be differences in the way a fault tree is constructed between different users, but these variations should be minor as there is less reliance on an individual's opinion.

The FTA approach also provides a detailed understanding of the role of on-line condition monitoring. In particular it allows a utility to examine and quantify the benefit of monitoring one parameter versus another for different applications of circuit breakers. For example, it reveals that monitoring the close coil current will potentially only result in a further 2.2% to 3.3% of circuit breaker failures being detected. On the other hand, it demonstrates the importance of measuring parameters such as the trip coil current regardless of the application of the circuit breaker. The FTA approach also highlights that the reliability of OLMSs must improve and in some cases, such as the SF_6 density measurement, provides evidence on why a dedicated OLMS transducer cannot be justified.

Overall, the FTA of the SF_6 circuit breaker has shown that on-line condition monitoring has a vital part to play in the future maintenance strategy of a circuit breaker. In addition, it has provided a basic specification of parameters that should be monitored, which is important if a utility is trying to develop and standardise on a common system or approach for on-line condition monitoring, regardless of the circuit breakers application.

The constraint of developing an accurate data set for FTA should also not be seen as a hindrance. Many utilities are under ever increasing pressure to increase the availability of plant and to reduce both operating and capital expenditure. To do this they need to understand the failure modes of the equipment, how the failure mechanisms occur, what influences them and how they should be addressed. Apart from using this information to prioritise plant for replacement, it can be used to calculate lifetime costs to ensure best value is achieved when purchasing new equipment.

Although considerable effort is required to construct the fault trees, by splitting the circuit breaker into functions, such as the operating mechanism, it allows parts of the fault tree to be re-used for other circuit breakers where there is commonality. Furthermore, as described in [Cigré, 259, 2004] functional design of control systems does not differ that much between different types and manufacturers of SF_6 circuit breakers. Therefore, where there is similar functionality, once a fault tree is constructed it should be easily adaptable to other types of circuit breakers.

Consequently, although the FTA approach is more demanding to apply than RCM, when one considers the cost of a new HV circuit breaker and that a utility normally purchases more than one circuit breaker, it is perhaps not such a large price to pay. In addition, when the future uses and benefits of FTA are considered in Chapter 8, such as being used to develop an asset management tool to prioritise the replacement of circuit breakers or indeed other items of plant, the technique presents promising opportunities. As with the RCM method, time and experience will be required to prove the results, but considering the potential shown in this chapter, it is believed that it is worth developing further.

6.9 Chapter Summary

In this chapter the FTA technique was introduced and applied to a 145kV GIS circuit breaker. It was explained that as it is replacing the FMECA stage of the RCM method, it is essentially a derivative of this technique.

Unlike RCM, it is more complicated to apply, but by constructing the fault tree in functional groups for the interrupter chamber, operating mechanism, drive linkage and control circuit, it allows them to be re-used or adapted where they are common to other types of circuit breakers.

As a component failure database does not exist for HV circuit breakers, a donor source was used, where lower and upper limits were applied to the mean failure rate to account for the uncertainty in the data.

The results showed that failures associated with the control circuit were more dominant than first thought. Moreover, after filtering results from a Cigré study [Cigré, 83, 1994] to be specific towards a metal enclosed circuit breaker, with a spring type mechanism, it was shown that they offer some degree of confidence upon which to develop a future maintenance strategy.

To allow a comparison with the TBM, CBM and RCM techniques, the RCM process was applied to the 145kV circuit breaker and through case studies it was shown that the FTA approach offers the potential to identify a more technical and economical maintenance strategy. In particular, it examines the role of on-line condition monitoring and provides a utility with a method to quantifiably compare the benefits of monitoring one parameter versus another. For example, it highlighted that it was not efficient to monitor the travel current and local close coil current on-line. In addition, it showed that using a separate transducer to monitor the SF_6 gas density introduces more failures than it detects. Overall, it demonstrated that there is an important role for on-line condition monitoring in the maintenance strategy of an HV circuit breaker. It also defined the minimum set of parameters that needs to be monitored, regardless of the circuit breaker application, allowing a utility to develop a common OLMS.

It is recognised that time and experience will be required to prove the results of the FTA and that each utility should carry out its own analysis. However, as HV circuit breakers involve a large capital investment and with increasing regulatory pressures to be more efficient with capital and operating expenditure, it was recommended that FTA is a positive step and worth developing further.

Chapter 7

7 Markov Modelling of HV Circuit Breaker Maintenance Strategies

In this chapter the concept of mathematical modelling is introduced and in particular Markov models are developed to compare the effect of different maintenance strategies on the life of an HV circuit breaker and whether heuristic maintenance methods can be replaced by mathematical modelling. The chapter also examines the effect of on-line condition monitoring and whether the economic case for OLMSs is weakened or strengthened.

7.1 Introduction

Maintenance is a central part of a utility's asset management strategy, particularly in this post-privatisation era, which is primarily characterised by a tightening of budget constraints, where a greater focus has been placed on issues such as economic asset management and attainment of performance targets set by an industry regulator. These conditions challenge operators of distribution and transmission assets to create near-optimal asset management policies, which will maximise both economic returns and maintain the high levels of reliability to which the end-users are accustomed.

It has been shown that techniques such as RCM, complemented by FTA, offer utilities the opportunity to achieve these goals compared to a purely CBM or TBM strategy. However, for a complete evaluation of one strategy against another, as described in [Endrenyi et al, 2001], it is necessary to understand how each strategy affects the health of a circuit breaker throughout its full lifetime. To establish this, a mathematical model of the deterioration process along with the influence of each maintenance approach is required.

It has already been demonstrated that the availability of a circuit breaker can be affected by the reliability of an OLMS, but so far it has been assumed that when a repair or restoration activity is carried out, for both the circuit breaker and OLMS, the component is returned to an 'as new' state. However, as described in [Cigré, 83, 1994] this is far from the truth. In reality, it is feasible for maintenance to either fail to detect an impending failure or introduce additional failures. At the extreme end of the scale, maintenance can lead to a catastrophic failure of a circuit breaker so that it needs to be replaced.

Consequently, as is shown in this chapter, through the development of a mathematical deterioration model for each of the aforementioned maintenance approaches, this missing link of a quantitative connection between reliability and maintenance is addressed thereby enabling a true comparison between the various maintenance methods to be achieved.

7.2 Modelling Methods

The primary requirement for an asset model for a circuit breaker is that it adequately represents the deterioration and failure processes, as well as allowing the inclusion of different methods of carrying out maintenance. In theory there are a number of methods which could be used to perform the modelling with possibly the most fundamental distinction being between deterministic and probabilistic techniques.

Deterministic techniques rely on prediction of time to failure based on equations which attempt to replicate the actual physical process of deterioration over time; for example, the dielectric strength of insulation as a function of stress and/or time. In recent times these kinds of methods have not been adopted, indeed very little new literature is available in this area. There are several possible explanations, where many researchers argue that the nature of deterioration is probabilistic rather than deterministic, i.e. that incipient failures are random and the time it takes for the system to deteriorate to failure cannot be predicted with certainty. Furthermore, models based on large data sets have to be statistical in nature because the data often represents a statistical sample from a fleet of assets, rather than a single piece of equipment. Another aspect to consider is the widespread use and perceived successful implementation of probabilistic methods, in a very wide range of asset engineering applications such as road networks [Thomas, 1996].

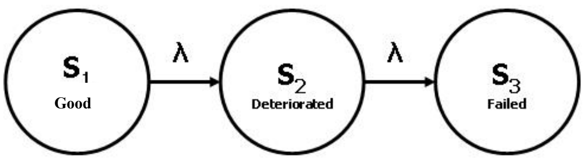
Within the umbrella of probabilistic methods it is possible to make many different distinctions. Some examples are the so-called ‘time-delay’ models, which are often based on a homogeneous Poisson process where the time delay is the time until the next significant outage or repair event. Nevertheless, Markov models and their numerous variants are overwhelmingly the dominant modelling framework for modelling deterioration and maintenance. Markov models in practical applications involve splitting the physical state of the equipment or system so that there are a finite number of states in which the asset can reside. These may represent different modes of failure, types of deterioration, operating condition or maintenance policy (this is entirely at the discretion of the modeller and depends on the objective of the work). Markov models can be defined either as continuous or discrete time. Generally the literature is biased in favour of continuous-time models, perhaps partly because this allows analytical style solutions to be extracted from a set of engineering equations, which characterise the system behaviour. Sometimes, however, discretization of the continuous process is carried out and solved using Monte Carlo simulation, especially for highly complex models where the analytic equations can become highly cumbersome and, in some cases, mathematically intractable. Alternatively, the chief advantage of the discrete time models is their adaptability and resultant ease of modification, even in systems involving multiple components.

When the nature of the Markov model has been decided, the modeller defines which transitions between states are possible and estimates the probability of occurrence of these transitions (transition probabilities for discrete time and transition rates for continuous time). A good understanding of the system under study or a thorough knowledge elicitation exercise can reveal which transitions are possible. Estimating the parameters may be more complex, since in some cases data may be plentiful, but in other cases no data may exist. In the latter case, engineering judgement can be used as an alternative; however caution must be used in deriving quantitative conclusions from qualitative information. In the case where data is plentiful, some thought must be given to how generic and representative this information is; for example, possible dependence of the data on operating philosophy, maintenance policy or environmental variables.

Other advantages specific to Markov models are the possibility of modelling condition monitoring information, since the state of the system in the Markov model can be linked to the maintenance approach, enabling accurate representation of a CBM policy. Since the system behaviour is dictated entirely by a Transition Probability Matrix (TPM), it follows that modifications to the model can be realized simply by adjustment of the matrix values, resulting in a high degree of model flexibility.

Existing approaches in the literature tend to focus on developing the theoretical model framework rather than addressing implementation issues. While development of theoretical aspects of modelling methodology is an important facet of research in this field, it must be remembered that ultimately these tools are developed in order to aid asset managers in their decision-making. Therefore the methodologies should also be straightforward to implement and robust enough to cope with different conditions. For example, utilities do not have a shared, universal standard for data collection and some may not collect the data necessary in order to quantify all of the necessary transition rates or probabilities. In such cases, the parameters could be estimated by using expert judgement. However, some approaches proposed in the literature are much too data-intensive for this to be practical (for example, the semi-Markov model [Black et al, 2003]). The strength of the proposed approach in this chapter lies in its practical and robust nature, and also in its consideration of key factors, which are often overlooked in other models. Crucially, novel features such as the reliability of an OLMS, equipment life-extension and imperfect maintenance actions are easily captured within the modelling framework proposed in this chapter.

The Markov models presented in this chapter were implemented using a commercial reliability software tool 'Reliability Workbench' [Isograph, 2002]. As well as enabling effective visualisation of the Markov chain, the software enables the user to switch between different model stages. For example, the deterioration process is implemented as a continuous-time model, while the maintenance process is discrete-time. This flexibility is useful when representing complex processes such as those presented in this thesis. To demonstrate why such a software tool and numerical solution is required consider Figure 7.1, which is a very simple three state Markov process in which both possible transitions are governed by transition rate λ.



where

S: A transition state of the system

Figure 7.1: Diagram of a simple three state condition model

Three metrics of particular interest in this work include the time-dependent expressions for state probability, as well as overall expressions for reliability and Mean Time To Failure (MTTF). In order to extract these metrics using direct mathematical methods, various time-consuming and highly tedious calculations must be performed. In most cases a mixture of substitution, Laplace transforms and integration are needed. Appendix B1 illustrates these calculations for the system in Figure 7.1. However, in summary the probabilities of being found in states S_1 and S_2 as a function of time given that the process started in state 1 at time $t = 0$ can be expressed as:

$$P_1 (t) = e^{-\lambda t} \tag{7.1}$$

and

$$P_2 (t) = \lambda t \, e^{-\lambda t} \tag{7.2}$$

where

$P_1(t)$: the probability of being in state S_1

$P_2(t)$: the probability of being in state S_2

λ: the process failure rate

By summing the time dependent probabilities $P_1(t)$ and $P_2(t)$ the reliability function, $R(t)$, of the process can be expressed as follows:

$$R(t) = (1 + \lambda t)e^{-\lambda t} \tag{7.3}$$

By integrating the reliability function, this in turn allows the MTTF to be defined as follows:

$$MTFF = 2/ \lambda \tag{7.4}$$

As the number of states and possible transitions increase, working out the aforementioned metrics using direct methods, as Appendix B1 illustrates, quickly becomes very difficult and time-consuming. Therefore, the Markov models presented in this thesis were implemented in the Reliability Workbench software, which obtains the solution by numerical methods that approximate the analytic solution using the Runge-Kutta 4th order algorithm.

7.3 Existing Experience with Markov Models of a Circuit Breaker

Since the early 1990's, a great deal of work has been done in importing probabilistic methods used in other applications to the power system asset management domain. The main framework adopted for such studies are Markov models or variants of those techniques. Anders, Endrenyi and associates have been particularly prolific in this field with papers [Anders et al, 1990; Anders et al, 1992; Anders, 2004; Endrenyi et al, 1998; and Endrenyi et al, 2004] addressing various issues associated with the application of Markov models to power systems asset modelling.

A probabilistic model to estimate the remaining life of generator insulation is presented in [Anders et al, 1990 and Anders et al, 1992]. The authors describe the factors affecting the frequency and deterioration of the insulation such as temperature, voltage, materials, maintenance and random events, and identify processes such as thermal ageing and abrasion. Two main methods of measuring such processes are proposed: either monitoring relevant signals via instrumentation or observable effects. The paper [Anders et al, 1990] also includes an interesting section describing the discrete and continuous-time versions of the model, as well as a small section on parameter estimation from available data. It is pointed out that taking measurements from equipment with similar operating conditions, such as rating, design and atmospheric environment, can reduce uncertainty in the model. Finally, it is concluded that the two main challenges for future research are the adequate definition of states to represent the deterioration and definition of the transition probabilities as the desired data may not exist.

In [Endrenyi et al, 2001] a review of the most frequently used maintenance strategies is presented and it is explained that although RCM has represented a significant step towards achieving the optimal balance between preventive and corrective maintenance, it is still heuristic and requires a considerable amount of experience and judgement. A survey of power utilities is performed and it is reported that methods based on probabilistic modelling are rarely used due to a limited availability of the required data and their lack of simplicity. However, despite their complex nature, it is concluded that as they are able to model the deterioration process of an asset and quantitatively examine the effect of a maintenance task, they offer the potential to achieve the highest savings or maximum reliability.

In [Endrenyi et al, 2004] two methods of evaluating the effects of maintenance on both reliability and operating costs are compared. These two methods are the Reliability-Centred Asset Manager (RCAM) and the Asset Sustainable Strategy Platform (ASSP). Both methods use reliability studies to rank the most influential system components and examine the impact of maintenance on the failure rates. RCAM establishes the relationship between maintenance policy, cause of failure and time. The development of the failure rate model is a complicated task and can be determined via two different methods. The first method is to assume a known distribution function for the component lifetime and calibrate it using existing data. Alternatively, a failure rate curve is plotted from available data to enable a known function to be fitted to it. The final step is to apply the failure rate models to all critical components in the system, for different maintenance strategies, to evaluate the effect on the overall system reliability. On the other hand, the ASSP method uses a Markov model where the effectiveness of each maintenance policy is determined from the mean time to failure from any given state in the model. The effect on the overall system reliability can then be ascertained by using the revised component failure rates in the system model. Both methods are capable of providing a cost effective maintenance strategy, but through the use of a Markov model, the ASSP method has the added advantage that it allows the effect of a maintenance task on the ageing process of a component to be evaluated.

A further application of the RCAM method is presented in [Bertling et al, 2005] where it is used to compare the effect of different maintenance approaches on distribution system assets. In particular it is applied to underground cables and the ‘system’ impact of different preventive maintenance options is quantified in terms of reliability-related indices. The results show a ‘do nothing’ scenario is the most cost-effective, while rehabilitation is more cost-effective than outright replacement.

In [Endrenyi et al, 1998] the authors present an analytical software tool linking maintenance effects to reliability component ageing. The authors describe the balance that must be struck between the level of maintenance activity, reliability and cost. Namely, whilst a lack of maintenance may reduce the equipment reliability and have severe economic consequences, too much maintenance may not be economically viable. The Markov model developed by the authors [Endrenyi et al, 1998] comprises of fours states: an initial stage; two levels of deterioration (minor and major); and a failure state to represent when the equipment requires extensive repair or replacement. Throughout the deterioration process, the model allows for carrying out regular inspections of the equipment and depending on the results, either doing nothing or conducting minor or major maintenance. Apart from modelling that the maintenance could improve the condition of the equipment, it also models the possibility that the maintenance could have either no effect or cause damage to the equipment and advance it to the next stage in the deterioration process. Continuous monitoring is also considered via a simplified model, and for both models a sensitivity study is conducted to yield the optimal maintenance policy.

In [Anders, 2004] the authors describe the application of two programs, the Asset Management Planner (AMP) and Asset Risk Management (ARM), to a 20 Megavolt Ampere (MVA) 138/12 kV transformer to estimate the remaining life, and associated operating and failure costs. The AMP is a Markov model and similar to [Endrenyi et al, 1998] the deterioration process is represented by four states. In addition, each deterioration state allows for inspection activities and instead of two types of repair (minor and major), the model includes a third type, which is described as medium. Model parameters are estimated in some cases from historical data (where they are available) and in others by expert opinion. Using the ARM software package, several alternative maintenance policies are studied by generating ‘life curves’. These curves show the relationship between the transformer condition, expressed in financial terms, versus time and therefore allow the cost differential between different maintenance strategies to be calculated. The case study demonstrates how the Markov model allows different parameters, such as the inspection frequency, to be varied with ease to select the optimal maintenance strategy. In this case, it is concluded that due to a high cost of failure in comparison with the maintenance costs, the ideal policy is to increase the maintenance effort either through an increase in the frequency of inspections or through an increase in the probability of 'medium' maintenance.

Meeuwsen & Kling [Meeuwsen et al, 1997] utilise a mixture of methods such as Markov models, reliability calculations and FMECA with the objective of finding the optimal interval for a TBM system applied to substation circuit breakers. The main innovation is the consideration of badly co-ordinated maintenance actions and failures due to the maintenance actions themselves. Four types of circuit breaker failures are modelled: active failures (short circuit fault), passive failures (open circuit fault), stuck condition (failure to operate or hidden failure) and overlapping failures (a second failure occurs before the initial one has been repaired). Different Markov transition rates (continuous time and analytical solution) represent the likelihood of each of these failure types occurring. The authors also model the substation topology comprising of the various switching elements. The results identify optimal points for the reliability versus TBM frequency trade off of the entire substation. The main drawback of this approach being that only TBM is evaluated and life extension through careful use of maintenance is not included.

The approach proposed by Mijailovic [Mijailovic, 2003] models two competing modes of failure in 145kV ABCBs: shock failures (exponential distribution) and wear-out (weibull distribution), though little information is provided on how the parameters of these models are chosen. One interesting innovation incorporated in the modelling is the use of Cigré figures relating to the effectiveness of condition monitoring. Namely, according to the Cigré data, 33.5% of all failures are predictable via condition monitoring systems, 60.8% are detectable and 5.7% are not detected. The goal, in keeping with other papers of this type, is to optimize the maintenance process. A probabilistic continuous-time state-based process characterises the deterioration of the circuit breaker. It is not specifically identified as a Markov model possibly owing to the fact that the transition rates are not constant over time since wear-out is modelled explicitly. Possible shortcomings of the approach are the seemingly arbitrary method of parameter estimation, the assumption of ‘good as new’ repair, and the fact that possible life extension through use of condition monitoring systems is not included.

Schneider et al. [Schneider et al, 2006] looked at asset management and risk management in electrical grids (including distribution), and identified four key asset management challenges: More specifically, integrating strategy and operations with stakeholder objectives; balancing of reliability, safety and financial aspects; reaping the benefits of performance-based operation targets; and avoidance of financial penalties. The most important strategies suggested, as used by grid operators, are optimized maintenance strategies, use of condition monitoring and asset simulation modelling, statistical analysis of faults, as well as life management of assets. The authors highlight the importance of accurate physical models to capture equipment ageing and deterioration, and suggest that this is an area where research should be concentrated. The asset simulations performed by the authors yield important indicative results, however, due to their statistical nature, they should not be considered accurate for individual items of plant. Namely, a balance must be struck between the accuracy of the theoretical models used to describe the equipment condition and the data available to populate such models. A key question raised by the authors, is: can everything be adequately parameterized? Finally the authors provide a simple example of a generator transformer and discuss the possible benefits of asset management along with some limited data. No results are presented and the authors conclude that much more research is required in terms of developing accurate asset deterioration models.

Hoskins et al. [Hoskins et al, 2002] aim to use condition information as an aid to asset management decision-making, using Markov chains to model changes in an item’s condition over time. The authors produced a homogeneous, discrete-time Markov model to represent the condition of an oil circuit breaker, which is solved using analytical methods. The dielectric strength of the oil is used as the condition measure and the time parameter resolution is one year. Over two hundred oil samples, taken after four and eight years of service, are classified into the condition states of the Markov method. Thereafter, the authors use two methods (maximum likelihood estimation and method of least squares) to deduce the transition probabilities from the data set and therefore to predict the state of the circuit breaker fleet in future years.

Black et al. [Black et al, 2003] propose the use of the semi-Markov method to model the deterioration of assets, using oil-filled switchgear and power transformers as two examples. The transition probabilities in the stochastic transitional probability matrix are not constant, rather they are dependent on the time spent in the current state and are fitted to a Weibull distribution. This non-homogeneous transition matrix results in a more flexible approach compared with the ordinary Markov method. It is a continuous-time model, solved analytically. The authors point out that curve fitting and Markov processes are the two most frequently used methods for predicting future condition, however the rate of deterioration is uncertain and so Markov models fulfil this requirement. They identify several successful implementations of Markov models, citing pavements, bridges, water and electrical networks. An interesting point is the consideration of deterioration itself being of a continuous nature: the authors argue that characterisation of the transition probabilities in the semi-Markov model using probability distributions leads to a more accurate representation of the physical processes. However, a major drawback of this method is the large body of extremely detailed data needed to populate the model, which may render the method impractical.

Langseth et al. [Langseth et al, 1998] use data for critical and degraded failures from the gas turbine Offshore Reliability Database (OREDA) in order to investigate the influence of periodic maintenance on the rate of critical system failures. The analysis is based on a Markov model including degraded (evolving) and critical (immediate) failures. Their model assumes that shock failures occur with a constant failure rate. In addition, repair times are ignored and when a repair is carried out the component is returned to a ‘good as new’ repair process state on the basis that primarily the failure rate is of interest. The failure rates are calculated by using corresponding ratios of observed failure events and the results illustrate a substantially increased MTTF with increasing periodic maintenance.

Barata et al. [Barata et al, 2002] consider a continuously monitored multi-component system, which deteriorates according to a discrete-time Markov chain and is solved via Monte Carlo simulation. The authors justify their approach by arguing that analytical approaches are unable to cope with the dimensionality of the problem when several multi-state components make up the system. Implicit in this approach is the fact that each system sub-component is run in a parallel Monte Carlo simulation. The problem is framed as a maintenance and safety threshold problem. Namely, at what point in the degradation process should components be maintained or replaced. The authors take an interesting approach to repair processes; the repair times follow a lognormal distribution, which is dependent on the level of recovery that the component achieves. When this time has elapsed, the repair is carried out with certainty (probability=1). The cost-optimisation of the model is done via a simple sensitivity study.

Bertling and associates have recently produced a number of interesting research contributions focusing on the application of probabilistic methods, including Markov models, to asset management problems in the power system domain [Endrenyi et al, 2004; Lindquist et al, 2004; and Bertling et al, 2005]. The authors make a strong case for the use of probabilistic mathematical models as the basis of asset management policy. However, while it can be seen that soundly constructed models can provide insightful information for asset managers, it is recognised that engineering judgement and common sense are equally important in decision making.

[Choonhapran et al, 2007] initially analyse an extensive interruption database of different types of circuit breakers in order to calculate the MTTF for various component parts, such as the control circuit and operating drive. They then construct a Markov model for an HV circuit breaker, where failure of each of the component parts is treated as a separate state to allow them to calculate the time that a circuit breaker resides in an operational state. Interestingly they find that the duration of remaining in a failure free state for oil circuit breakers is higher than for SF_6 circuit breakers, but unfortunately do not offer an explanation for this finding.

7.4 Development of a modified circuit breaker Markov model

The previous section demonstrates that, within the power systems domain, a substantial body of research exists about mathematical modelling and in particular Markov modelling. Through various examples, Markov models have been shown to possess the potential to enable utilities to select the optimal asset replacement and maintenance strategy for their equipment. In addition, using the four state model developed by [Endrenyi et al, 1998] and applying it to the circuit breaker used in the case studies in Chapters 4, 5 and 6, it can be observed how the economic and technical evaluation of each maintenance strategy can be completed.

This model [Endrenyi et al, 1998] proposes that the probabilistic deterioration of most types of equipment can be represented by four discrete stages: (i) normal state; (ii) minor deterioration; (iii) significant deterioration; and (iv) equipment failure. Throughout the life of the equipment it is assumed that the equipment will deteriorate in stages, where this deterioration could be caused by a number of factors, such as operating wear and tear, physical environment or even the maintenance practices themselves. Unless maintenance is carried out, equipment failure will result, where extensive repair or overhaul will be required to refurbish the equipment or, in the worst case, the equipment may need to be replaced.

In the experience of a domain expert, the deterioration process for a SF_6 circuit breaker can be described by the aforementioned stages. However, for a true evaluation to be achieved between the various maintenance strategies, the Markov model needs to be modified to reflect the reliability of an OLMS. In addition, on the basis that the final state represents a failure that either requires a circuit breaker to be refurbished or replaced, the minor and major failure rates, as described by [Cigré, 83, 1994] need to be included as well. Some of these failures are due to the natural deterioration of a circuit breaker but others occur as a result of other causes not associated with typical aging such as a manufacturing defect with an SF_6 density valve causing a reduction in the gas density. Therefore, as shown later in this chapter there is the possibility that whilst in any one of the circuit breaker deterioration states (good condition, minor deterioration or major deterioration), there is the possibility of transiting into an OLMS failure state, a circuit breaker failure state, or a maintenance or inspection state.

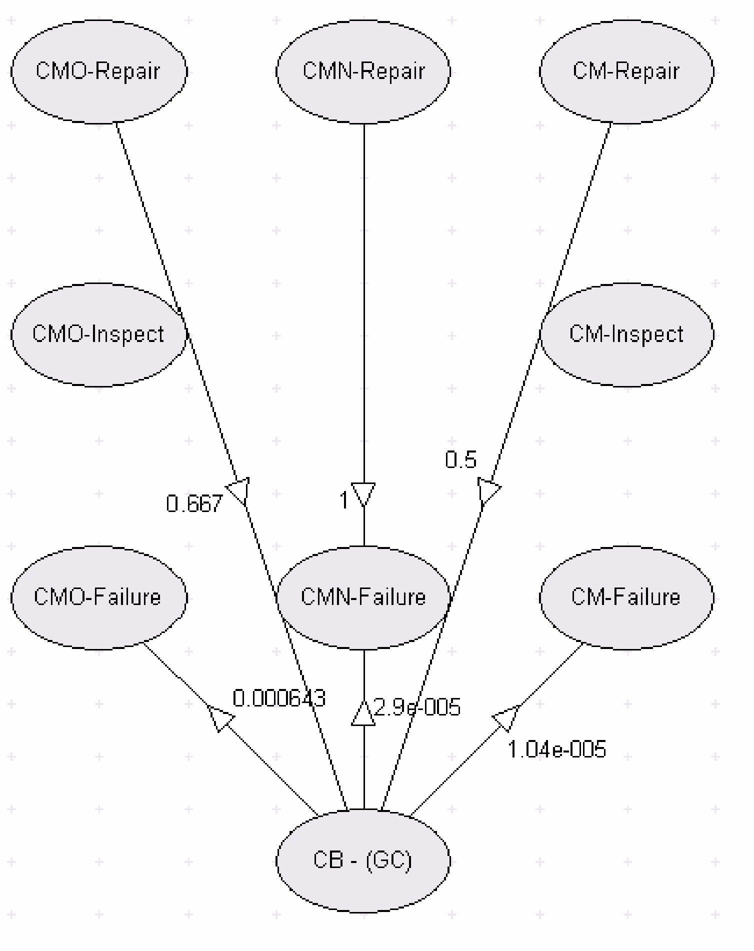
As described previously, the following Markov models were developed and solved using the commercial reliability software tool, Reliability Workbench [Isograph, 2002], which allows a user to model discrete and continuous time phases within the same Markov model. However, unfortunately Reliability Workbench does not allow the two different transitory phases (discrete and continuous) to be shown on the same diagram and therefore the following figures present the continuous and discrete phases of a Markov model in separate diagrams. For example to model OLMS failures and how they affect the condition of a circuit breaker, the continuous time transitory states to enter an OLMS failure state are shown in one diagram, Figure 7.2, but a separate diagram, Figure 7.3, is required to show the discrete transitory states. Namely, having entered an OLMS failure state there is a probability of the circuit breaker remaining in the same condition or the probability of the OLMS failure causing a deterioration of the condition of the circuit breaker.

With the regard to the data for the Markov models, as described for each maintenance models later in this chapter, this has been sourced from a combination of Cigré [Cigré, 83, 1994], Oreda [Oreda, 2002] and ScottishPower. In the case of the latter, historical records [SP, 2002a] were used, such as for the circuit breaker major failure rate. However, where there this was not possible, such as the probability of a maintenance action improving or causing further deterioration of a circuit breaker, the knowledge of a highly experienced operational engineer was employed. It should be noted that the continuous and discrete time transition rates are expressed as a rate per day and probability figure, respectively. Furthermore, the values are shown adjacent to each respective transition line in the Markov models, where the transition direction is indicated by an arrow.

7.4.1 Integration of an OLMS into a Circuit Breaker Markov Model

In the model developed by [Endrenyi et al, 1998], the assumption is made that an OLMS does not affect the condition of the plant that it is monitoring. However, as highlighted in section 4.3 and as shown in Figure 7.2, an OLMS can affect a circuit breaker in three ways. Namely, it can cause a major failure or it can result in a minor failure that, depending on the type of failure and how it is connected to a circuit breaker, may or may not require an outage to repair it.

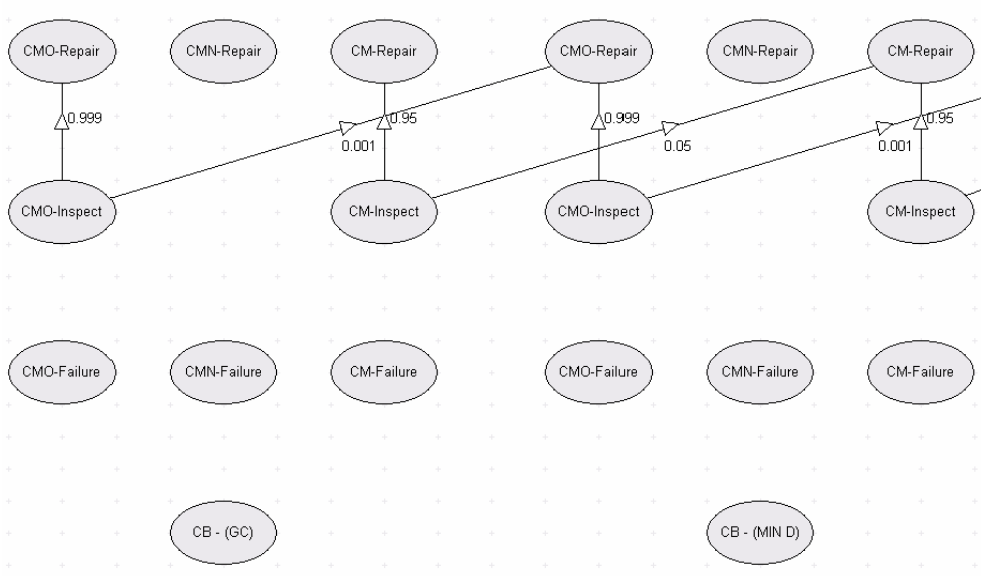
To retain consistency with the previous case studies, the minor and major failure rates for an OLMS are taken from [Oreda, 2002]. Once an OLMS has entered a failure state (CMO-Failure, CMN-Failure or CM-Failure), there is a 100% probability of carrying out an inspection or repair. For an OLMS failure that requires an outage of a circuit breaker, there is a probability that it will be successful or there is the possibility that it could cause damage and further deterioration of a circuit breaker; an example being a repair to a travel transducer whereby the timing of a circuit breaker is inadvertently altered. To model this possibility in Reliability Workbench software, a transitory state needs to be introduced and for the reasons mentioned previously these discrete time transitions need to be shown on a separate figure from the continuous time transitions in Figure 7.2. They are shown in Figure 7.3 and it can be observed that these states are labelled ‘CM-Inspect’ for an OLMS major failure and ‘CMO-Inspect’ for an OLMS minor failure that requires an outage of a circuit breaker. To model the duration of a repair or inspection, the software requires another state to be introduced, which, depending on the type of OLMS failure, is labelled as CMO-Repair, CMN-Repair or CM-Repair in Figure 7.3. It should be noted that in the case of an OLMS failure that does not require an outage of a circuit breaker, CMN-Failure, the probability of causing further damage to a circuit breaker is zero and therefore the Markov model will progress directly to the associated repair state (CMN-Repair). With regard to the maintenance and repair intervals for an OLMS and the probability that a repair would cause further deterioration of a circuit breaker, the experience of a domain expert was utilised.



where

CMO:	a failure of an OLMS that will need an outage of a circuit breaker to repair or re-commission it.
CMN:	a failure of an OLMS where it can be repaired without causing an outage of a circuit breaker.
CM:	a failure of an OLMS that will cause a major failure of a circuit breaker.
CB - (GC):	circuit breaker – good condition state

Figure 7.2: Markov model showing minor and major failures of an OLMS



where

CB- (MIN D): Circuit breaker – minor deterioration

Figure 7.3: Markov model of a circuit breaker showing outcome of repairs due to an OLMS minor or major failure

7.4.2 Development of a Circuit Breaker Markov Model for Different Maintenance Strategies

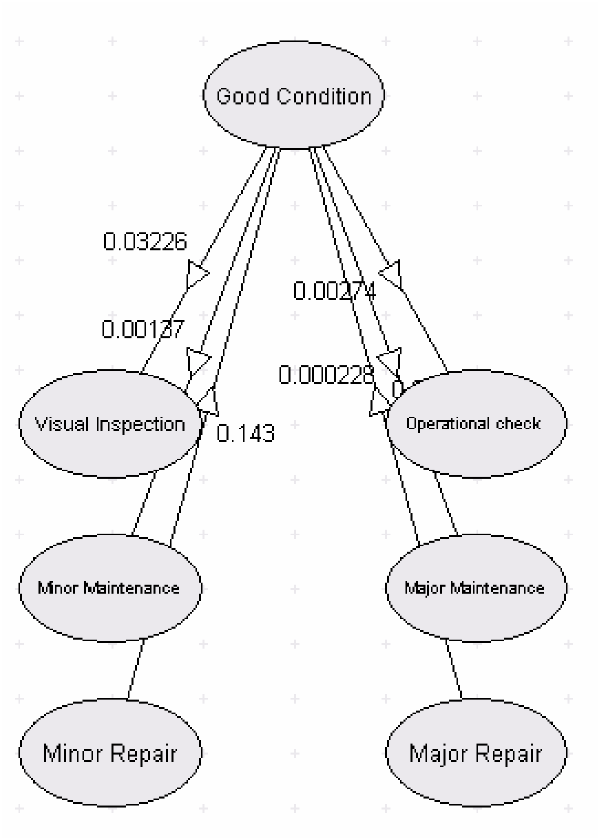
The final form of the circuit breaker Markov model depends on the adopted maintenance strategy. Although the TBM and off-line CBM models are not affected by an OLMS, as mentioned previously, the models for both these strategies have been developed to allow a comparison to be made with the on-line CBM and RCM models.

To compare each of the maintenance strategies, the models also need to be populated with data. The minor and major failure rates for a circuit breaker were sourced from [Cigré, 83, 1994] and [SP, 2002a], respectively to maintain consistency with the case studies in Chapters 2, 4 and 5. On the other hand, as these figures consist of random failures and failures due to the natural deterioration of a circuit breaker, in practice there would be a difference between the failure rates for each of the deterioration states. Namely, as a circuit breaker deteriorates in condition, the failure rate would increase. Furthermore, the adopted maintenance strategy will also have an effect on the frequency of the minor and major failures. As highlighted in previous chapters, although utilities are increasingly moving from a TBM to a CBM or RCM strategy, until more detailed failure data is available a common rate for the minor and major failures will need to suffice for this analysis. However, as the figures are based mainly on a TBM strategy and considering the conclusions of Chapters 4 and 5 that a CBM or RCM strategy potentially offers an improvement in the availability of a circuit breaker, the analysis here presents a worst case scenario; should CBM or RCM prove to have a detrimental effect on the failure rate of a circuit breaker then this assumption will need to be re-visited.

To determine the intervals between the various condition states of a circuit breaker and the probabilities of the outcome from the various maintenance activities, use was made of historical records [SP, 2002a] and knowledge from a domain expert. Similarly, the probabilities for the outcome of the major and minor failure repairs were obtained from a domain expert.

7.4.2.1 Markov Model for a TBM Strategy

As shown in Figure 7.4, for a TBM approach, maintenance is carried out at predetermined maintenance intervals regardless of whether the maintenance is required or not. Using the strategy discussed in section 2.4.7.3, a minor maintenance is carried out at three yearly intervals and major maintenance is carried out mid-life after twenty years of service. In addition, a monthly visual inspection and annual thermovision check is conducted.



where

the state 'Good Condition' represents the initial state of a circuit breaker

Figure 7.4: TBM Markov model showing regular maintenance activities

Referring to Figure 7.5, if an inspection or an operational check is carried out the outcome could be either to do nothing or initiate a minor or major maintenance. On completion of the maintenance, there is the probability that the condition of a circuit breaker remains the same, is improved or there is the possibility that it is made worse. Similar to the OLMS failures, this discrete time transition phase needs to be presented on a separate diagram and consequently is shown in Figure 7.6.

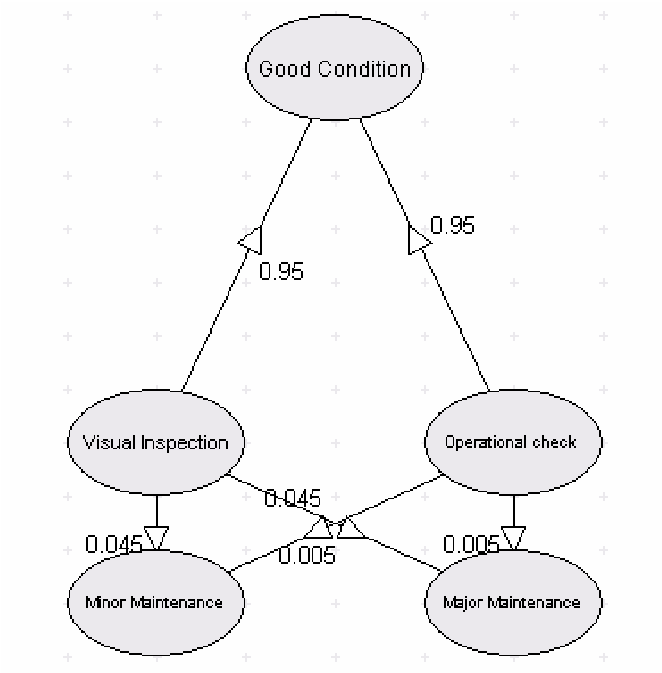


Figure 7.5: TBM Markov model showing outcome from visual inspection and operational check

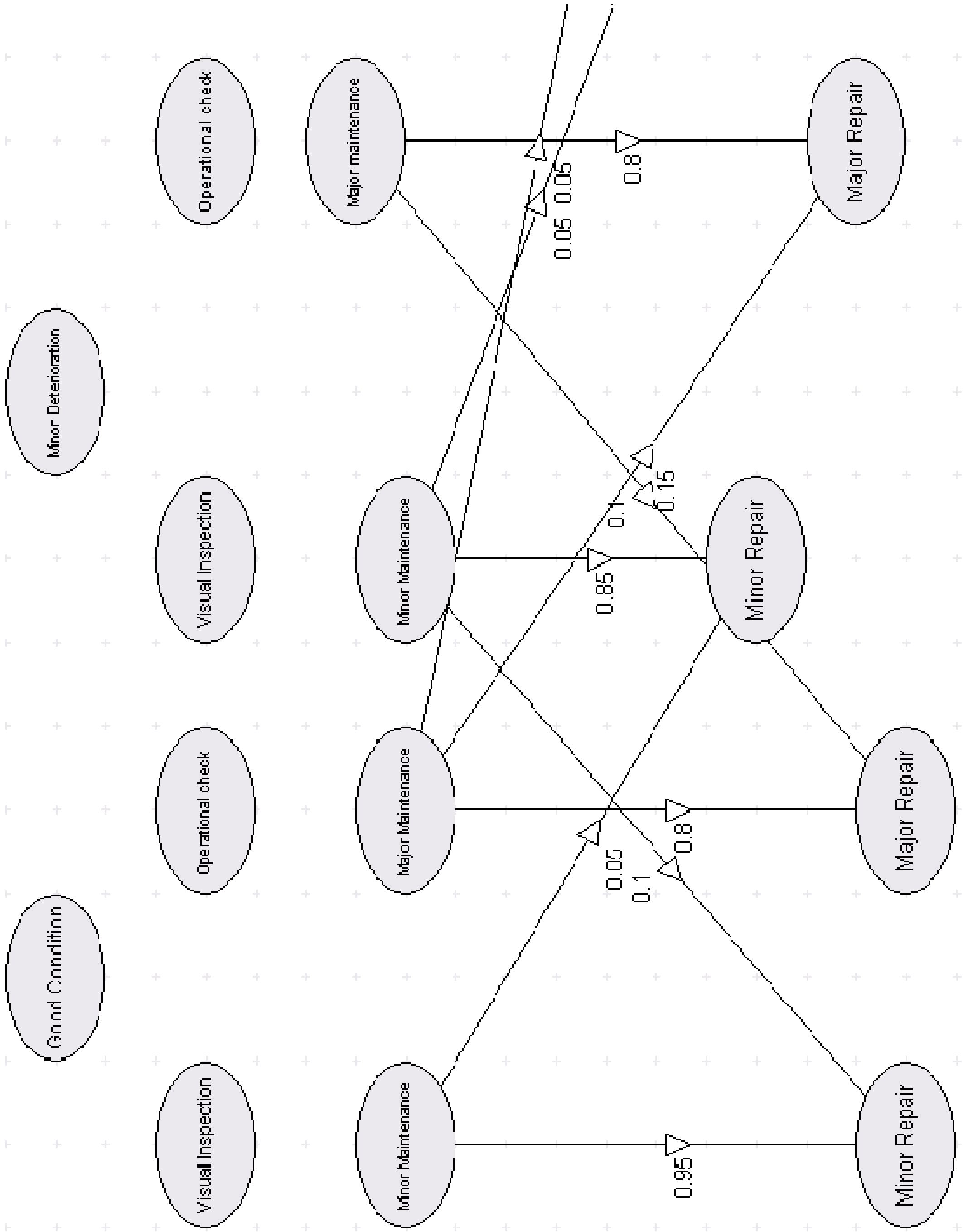


Figure 7.6: TBM Markov model showing outcome from minor and major maintenance activities

As shown in Figure 7.7, there is also the potential for a minor or major failure to occur at any time throughout the life of a circuit breaker.

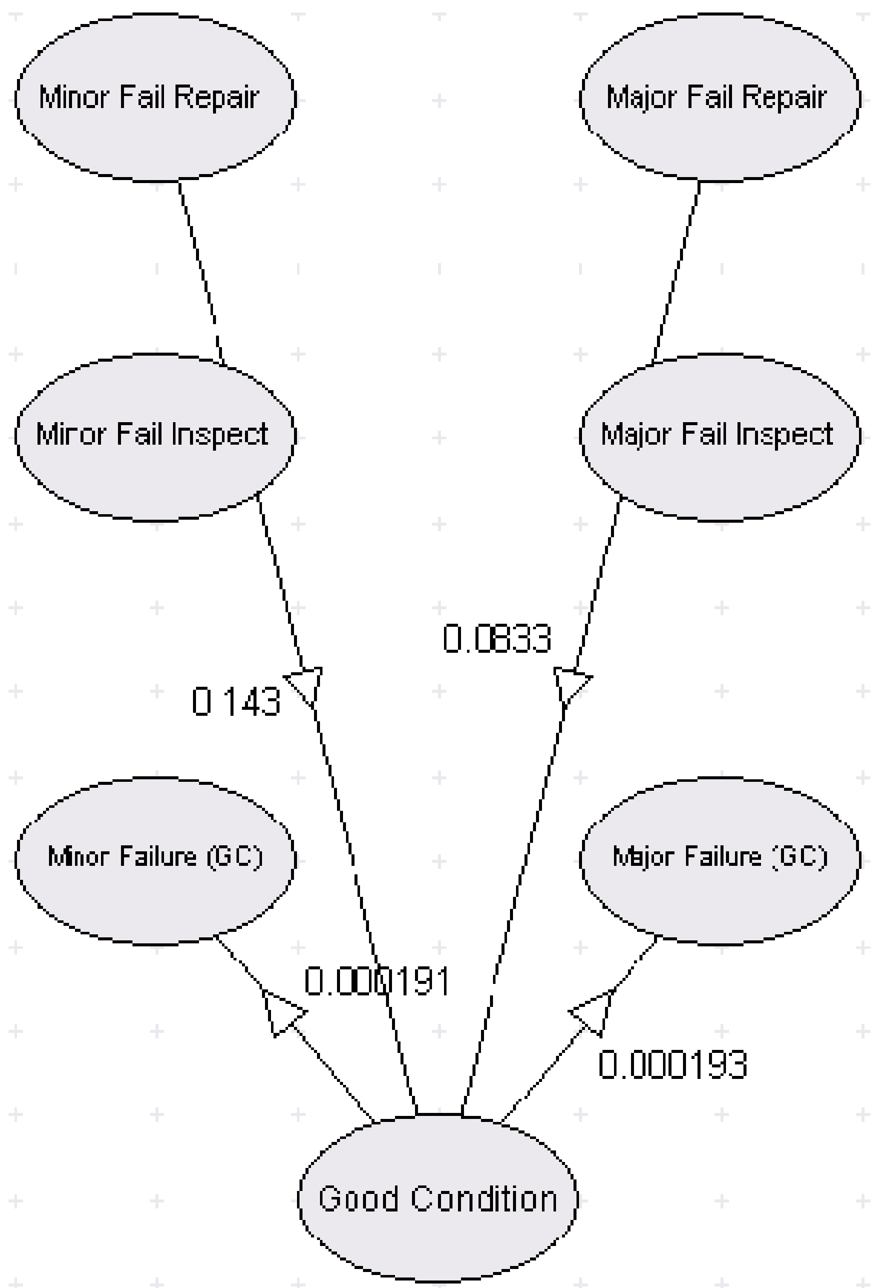


Figure 7.7: TBM Markov model showing minor and major failures

Depending on the timing, nature and severity of the failure, the operator may take the opportunity to combine the repair with a minor or major maintenance or simply concentrate on the repair itself (Refer to Figure 7.8). Unlike the former approach where there is a possibility that the overall condition of a circuit breaker can be improved, the latter, at best, results in the current condition being maintained. Other operators may take a different view, but based on the experience of a domain expert a minor or major maintenance needs to be carried out to improve the condition of a circuit breaker.

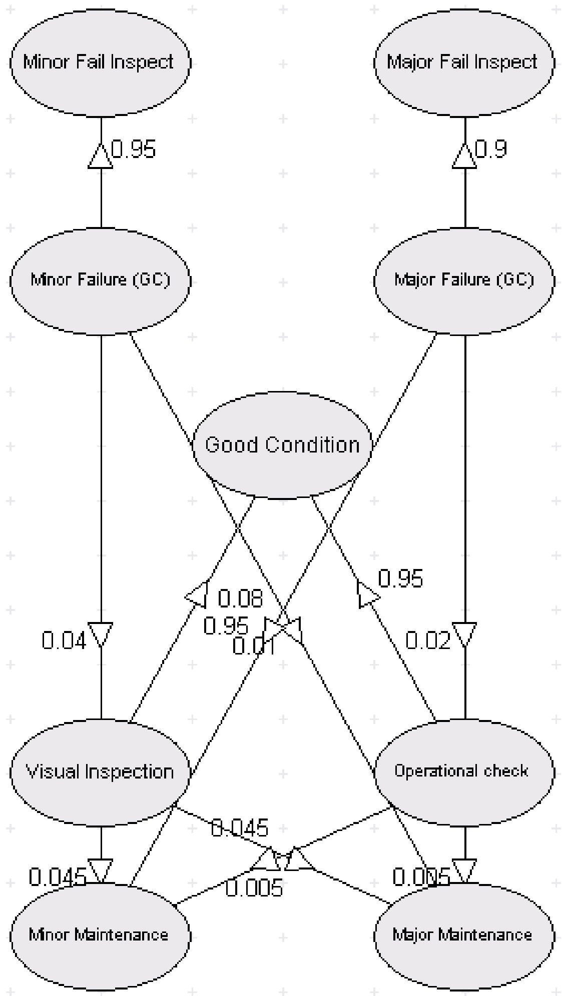
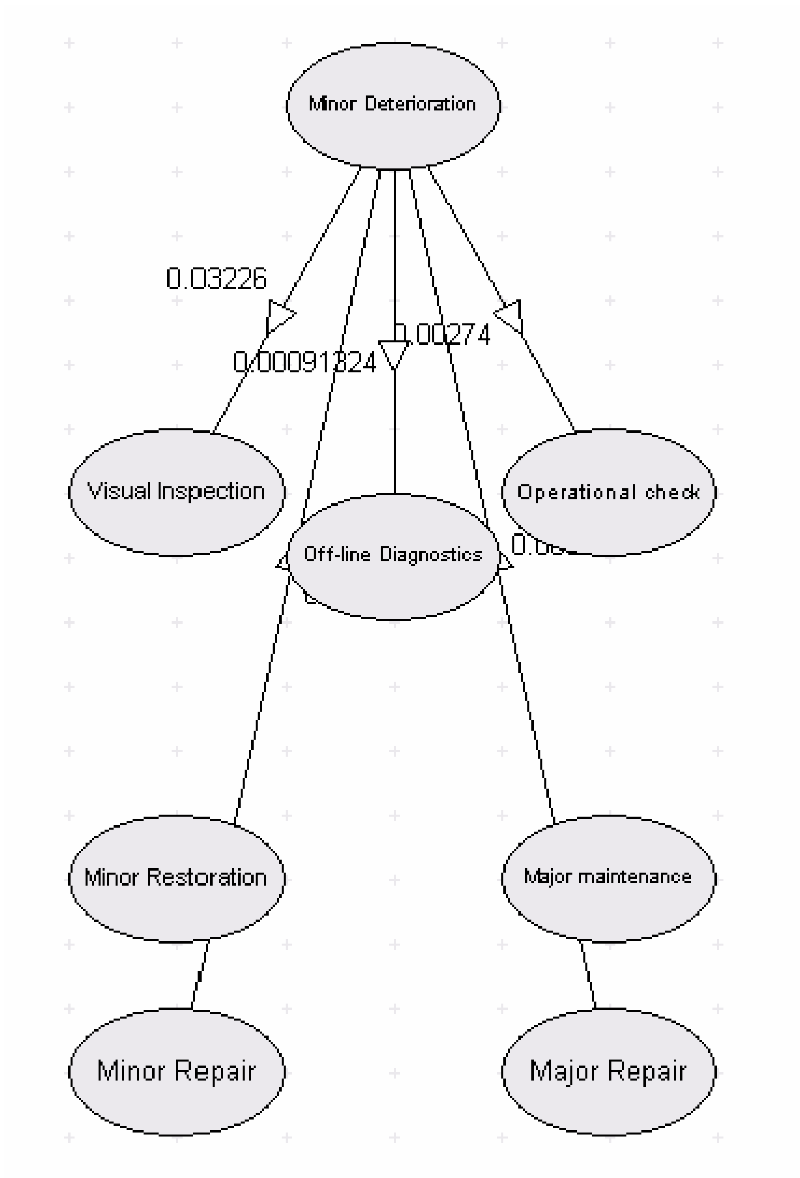


Figure 7.8: TBM Markov model showing outcome from minor and major failures

7.4.2.2 Markov Model for an off-line CBM Strategy

For the off-line CBM Markov model the operational and visual checks still remain. However, as shown in Figure 7.9 and explained in section 2.4.8.1, off-line diagnostic monitoring has replaced the minor maintenance activity.



where

> the state 'Minor Deterioration' represents the first stage of deterioration of a circuit breaker

Figure 7.9: Off-line CBM Markov model showing regular maintenance activities

As shown in Figure 7.10, the results dictate if major intrusive maintenance is required or actions such as lubricating the mechanism are sufficient to restore the condition of a circuit breaker. Regardless of the action taken, the outcome of these activities can be treated in the same way as the minor and major maintenance tasks in the TBM Markov model; namely, there is the possibility that the condition of a circuit breaker is not improved and in the very worst case is aggravated further.

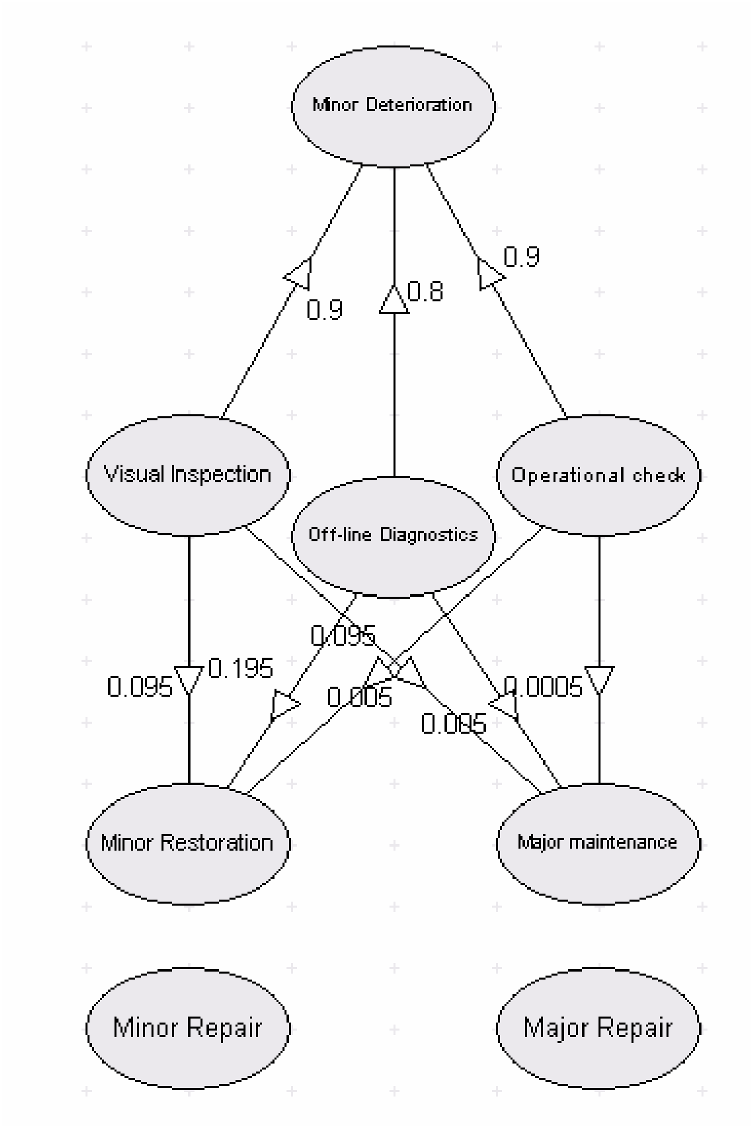


Figure 7.10: Off-line CBM Markov model showing outcome from off-line diagnostic checks

With regard to the minor and major circuit breaker failures, they can be treated in the same way as shown for the TBM Markov model.

7.4.2.3 Markov Model for a on-line CBM Strategy

The Markov model for the on-line CBM approach can be developed from the off-line CBM version by replacing the off-line diagnostic checks with an on-line monitoring activity. However, as explained in section 4.4 and shown in Figure 7.11, calibration checks need to be included due to the drift rate of some of the transducers [Trafag, 2002].

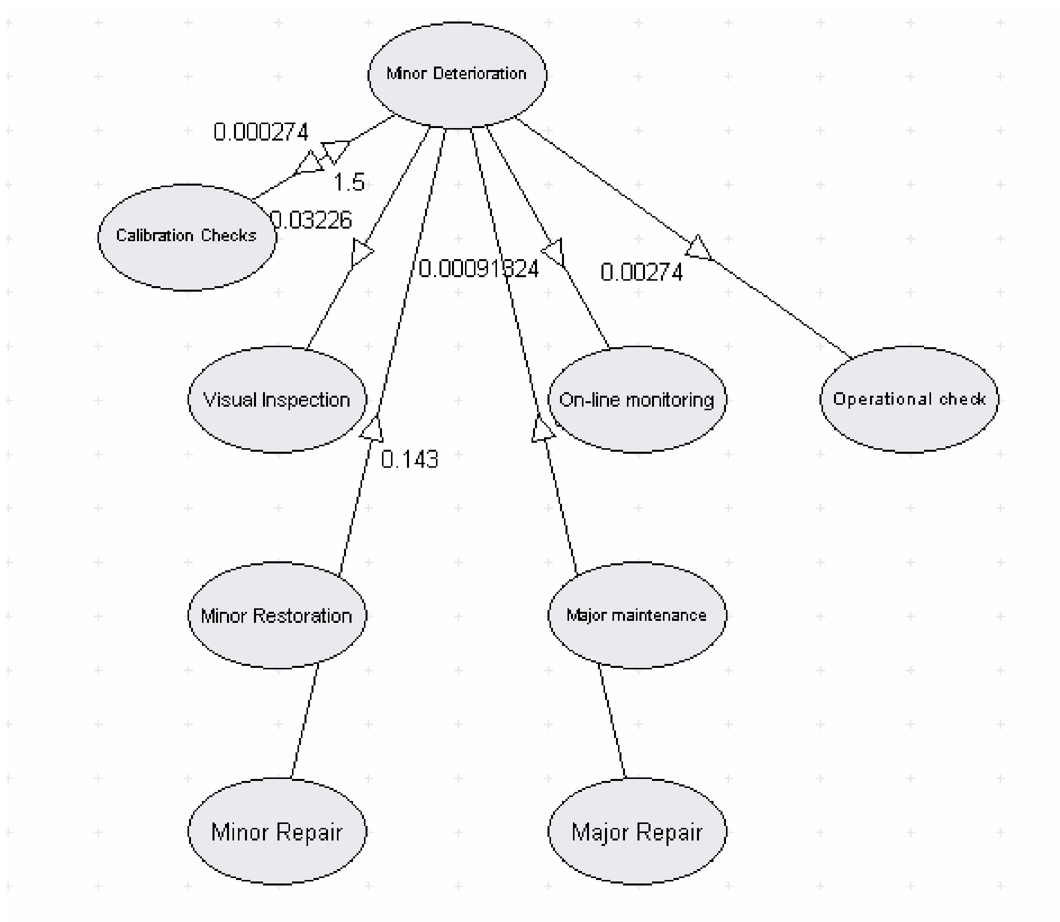


Figure 7.11: On-line CBM Markov model showing monitoring and maintenance activities

As for the outcome from an OLMS check, as shown in Figure 7.12, it is similar to the off-line CBM approach.

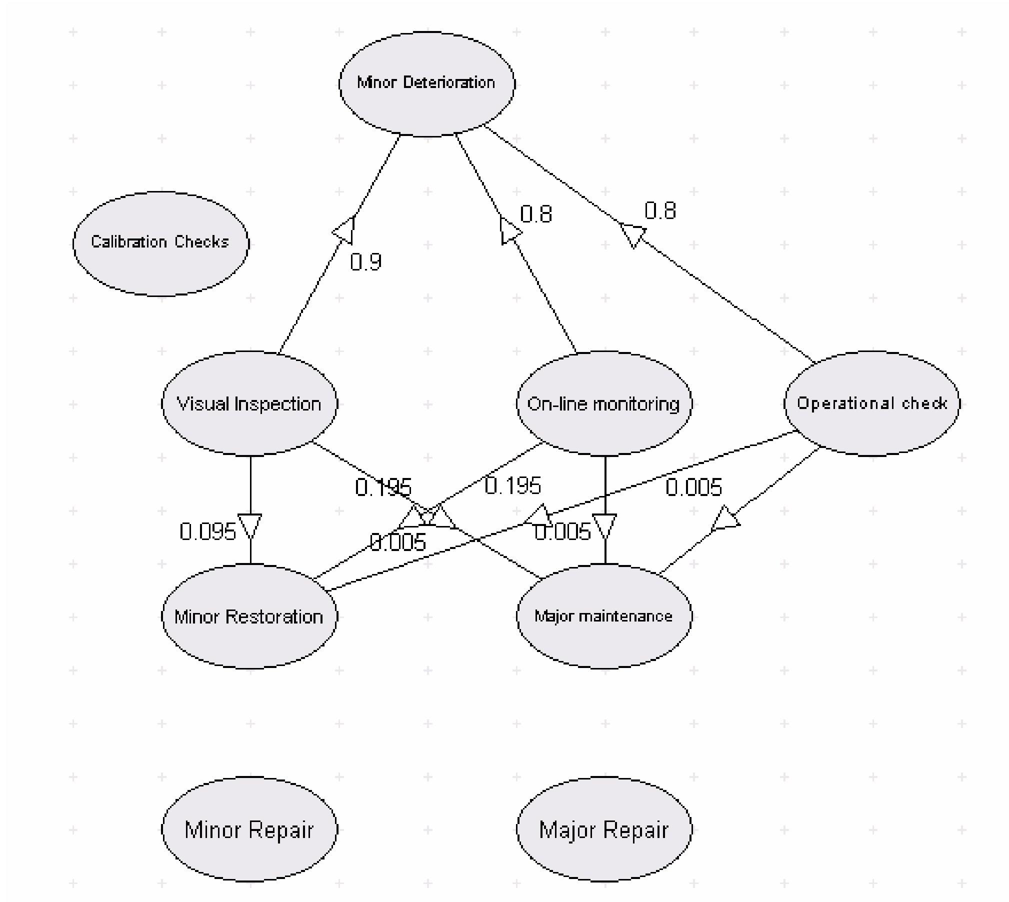
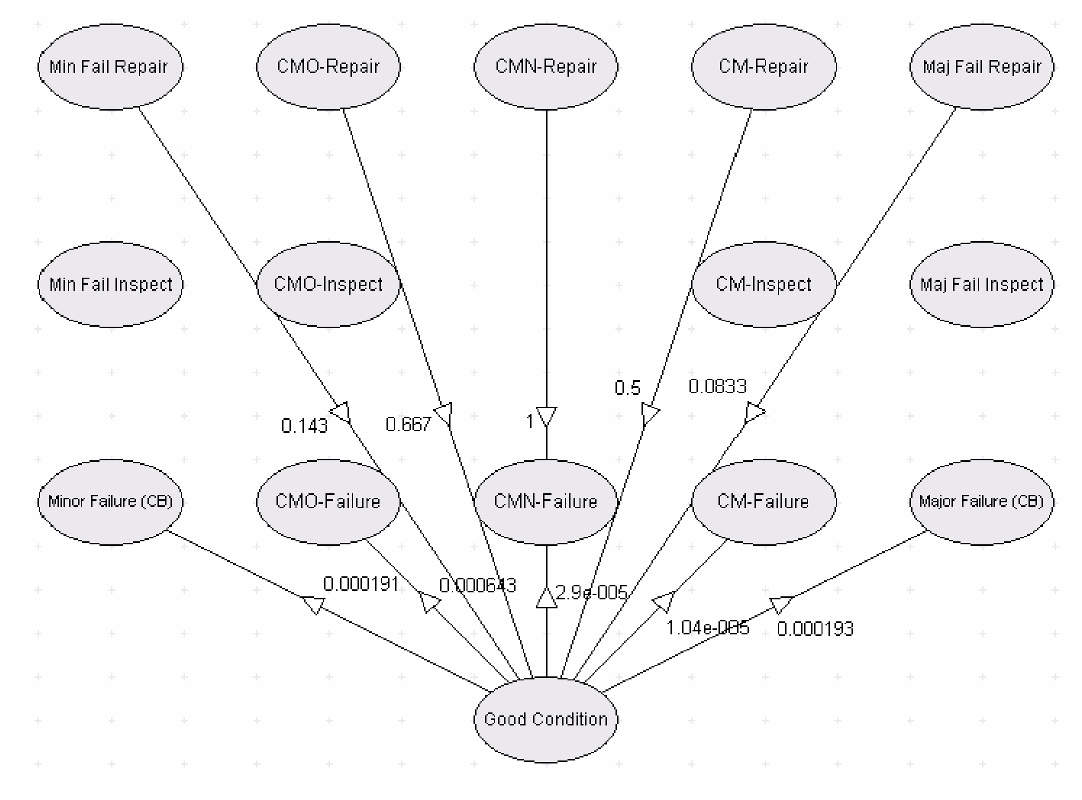


Figure 7.12: On-line CBM Markov model showing outcome from on-line condition monitoring checks

Apart from the minor and major failures of a circuit breaker, as described in section 7.4.1 and shown in Figure 7.13, the failure modes of an OLMS need to be considered as well.



where

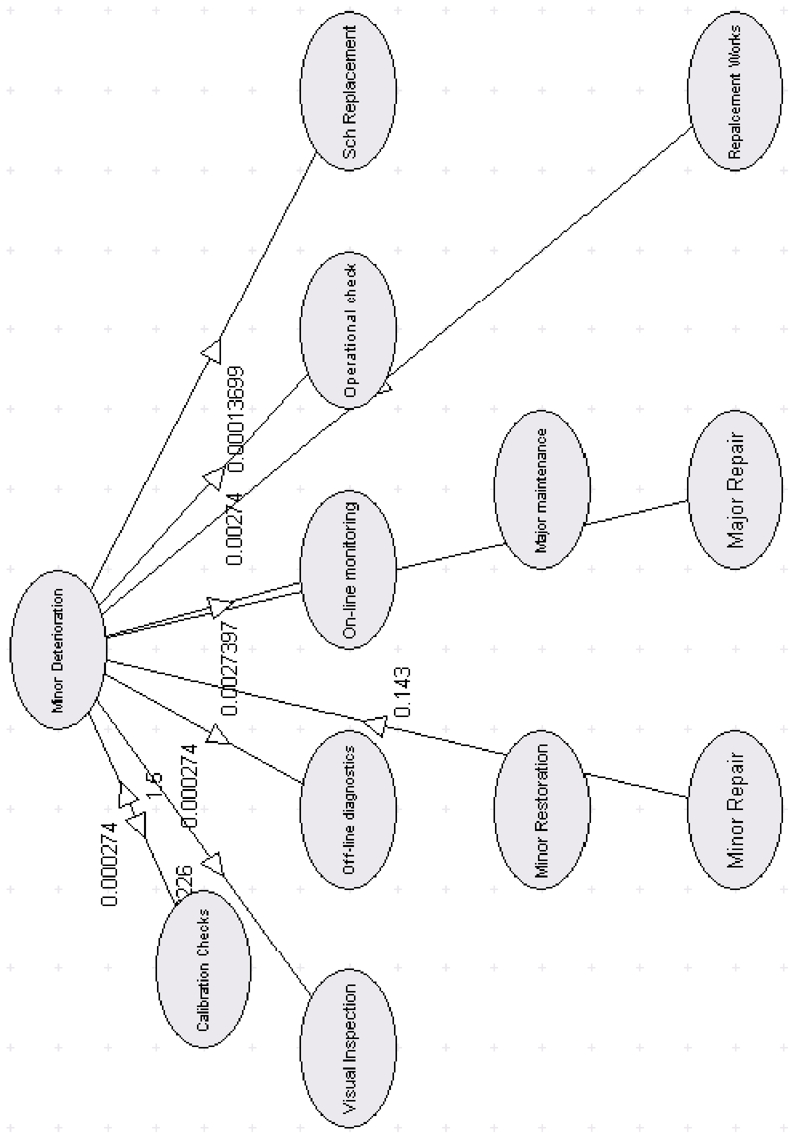
Min: Minor

Maj: Major

Figure 7.13: On-line CBM Markov model showing minor and major failures of a circuit breaker and an OLMS

7.4.2.4 Markov Model for an RCM Strategy

As described in Chapters 2 and 5, RCM is not a common maintenance procedure like TBM or CBM, but a combination of approaches. Consequently, as shown in Figure 7.14, it involves on-line monitoring, off-line diagnostics and scheduled replacement tasks.



where

Sch: Scheduled

Figure 7.14: RCM Markov model showing preventive maintenance tasks

The outcome of on-line monitoring and off-line diagnostics is the same as described previously for the on-line CBM and off-line CBM Markov models, respectively. In addition, similar to the outcome of the minor restoration and major maintenance works, there is the probability that the scheduled replacement works, such as replacing the interrupters, could result in the condition of a circuit breaker being improved, remaining the same or being made worse.

With regard to the minor and major failures of a circuit breaker and OLMS, these are the same as described for the on-line CBM Markov model (Refer to Figure 7.13).

7.5 Comparison of maintenance strategies using Markov Model method

The probability of being in the final failure state for each of the maintenance models, developed in the previous section, can now be calculated for each year that a circuit breaker is in service. Assuming a forty year life for a circuit breaker and repeating this for each maintenance strategy, as shown in Figure 7.15, the results can be plotted on a graph to compare how each maintenance strategy affects the lifetime of a circuit breaker with respect to the probability of it requiring refurbishment for each year in service.

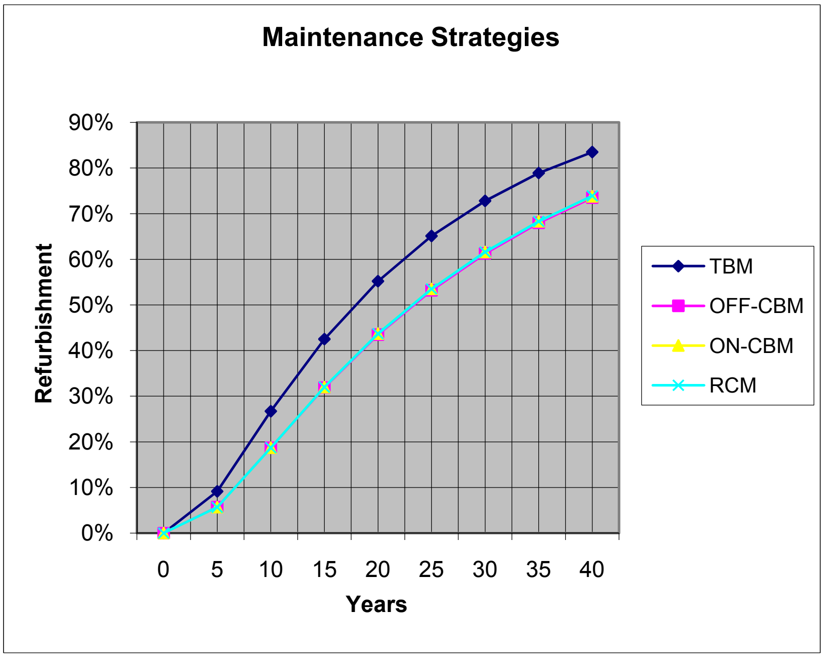


Figure 7.15: Graph showing probability of a circuit breaker requiring refurbishment versus years in service for each maintenance strategy

7.6 Discussion of results and conclusions

The results show that over the forty year typical lifetime period, there is a greater probability of a circuit breaker requiring to be refurbished or replaced using the TBM approach compared to the other maintenance strategies. In particular, after forty years the TBM approach shows that the probability of a circuit breaker requiring refurbishment or replacement is 84% compared to 74% for the other strategies. To understand what this means in terms of capital investment, when there is a 74% probability of a circuit breaker requiring refurbishment using the TBM approach, this occurs after thirty one years in service; namely it represents a nine year delay in investment if adopting a CBM or RCM strategy. Using an NPV analysis and costs from [SP, 2002b and SP, 2002c] this saving equates to 5.2% of the cost of a new circuit breaker.

The main factor that contributes to this difference is that with TBM, minor and major maintenances are being performed regardless of whether they are required or not. Consequently, as shown in Figure 7.6, there is a greater chance of causing more damage to a circuit breaker through human error. Although it is not clear from Figure 7.15, it is interesting to note that after forty years the probability of reaching the refurbishment/repair state is slightly greater for on-line CBM and RCM compared to off-line CBM; the difference being 0.3% and 0.4%, respectively. This can be attributed to the unreliability of the on-line condition monitoring and again emphasises previous conclusions that the extent of its inclusion in any maintenance strategy needs to be considered carefully.

With respect to validating the results, each utility needs to carry out its own assessment, as the results are dependent on historical records and their own failure data. As mentioned previously, international data sources such as [Cigré, 83, 1994] can be used, but as the early circuit breakers that were used in this study are now only approaching forty years of operational service, as yet, up to date information on their condition is not available. The results are also dependent on the subjective view of experts, which can have a significant effect on the results. For example, if the transition rate for moving from a “Good Condition” to a “Minor Deterioration” state of the circuit breaker is varied between 5 years and 15 years, the probability of the circuit breaker requiring refurbishment after 40 years of service for the TBM model varies between 64% and 86%, respectively. Alternatively for the same TBM model, if the circuit breaker is in a “Good Condition” state and the probability of causing further deterioration to the circuit breaker is increased from 5% to 50% when repairing a minor failure, the probability of the circuit breaker requiring refurbishment after 40 years increases from 74% to 79%, respectively. Therefore, until more experience and data has been accumulated, it also important for utilities to carry out sensitivity studies on any data where there is a large degree of uncertainty.

On the other hand, provided the data limitations are recognised, Markov modelling has proven to be an invaluable technique when comparing how each maintenance strategy affects the lifetime of a circuit breaker, as it provides a quantitative link between the life of a circuit breaker and the effect of a maintenance activity. Unlike the heuristic techniques such as RCM and CBM, and as described by [Endrenyi et al, 1998], Markov models also provide the opportunity to determine the optimum maintenance frequency by carrying out a sensitivity analysis on the frequency of the CBM checks and scheduled maintenance tasks. However, techniques such as RCM, whether using FMECA or FTA, are still required to determine the critical failure modes. Whilst Markov modelling could be used to examine the effect of increasing the number of parameters to be monitored on-line, the previous results demonstrate that the effect on the overall life of a circuit breaker is negligible. Namely, when moving to a fully on-line CBM strategy, the probability that a circuit breaker requires to be replaced or refurbished decreases by 0.3% when compared to the off-line CBM approach. In addition, techniques such as FTA are better suited to optimising the parameters to be monitored as they quantify the contribution of each failure mode towards the overall circuit breaker availability, thereby allowing a utility to determine the effect of monitoring one parameter versus another (Refer to section 6.6).

Therefore, rather than duplicate or replace approaches such as RCM, Markov modelling complements these methods to achieve the optimum maintenance strategy both from an economic and technical perspective. The economic analysis is of particular importance, as it examines the effect on the life of a circuit breaker as opposed to just the corrective and preventive costs considered in Chapters 4, 5 and 6. However, the results are still very much dependent on the accuracy of historical records and the experience of utilities. Consequently, as with CBM and RCM, it will take time and experience to prove or disprove the results.

7.7 Chapter Summary

In this chapter the concept of mathematical modelling was introduced to understand how different maintenance strategies affect the lifetime of a circuit breaker. In particular, it was shown that Markov models are overwhelmingly the dominant modelling framework for modelling deterioration and maintenance.

The Markov model splits the deterioration process into discrete states, where each state represents a specific condition of the asset being analysed. The number of states and how the different maintenance policies are modelled is at the discretion of each utility or asset modeller. However, in this case, a four state model was utilised to represent the life of a circuit breaker, which allowed individual models to be developed for a TBM, off-line CBM, on-line CBM and RCM strategy. Unlike previous models, the effect of on-line condition monitoring on the deterioration process of a circuit breaker was considered and where appropriate was included within the relevant models.

Historical records and expert judgement were used to populate the models, and using commercially available analysis software a comparison between the different maintenance strategies was undertaken.

The results reinforced the potential benefits in moving away from a TBM strategy where a decision to re-invest in refurbishing or replacing a circuit breaker can be delayed by nine years if adopting a CBM or RCM strategy. Similar to previous findings, the results also highlighted the potential detrimental effect of on-line condition monitoring, although this issue is negligible when considering the effect on the life of a circuit breaker.

Time and experience will be required to validate the results. However, addressing the original objective of this chapter, which was to assess the role of Markov modelling in assessing different maintenance strategies and how it compares to other techniques, it was concluded that it is invaluable as it provides a quantitative link between the life of a circuit breaker and the effect of a maintenance activity. Therefore rather than replace the economic models developed in Chapter 4 or the

FTA in Chapter 6 it complements these methods thereby allowing the optimum maintenance strategy to be selected.

Chapter 8

8 Conclusions and Further Work

8.1 Conclusions

The research presented within this thesis examined the role of condition monitoring and whether it was feasible to move from a TBM to a CBM or RCM strategy for high voltage circuit breakers. It has been shown that there are a large variety of commercially available systems, which differ in a number of ways from the type of sensors used to the overall design of the system. These systems permit a wide range of parameters to be monitored, but when the reliability of the condition monitoring is taken into account, it has been shown that the initial perceived savings in moving to an on-line CBM strategy are greatly reduced and in some applications it is questionable whether condition monitoring can be justified. For example, through case studies for an EHV SF_6 circuit breaker it has been shown that the initial perceived savings for the corrective maintenance costs can reduce by as much as 86% when the reliability of an OLMS is taken into account and the preventive costs can increase by as much as 17% per year when the maintenance requirements of an OLMS are included. Economic models that assume that the reliability of the condition monitoring can be ignored could lead utilities to making incorrect investment decisions and degrading a circuit breaker's reliability rather than improving it.

Using the economic model developed in Chapter 4, it is recommended that a utility use their own data when carrying out a feasibility study to assess the use of condition monitoring. Through sensitivity studies for an EHV circuit breaker it has been shown that that the critical and most sensitive parameters are the major failure rate for a circuit breaker, the probability of successfully detecting the early signs of a major failure, the minor repair cost and finally, the minor failure rates of a condition monitoring system. In particular, it has been demonstrated that when some of the factors, such as the major failure rate for a circuit breaker, are varied they can have a significant impact on the result and in some cases reverse it. For example, when the major failure rate of a circuit breaker is increased by a factor of ten, the corrective costs reduce by as much as 68% whereas ,if the failure rate is reduced by a tenth, the corrective costs for a circuit breaker increase by as much as 75% compared to a TBM strategy.

There are also differences between manufacturers, with some condition monitoring systems being more intrusive in how they are applied to circuit breakers compared to others. This could be due to the type of parameter being monitored, such as the hydraulic pressure in a mechanism where a direct connection between the circuit breaker and the condition monitoring system cannot be avoided. Alternatively, it could be due to the type of transducer that is employed, such as a Hall-effect device versus a shunt to measure trip coil current.

Utilities also need to consider the application of a circuit breaker, as the case studies demonstrated that the substation configuration and treatment of planned and unplanned outage costs can have a significant influence on the economic viability study. Namely, for a substation configuration such as a one and half switch layout, unless there is an outage of the adjacent circuit breaker, there is an alternative electrical path and therefore an outage cost can be avoided. However, for a double busbar configuration an outage cost is unavoidable.

Considering the aforementioned factors, and above all, until there is an improvement in the reliability of condition monitoring systems, it is essential that a utility make a careful assessment of each condition monitoring system, how it is applied and the role of each circuit breaker in the electrical network.

The same recommendations also apply to monitoring systems for other types of assets. For example, the research demonstrated that when the economic model developed in Chapter 4 is applied to gas insulated substations, the economic case for PDM is marginal when the planned or unplanned outage cost is low.

There is a still an economic case and clear technical benefits to moving towards a CBM strategy from TBM, but in certain scenarios, it may be more prudent to employ off-line diagnostics as opposed to on-line monitoring. This raised the question as to whether existing maintenance practices are addressing the needs of modern, single pressure SF_6 high voltage circuit breakers. With the advances in interrupter technology and the ever-increasing use of electronics and spring type mechanisms, is there a need to carry out certain maintenance tasks or is there a more effective way of detecting an impending failure? Similarly, with on-line condition monitoring, can the number of monitored parameters be optimised or are there other parameters that would be more effective in highlighting an impending failure?

This leads to the concept of RCM, which is a highly methodical approach designed to optimise the balance between condition based tasks and scheduled restoration tasks. Unlike TBM and CBM, RCM is not a common maintenance procedure, but a process that produces a maintenance programme for an asset or system to ensure the designed-in levels of safety are protected whilst balancing reliability and availability versus cost.

A key part of the RCM process is the identification of the functional failures and the associated critical failure modes of a system or asset. It is essential that a utility involve all parts of the organisation in this process, from design engineers through to maintenance and operations personnel, as failure to do this could result in some of the critical failure modes being missed. Although the RCM process produces a maintenance programme that gives 'best value for money' and it is relatively straight forward to apply, the FMECA stage of the RCM process is still a very subjective exercise and as seen through the application studies, expert opinion and judgement are required to ascertain which failures modes are credible and those that can be discounted from any further analysis. For example, in Chapter 5, 134 failure modes were initially identified for the EHV SF_6 circuit breaker, but to make the process more manageable, experience and expert knowledge had to be used to reduce this number to 55 failure modes. Failure modes such as the 'Piston Valves – Lack of lubrication' were excluded on the basis that provided the number of circuit breaker operations is within the limit of a circuit breaker type test [IEC 62271-100, 2001], there is a low probability of this event occurring. However, as has been shown in Chapter 6, one of the top fifty failure mode events that occurs in the lower limit, mean and upper limit failure rates, is the 'Adhesion of interrupter piston valves'. This may be due to a circuit breaker remaining in a static position for a lengthy period of time, but it demonstrates the fallibility of the FMECA process that even if an extremely disciplined approach is adopted there is still a risk that some of the critical failure modes may be missed or underestimated.

Nevertheless, RCM has shown that for failure modes such as the main and arcing contacts of an interrupter being worn or the blast nozzle being worn, it is more economical in the generator and NSC circuit breaker applications to carry out a scheduled refurbishment task than to use a condition monitoring technique such as monitoring the primary current. Equally, RCM has identified the critical failure modes and allowed the number of on-line monitored parameters to be rationalized, such as eliminating the need to monitor the open and close auxiliary contacts, and the primary current for the generator and NSC circuit breaker applications. Overall, the results appear promising, however, to validate them and show the real impact of RCM, long-term studies are required. In addition, similar to CBM, the intelligent diagnostic software that assists a user in faultfinding and analysing switchgear performance needs to be further developed. It will require collaboration between research establishments such as universities, manufacturers and utilities to fully develop the potential of condition monitoring systems whether used as part of a CBM or RCM strategy.

To address the potential shortcomings of FMECA and assess whether the maintenance recommendations from the RCM process can be refined or even challenged, FTA is a method that quantitatively links each component part to the overall availability of a circuit breaker. It is a rigorous method that forces a utility to replicate the design of a circuit breaker in the form of a logic diagram. Apart from requiring access to design drawings it does require the assistance and openness of manufactures to share their experience and advise on the detailed construction of the circuit breaker under analysis.

Admittedly FTA is a far more complicated process compared to FMECA. However, it is recommended that the FTD be designed in modular elements, such as the interrupter and mechanism, to enable part of the FTD to be re-used or adapted for other circuit breakers. More specifically, due to the expense of designing and testing a new circuit breaker, it is common for manufacturers to re-use the mechanism or interrupter for another model of circuit breaker rather than re-design from first principles. Equally, as can be observed from Chapters 2 and 6, due to international standards, systems such as control circuits follow the same functional design principles. Consequently, having invested in the effort of constructing a FTD for one type of circuit breaker, the effort should be minimised when applying it to another type.

When an FTD has been constructed a utility has an extremely powerful tool to not only ascertain the critical failure modes, but as the results in Chapter 6 demonstrated, it allows a utility to quantitatively measure the effect of monitoring one parameter versus another. FTA does not replace the RCM approach, but instead is a refinement of the methodology in that it provides an alternative to FMECA. The results indicated that, compared to using FMECA, it is more technically and economically beneficial to restrict the on-line monitored parameters to the trip coil current and ambient temperature. Not only does this further reduce the preventive maintenance costs, but the corrective costs are also less. Despite the FTA recommending more off-line checks, this cost is more than offset by a reduced capital cost and associated repair cost from a more simplified OLMS. Consequently, this emphasised once again that further work is required to improve the reliability of on-line condition monitoring systems.

As a result of taking the recommended action from the RCM analysis to monitor fewer parameters, it raised an interesting question and challenged the belief that there is a need for dedicated stand-alone OLMSs. Namely, for some utilities like ScottishPower, existing substation data acquisition systems are already monitoring the trip coil current and ambient temperature. Alternatively, if these parameters were not currently being monitored, it would require minimal effort to install equipment to measure them and incorporate them into existing data systems. Apart from allowing further savings, this may be a more efficient way for a utility to develop their monitoring strategy rather than trying to integrate a number of systems from different manufacturers that are usually designed around what a manufacturer believes a utility needs rather than the other way around. Furthermore, such an incremental approach to introducing on-line monitoring would allow a common approach to be adopted in developing the diagnostic software, which is essential for the future success of monitoring systems.

This raised a further key point, which is covered later in this chapter. Namely, FTDs are essentially a knowledge capturing technique, which could facilitate the development of such diagnostic software. In addition, FTDs could also be used to understand the factors that affect the life of a circuit breaker, which could be used as part of an asset management strategy to programme when circuit breakers should be replaced or refurbished or alternatively to improve the technical specifications used when purchasing new circuit breakers.

The final area of research covered in this thesis was the role of mathematical modelling, and in particular Markov models, in either determining a maintenance strategy for a circuit breaker or being used to assess the effectiveness of one maintenance strategy versus another.

The results indicated that moving from a TBM to CBM or RCM approach can have a positive and significant effect on the service life of a circuit breaker due to there being less scheduled intrusive maintenance; namely, there is less risk of causing damage to a circuit breaker during maintenance rather than improving its condition as intended. On the other hand, the reliability effects of condition monitoring systems are less significant on the life of a circuit breaker and in fact can be considered negligible.

The overall conclusion was that there is a place for Markov models, as they can be used by a utility to strengthen the argument for moving away from a TBM strategy. Furthermore, they can be used to optimise maintenance schedules. However, they certainly are not a replacement for techniques such as RCM, particularly when FTA is employed.

The proof of the results presented in this thesis, such as the identification of the critical failure modes of a circuit breaker and the subsequent recommendations on the on-line circuit breaker parameters that should be monitored will be very much dependent on time and experience. This includes the decisions surrounding the selection and application of the donor data to the FTA, the assumptions on the effectiveness of on-line condition monitoring to detect an impending failure, and the probability figures and failure frequencies used in the Markov models to compare one maintenance strategy with another. Furthermore, the specifics of the maintenance tasks and the associated frequencies may be different from one utility to another, whether it is due to factors such as their treatment of unplanned outage costs or the type of circuit breakers they purchase. However, using the approach of RCM combined with FTA and where appropriate Markov modelling presents a method that has the potential to lead to the development of a maintenance strategy that is the optimum from both a technical and economical perspective. As circuit breaker technology evolves and the reliability of condition monitoring no doubt improves, the proposed maintenance strategy will need to be re-examined but the principles and techniques presented in this thesis should still be valid for this purpose.

8.2 Main Research Contributions

Based on the previous conclusions, the five main contributions that this research has produced are as follows:

- **The development of an economic model to assess the viability of on-line condition monitoring**

  Current evaluation methods make the assumption that the reliability of OLMSs can be ignored when assessing the viability of applying them to circuit breakers [Cigré, 167, 2000]. However, the research took a novel approach and developed a model that took account of the reliability of an OLMS. Through sensitivity studies it proved that the conventional assumption is incorrect and could lead to a utility being ill-advised when determining when and where to apply on-line condition monitoring.

  By carrying out further research it has been shown that this model can easily be adapted to assess monitoring systems for other assets, such as PDMs for GIS.

- **The role of on-line condition monitoring systems in moving to a CBM or RCM strategy**

  The research built upon previous experience with off-line diagnostics and examined, both economically and technically, how on-line condition monitoring could be used as part of a CBM or RCM policy for SF_6 single pressure circuit breakers.

  Through case studies, the merits of each maintenance strategy were examined and potential application issues were identified.

- **Development of a circuit breaker model to identify the critical failure modes**

  Using FTA an extensive model was developed, which quantitatively links the basic component parts of a circuit breaker to its overall availability. Compared to techniques such as FMECA, as currently used in RCM, the FTA model was more accurate in identifying the critical failures modes. It was also shown that the model allows a utility to understand how a failure develops and thereby select the most appropriate maintenance task to detect its early inception.

  A further benefit of FTA is that it will prove invaluable in the development of a future 'Expert System' as its top down structure and logic system approach lends itself well to developing rules to assist a utility in fault finding.

- **The development of Markov models to compare the effect of different maintenance strategies on the life of a circuit breaker**

  Markov models for different maintenance strategies were developed to allow a comparison to be made between the different approaches and to assess the merits of mathematical modelling versus heuristic approaches such as CBM and RCM.

  Unlike existing research, the modelling also examined the effect of on-line monitoring on the life of a circuit breaker.

- **Development of a methodology to determine the optimum maintenance strategy for high voltage circuit breakers**

  Using RCM, complemented with FTA, and where appropriate Markov modelling, a methodology was developed that allows utility to determine the optimum maintenance strategy for an SF_6 high voltage circuit breaker.

  The methodology considers the use of a number of maintenance techniques, such as on-line monitoring, and leads a utility to develop a strategy that is the optimum from both an economical and technical perspective. Although the principles and techniques are focused towards an SF_6 high voltage circuit breaker, they are valid for other types of circuit breakers and indeed could be extended to other assets, such as cables and transformers.

8.3 Further Work

Through the development of a maintenance schedule for an SF_6 high voltage circuit breaker and using techniques such as FTA and Markov models to establish the critical failure modes and the role of on-line condition monitoring, the following five main areas of future work have been identified.

8.3.1 Development of Diagnostic Software

One area of research that must be addressed is the development of diagnostic software that can monitor the signals from condition monitoring to assist in fault finding and assessing the performance of a circuit breaker. It is envisaged that this would take the form of an 'expert system', which effectively emulates the reasoning of a human expert.

Within the realm of expert systems a variety of techniques are employed, where each one differs in the format of knowledge storage or coding and the reasoning approach utilised. Fortuitously, the FTA method is essentially a knowledge capturing exercise and therefore lends itself to a knowledge based system. Furthermore, through the use of the FTA logic symbols, algorithms can be easily formalised to store the knowledge.

An example of a diagnostic production rule would be:

IF the power is on AND the heater does not work THEN the fuse is blown.

8.3.2 Development of an Asset Management System to Prioritise the Replacement/Refurbishment of Circuit Breakers

Clearly, whether due to cost, system or logistical reasons, it is not practicable for a utility to replace or refurbish their population of circuit breakers at the same time. Therefore, a further area of research is using the critical failure modes from the FTA to develop an asset management tool to prioritise the replacement of circuit breakers. One method of achieving this could be through the use of multiple criteria decision making.

The criteria or attributes could be the critical failure modes combined with factors such as the circuit breaker being used in a generator or NSC application.

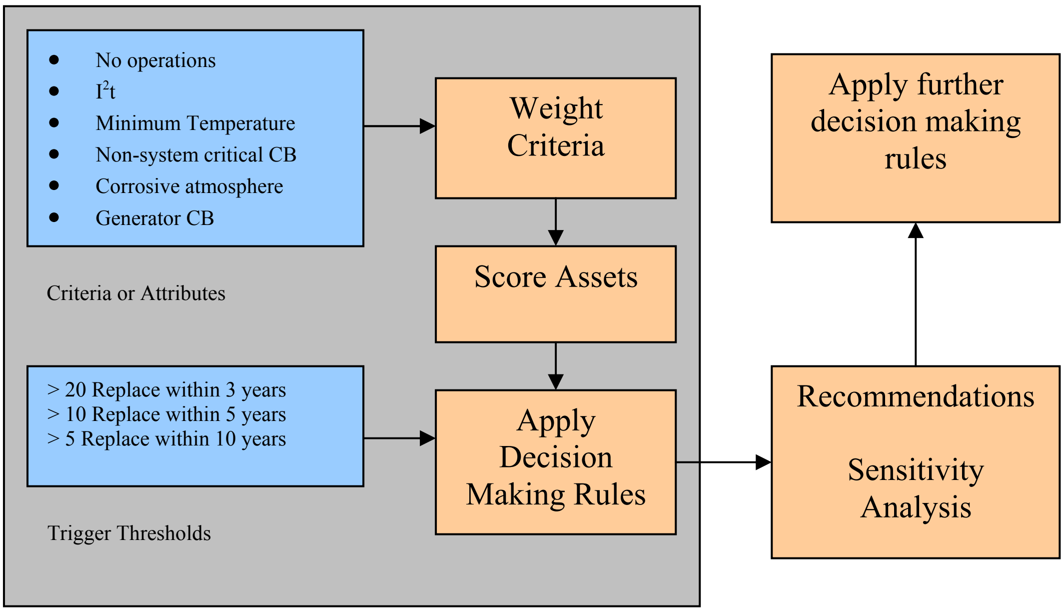


Figure 8.1: Diagram showing multiple criteria decision making for prioritizing the replacement/refurbishment of circuit breakers

However, as shown in Figure 8.1, it is highly probable that a more in depth understanding of the mechanisms that influence the critical failure modes will be required to obtain criteria that are measurable. For example, what has caused the failure of a drive lever; is it the number of operations or are there external influences such as the environment? Depending on the ease of restoring these factors that affect the condition of a circuit breaker they could then be used to determine the weights that would be applied to the multiple criteria assessment.

The multiple criteria decision technique could also be compared with using a Markov model approach, where again the FTA could be used determine the factors that determine which state of deterioration a circuit breaker is in at any one time.

Examining Figure 8.2, the Markov models could even be combined with multiple criteria decision techniques to examine whether it is worth refurbishing or repairing a circuit breaker at an early state of deterioration or letting it progress towards a state where it will have to be replaced.

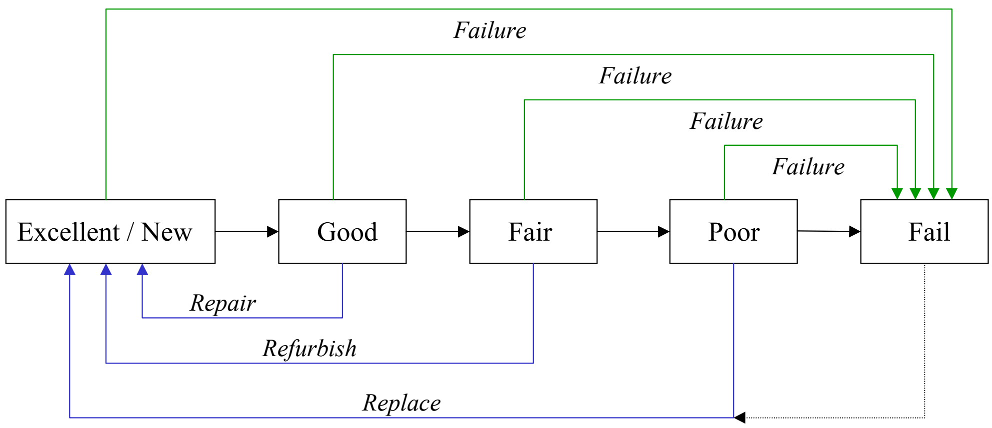


Figure 8.2: Diagram showing multiple criteria decision making to optimize the investment plan for a circuit breaker

8.3.3 Development of an Integrated Common OLMS Using Existing Substation Control Systems

A further area of research relates to a point that was made previously that it may be more beneficial and cost effective for a utility to use existing systems, such as fault recorders, to measure on-line parameters as opposed to purchasing a manufacture's dedicated OLMS. The experience of ScottishPower has shown that some manufacturers are reluctant to adapt existing monitoring systems to the company's requirements and as some of the systems are not user friendly, operations staff have not used them to their full potential.

8.3.4 Development of an Overall Substation Plant Maintenance Strategy

The research in this thesis has been focused on circuit breakers, but many of the principles could be applied to other assets such as transformers, cable systems and disconnectors/earth switches. The latter are of particular interest as for some utilities the maintenance programme for disconnectors and earth switches is driven by the associated circuit breaker to co-ordinate resources and minimise circuit outages. Apart from understanding the critical failure modes, utilities will be keen to understand if resources can be co-ordinated in the same manner because if this is not the case there could be a significant economic impact.

8.3.5 Sensitivity Studies of Existing Data Sets

As detailed in Chapter 6, use had to be made of a donor set of data due to the lack of component failure information for a circuit breaker. Consequently, there is an opportunity to undertake further research by carrying out sensitivity studies on the current data to understand how this could influence the results. Furthermore, this sensitivity work could be extended to the Markov models, particularly to the probability rates that are relying on the judgement of a domain expert.

Appendix

A1. RCM Worksheets

Failure Functions of a Circuit Breaker

Failure Function	Failures Modes
1. To interrupt current up to a value in compliance with Note 1	A. Fails to open on command
	B. Opens but fails to interrupt up to specified value
2. To make current up to a value in compliance with Note 1	A. Fails to close on command
	B. Closes but fails to conduct up to specified value
3. To continuously carry load current up to value in compliance with Note 1	A. Opens without command
	B. Fails to maintain contact
4. To ensure the gas leakage rate is no more than 0.5% per annum (pa)	A. Fails to contain gas
	B. Leakage rate greater than 0.5% pa
5. To ensure safety of operation	A. Fails to contain moving parts

	B. Fails to prevent porcelain insulators shattering
6. To provide insulation in compliance with Note 1	A. Fails to provide insulation to ground in compliance with Note 1
	B. Fails to provide insulation across the open interrupter gap in compliance with Note 1
	C. Closes without command
7. To indicate correct open/close indication	A. Fails to indicate correct local open indication
	B. Fails to indicate correct remote open indication
	C. Fails to indicate correct local close indication
	D. Fails to indicate correct remote close indication
8. To indicate correct spring charged/discharged indication	A. Fails to indicate correct local springs charged indication
	B. Fails to indicate correct local springs discharged indication
	C. Fails to indicate correct remote springs charged indication
	D. Fails to indicate correct remote springs discharged indication
9. To prevent a closure when circuit breaker already closed	A. Failure of mechanical interlock
	B. Failure of anti-pumping device
10. To indicate gas density correctly in compliance with Note 1	A. Gauge reading outwith lower tolerance level as specified in Note 1
	B. Gauge reading outwith upper tolerance level as specified in Note 1

	C. Gauge failure
11. To charge close springs in compliance with Note 1	A. Failure to charge close springs
	B. Failure to charge springs to 100%
12. To display circuit breaker SF_6 lockout alarm in compliance with Note 1	A. Failure to display circuit breaker lockout alarm
	B. Circuit breaker lockout alarm incorrectly displayed
	C. Circuit breaker lockout alarm operates outwith upper tolerance level
	D. Circuit breaker lockout alarm operates outwith lower tolerance level
13. To display circuit breaker SF_6 falling alarm in compliance with Note 1	A. Failure to display SF_6 falling alarm
	B. SF_6 falling alarm incorrectly displayed
	C. SF_6 falling alarm operates outwith upper tolerance level
	D. SF_6 falling alarm operates outwith lower tolerance level
14. To display the correct number of circuit breaker operations	A. Fails to register number of operations

Note 1: ScottishPower specification for 300kV breakers [SP, 2002e] and IEC 62271-100 [IEC 62271-100, 2001].

Failure Modes of Circuit Breaker

Failure Function	Failures Modes
1A. Fails to open on command	1. Mechanism linkage failure*
	2. Trip latch assembly stuck due to lack of lubrication
	3. Trip coil/magnet burnt out
	4. External circuit open circuit
	5. Trip spring assembly failure*
	6. Seal failure – CB operation blocked due to low gas density
	7. Heater failure – mechanism cabinet below required temperature*
	8. Mechanism bearings – lack of lubrication*
1B. Opens but fails to interrupt up to specified value	1. Blast nozzle worn
	2. Piston valves - lack of lubrication*
	3. Blast cylinder damaged*
	4. Seal leakage - low gas density
	5. Over damping - damper corroded*
	6. Mechanism out of adjustment*
	7. Main drive bearings worn
	8. Trip spring bearings worn
	9. Trip spring beyond useful working life*
	10. Over damping - wrong fluid*
	11. Contacts worn
	12. Tulip contact worn
	13. Tulip contact springs broken *
	14. Contact rod worn

	15. Contact springs broken*
	16. Trip latch worn
	17. Trip latch assembly - lack of lubrication
	18. Trip spring broken*
	19. Trip bearings corroded*
	20. Main drive bearings corroded*
	21. Fault level above specified value*
	22. Loss of damper fluid - seal failure
	23. Latch hits backside of cam - cam in incorrect position
	24. Control voltage below 70% of nominal*
2A. Fails to close on command	1. External circuit open circuit
	2. Close latch assembly seized due to lack of lubrication
	3. Mechanism linkage failure*
	4. Main drive bearings seized – corroded*
	5. Main drive bearings worn
	6. Idler gear seized – corroded*
	7. Closing shaft failure*
	8. Closing shaft bearing worn
	9. Circuit breaker rebounds – cam worn
	10. Close coil/magnet burnt out
	11. Close spring assembly failure*
	12. Close spring beyond useful working life*
	13. Close spring not fully charged*
	14. Control voltage below 85% of nominal value*

2B. Closes but fails to conduct current up to specified value	1. Contacts worn
	2. Contact finger failure*
	3. Contact spring failure*
	4. Failure of linkage*
	5. Closing current above specified value*
3A. Opens without command	1. External circuit failure – mutual induction*
	2. Trip latch assembly loose*
	3. Trip latch assembly corroded
	4. Trip magnet faulty*
	5. Trip latch – lack of lubrication
3B. Fails to maintain contact	1. Contacts worn
	2. Incorrectly set up*
	3. Contact springs broken*
	4. Contact finger failure*
4A. Fails to contain gas	1. Cracked porcelain – External damage*
4B. Leakage rate greater than 0.5% per annum (pa)	1. Enclosure seal brittle
	2. Gas density transducer seal brittle
	3. Enclosure flange corrosion*
	4. Gas density valve corroded*

	5. Gas connection seal brittle
	6. Gas connection valve corroded*
	7. Gas pipework joints corroded
5A. Fails to contain moving parts	1. Mechanism cover left off*
5B. Fails to prevent porcelain insulators shattering	1. Porcelain cracked through external damage*
	2. Porcelain electrical strength degraded through age*
	3. Contacts worn
6A. Fails to provide insulation to ground in compliance with Note 1	1. Presence of foreign particles/moisture
	2. Absorber needs replaced
	3. Porcelain contaminated by pollution*
6B. Fails to provide insulation across the open interrupter gap in compliance with Note 1	1. Presence of foreign particles/moisture
	2. Contact failure*
	3. Contact rod failure*
	4. Tulip contact failure*
6C. Closes without command	1. External circuit failure – mutual induction*
	2. Close latch assembly loose*

	3. Close latch assembly corroded
	4. Crank operating lever failure*
	5. Close latch – lack of lubrication
7A. Fails to indicate correct local open indication	1. Indication drive mechanism pin loose*
	2. Indication drive mechanism failure*
7B. Fails to indicate correct remote open indication	1. Indication drive mechanism pin loose*
	2. Indication drive mechanism failure*
	3. Open auxiliary switch failure
7C. Fails to indicate correct local close indication	1. Indication drive mechanism pin loose*
	2. Indication drive mechanism failure*
7D. Fails to indicate correct remote close indication	1. Indication drive mechanism pin loose*
	2. Indication drive mechanism failure*
	3. Close auxiliary switch failure
8A. Fails to indicate correct local springs charged indication	1. Indication drive mechanism pin loose*
	2. Indication drive mechanism failure*
8B. Fails to indicate correct local springs discharged indication	1. Indication drive mechanism pin loose*

	2. Indication drive mechanism failure*
8C. Fails to indicate correct remote springs charged indication	1. Indication drive mechanism pin loose*
	2. Indication drive mechanism failure*
	3. Motor limit switch failure – stuck open
8D. Fails to indicate correct remote springs discharged indication	1. Indication drive mechanism pin loose*
	2. Indication drive mechanism failure*
	3. Motor limit switch failure – stuck closed
9A. Failure of mechanical interlock	1. Drive mechanism pin loose*
	2. Drive mechanism failure*
9B. Failure of anti-pumping device	1. External circuit failure – open circuit
10A. Gauge reading outwith lower tolerance level as specified in Note 1	1. Accuracy drift over time
10B. Gauge reading outwith upper tolerance level as specified in Note 1	1. Accuracy drift over time
10C. Gauge failure	1. Seal brittle - leaking
	2. Gauge corroded*

11A. Failure to charge close springs	1. Spring charge motor burnt out*
	2. Spring charging external circuit failure – open circuit
	3. Spring charging gearing worn
	4. Spring charging gearing lack of lubrication
	5. Spring charging gearing loose*
	6. Spring charging gearing corroded
11B. Failure to charge close springs to 100%	1. Spring charging gearing lack of lubrication
	2. Spring charging gearing loose*
	3. Spring charging gearing worn
12A. Failure to display circuit breaker lockout alarm	1. Contact failure – stuck open
12B. Circuit breaker lockout alarm incorrectly displayed	1. Contact failure – stuck closed*
12C. Circuit breaker lockout alarm operated outwith upper tolerance level	1. Accuracy drift over time
	2. Incorrectly set*
12D. Circuit breaker lockout alarm operated outwith lower tolerance level	1. Accuracy drift over time
	2. Incorrectly set*

13A. Failure to display SF_6 falling alarm	1. Contact failure – stuck open
13B. SF_6 falling alarm incorrectly displayed	1. Contact failure – stuck closed*
13C. SF_6 falling alarm operates outwith upper tolerance limit	1. Accuracy drift over time
	2. Incorrectly set*
13D. SF_6 falling alarm operates outwith lower tolerance limit	1. Accuracy drift over time
	2. Incorrectly set*
14A. Fails to register correct number of operations	1. Counter failure*
	2. Mechanism linkage failure*

Note 1: ScottishPower specification for 300kV circuit breakers [SP, 2002e] and IEC 62271-100 [IEC 62271-100, 2001].

Note 2: * Denotes failure modes not progressed due to low probability of occurring.

RCM Failure Consequence and Task Selection Worksheet for the Interconnector Circuit Breaker

Failure Mode Reference No.	Failure Consequences	Maintenance Task	Maintenance Frequency	Responsibility for Task
1A2	Hidden	Monitor trip coil current. Switch CB.	1 year	GCC
1A3	Hidden	Monitor trip coil current. Switch CB.	1 year	GCC
1A4	Operational	Trip circuit supervision.	Continuously	GCC
1A6	Environmental	Monitor gas density.	Continuously	GCC
1B1	Hidden	Monitor Isqt (square of primary current).	Continuously	GCC
1B4	Operational	Trip circuit supervision.	Continuously	GCC
1B7	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
1B8	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
1B11	Hidden	Monitor Isqt.	Continuously	GCC

1B12	Hidden	Monitor Isqt.	Continuously	GCC
1B14	Hidden	Monitor Isqt.	Continuously	GCC
1B16	Hidden	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
1B17	Hidden	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
1B22	Hidden	Monitor travel curve.	1 year	GCC
1B23	Hidden	Monitor travel curve.	1 year	GCC
2A1	Hidden	Switch CB.	1 year	GCC
2A2	Hidden	Monitor motor close coil current. Switch CB.	1 year	GCC
2A5	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
2A8	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
2A9	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
2A10	Hidden	Monitor motor close coil current. Switch CB.	1 year	GCC

2B1	Safety	Monitor Isqt.	Continuously	GCC
3A3	Operational	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
3A5	Operational	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
3B1	Safety	Monitor Isqt.	Continuously	GCC
4B1	Environmental	Monitor gas density.	Continuously	GCC
4B2	Environmental	Monitor gas density.	Continuously	GCC
4B5	Environmental	Monitor gas density.	Continuously	GCC
4B7	Environmental	Monitor gas density.	Continuously	GCC
5B3	Safety	Monitor Isqt.	Continuously	GCC
6A1	Operational	Check gas quality.	10 years	Maintenance
6A2	Operational	Replace absorber.	20 years	Maintenance
6B1	Operational	Check gas quality.	10 years	Maintenance
6C3	Operational	Monitor travel curve. Switch CB.	1 year	GCC
6C5	Operational	Monitor travel curve. Switch CB.	1 year	GCC

7B3	Non-operational	Switch CB. Monitor CB indication.	1 year	GCC
7D3	Hidden	Switch CB. Monitor CB indication.	10 years	Maintenance
8C3	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
8D3	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
9B1	Hidden	Check anti pumping action.	10 years	Maintenance
10A1	Hidden	Calibrate gauge.	10 years	Maintenance
10B1	Hidden	Calibrate gauge.	10 years	Maintenance
10C1	Environmental	Monitor gas density.	Continuously	GCC
11A2	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
11A3	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC

11A4	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
11A6	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
11B1	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
11B3	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
12A1	Hidden	Calibrate gauge.	10 years	Maintenance
12C1	Hidden	Calibrate gauge.	10 years	Maintenance
12D1	Hidden	Calibrate gauge.	10 years	Maintenance
13A1	Hidden	Calibrate gauge.	10 years	Maintenance
13C1	Hidden	Calibrate gauge.	10 years	Maintenance
13D1	Hidden	Calibrate gauge.	10 years	Maintenance

Note: GCC denotes Grid Control Centre

RCM Failure Consequence and Task Selection Worksheet for Non-System Critical and Generator Circuit Breakers

Failure Mode Reference No.	Failure Consequences	Maintenance Task	Maintenance Frequency	Responsibility for Task
1A2	Hidden	Monitor trip coil current. Switch CB.	1 year	GCC
1A3	Hidden	Monitor trip coil current. Switch CB.	1 year	GCC
1A4	Operational	Trip circuit supervision.	Continuously	GCC
1A6	Environmental	Monitor gas density.	Continuously	GCC
1B1	Hidden	Replace Interrupter.	20 years	Maintenance
1B4	Operational	Trip circuit supervision.	Continuously	GCC
1B7	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
1B8	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
1B11	Hidden	Replace Interrupter.	20 years	Maintenance

1B12	Hidden	Replace Interrupter.	20 years	Maintenance
1B14	Hidden	Replace Interrupter.	20 years	Maintenance
1B16	Hidden	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
1B17	Hidden	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
1B22	Hidden	Monitor travel curve.	1 year	GCC
1B23	Hidden	Monitor travel curve.	1 year	GCC
2A1	Hidden	Switch CB.	1 year	GCC
2A2	Hidden	Monitor motor close coil current. Switch CB.	1 year	GCC
2A5	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
2A8	Hidden	Monitor travel curve. Switch CB.	1 year	GCC
2A9	Hidden	Monitor travel curve. Switch CB.	1 year	GCC

2A10	Hidden	Monitor motor close coil current. Switch CB.	1 year	GCC
2B1	Safety	Replace Interrupter.	20 years	Maintenance
3A3	Operational	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
3A5	Operational	Monitor trip coil current & travel curve. Switch CB.	1 year	GCC
3B1	Safety	Replace Interrupter.	20 years	Maintenance
4B1	Environmental	Monitor gas density.	Continuously	GCC
4B2	Environmental	Monitor gas density.	Continuously	GCC
4B5	Environmental	Monitor gas density.	Continuously	GCC
4B7	Environmental	Monitor gas density.	Continuously	GCC
5B3	Safety	Replace Interrupter.	20 years	Maintenance
6A1	Operational	Check gas quality.	10 years	Maintenance
6A2	Operational	Replace absorber.	20 years	Maintenance

6B1	Operational	Check gas quality.	10 years	Maintenance
6C3	Operational	Monitor travel curve. Switch CB.	1 year	GCC
6C5	Operational	Monitor travel curve. Switch CB.	1 year	GCC
7B3	Non-operational	Switch CB. Monitor CB indication.	1 year	GCC
7D3	Hidden	Switch CB. Monitor CB indication.	10 years	Maintenance
8C3	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
8D3	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
9B1	Hidden	Check anti pumping action.	10 years	Maintenance
10A1	Hidden	Calibrate gauge.	10 years	Maintenance
10B1	Hidden	Calibrate gauge.	10 years	Maintenance
10C1	Environmental	Monitor gas density.	Continuously	GCC

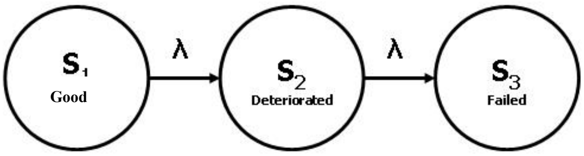
11A2	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
11A3	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
11A4	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
11A6	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
11B1	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
11B3	Operational	Switch CB. Monitor spring charging alarm.	1 year	GCC
12A1	Hidden	Calibrate gauge.	10 years	Maintenance
12C1	Hidden	Calibrate gauge.	10 years	Maintenance
12D1	Hidden	Calibrate gauge.	10 years	Maintenance
13A1	Hidden	Calibrate gauge.	10 years	Maintenance

13C1	Hidden	Calibrate gauge.	10 years	Maintenance
13D1	Hidden	Calibrate gauge.	10 years	Maintenance

Note: GCC denotes Grid Control Centre

B1. Solving a simple 3 state condition model using Laplace transforms

Derivation of time dependent probabilities, reliability and Mean Time To Failure (MTTF) of a three state system, shown in Figure B1.1, with state three set as an absorbing state (necessary for calculating MTTF).



where

S: A transition state of the system

Figure B1.1: Diagram of a simple three state condition model

With reference to Figure B1.1, the probability of being in states S1, S2 and S3 after a time interval δt is given by equations B1.1, B1.2 and B1.3, respectively:

$$P_1(t+\delta t) = (1-\lambda\delta t)\ P_1(t) \qquad \text{(B1.1)}$$

$$P_2(t+\delta t) = (1-\lambda\delta t)\ P_2(t) + \lambda\ P_1\delta t \qquad \text{(B1.2)}$$

$$P_3(t+\delta t) = \lambda P_2(t)\ \delta t\ + P_3(t) \qquad \text{(B1.3)}$$

where

$P_1(t + \delta t)$: the probability of being in state S_1 after time interval δt

$P_2(t + \delta t)$: the probability of being in state S_2 after time interval δt

$P_3(t + \delta t)$: the probability of being in state S_3 after time interval δt

λ: the process failure rate

Rearranging equations B1.1, B1.2 and B1.3 yields:

$$\frac{P_1(t+\delta t) - P_1(t)}{\delta t} = -\lambda \ P_1 \tag{B1.4}$$

$$\frac{P_2(t+\delta t) - P_2(t)}{\delta t} = -\lambda \ P_2 + \lambda \ P_1 \tag{B1.5}$$

$$\frac{P_3(t+\delta t) - P_3(t)}{\delta t} = \lambda \ P_2 \tag{B1.6}$$

If δt becomes sufficiently small then this linear approximation of the function can be expressed as a differential. The three resulting differential equations are best summarised in matrix form:

$$\lfloor P'_1(t) \quad P'_2(t) \quad P'_3(t) \rfloor =$$

$$\begin{bmatrix} -\lambda & \lambda & - \\ - & -\lambda & \lambda \\ - & - & - \end{bmatrix} \times \left[P_1(t) \quad P_2(t) \quad P_3(t) \right] \tag{B1.7}$$

In order to solve more easily, firstly transform into the s-domain:

$$sP_1(s) - P_1(0) = -\lambda P_1(s) \tag{B1.8}$$

$$sP_2(s) - P_2(0) = +\lambda P_1(s) - \lambda P_2(s) \tag{B1.9}$$

$$sP_3(s) - P_3(0) = +\lambda P_2(s) \tag{B1.10}$$

Assuming the initial conditions at time t=0 are $P_1(0)$=1, $P_2(0)$=0 and $P_3(0)$=0, then:

$$sP_1(s) - 1 = -\lambda P_1(s) \tag{B1.11}$$

and $(s+\lambda) \ P_1(s) = 1$ (B1.12)

Similarly:

$$sP_2(s) + \lambda P_2(s) = \lambda P_1(s) \tag{B1.13}$$

and

$$(s+\lambda)\ P_2(s) = \lambda P_1(s) \tag{B1.14}$$

and

$$sP_3(s) = \lambda P_2(s) \tag{B1.15}$$

Rearranging the above expressions yields:

$$P_1(s) = \frac{1}{(s+\lambda)} \tag{B1.16}$$

$$P_2(s) = \frac{\lambda}{(s+\lambda)} P_1(s) \tag{B1.17}$$

$$P_3(s) = \frac{\lambda}{s} P_2(s) \tag{B1.18}$$

Substitute (B1.16) into (B1.17):

$$P_2(s) = \frac{\lambda}{(s+\lambda)} \times \frac{1}{(s+\lambda)} \text{ or } P_2(s) = \frac{\lambda}{(s+\lambda)^{2}} \tag{B1.19}$$

Convert expressions for P_1 and P_2 from s-domain back to time domain using Laplace transforms:

$$P_1(t) = e^{-\lambda t} \tag{B1.20}$$

$$P_2(t) = \left[\frac{1}{(2-1)\,!} t^{2-1}\ e^{-\lambda t}\right]\lambda \text{ or } P_2(t) = \lambda\ t\ e^{-\lambda t} \tag{B1.21}$$

To form an expression for reliability, the time dependent probabilities for the functional states are summed:

$$\therefore\ R\ (t) = P_1(t) + P_2(t) = e^{-\lambda t} + \lambda\ t\ e^{-\lambda t} = (1+\lambda t)\ e^{-\lambda t} \tag{B1.22}$$

The mean time to failure (MTTF) is obtained by integrating the expression for reliability:

$$MTTF = \int_0^{\infty} R\left(t\right) \delta t$$

(B1.23)

$$MTTF = \left[-\frac{2}{\lambda}e^{-\lambda t} - t\ e^{-\lambda t}\right]_0^{\infty} = [0]^{\infty} - \left[-\frac{2}{\lambda}\right]^0$$

(B1.24)

$$\therefore\ MTTF = \frac{2}{\lambda}$$

(B1.25)

$$\therefore\ MTTF = \left[-\frac{1}{\lambda}e^{-\lambda t} + \lambda\frac{e^{-\lambda t}}{\lambda^2}\left(-\lambda t - 1\right)\right]_0^{\infty}$$

(B1.26)

$$= \left[-\frac{1}{\lambda}e^{-\lambda t} - t\ e^{-\lambda t} - \frac{1}{\lambda}e^{-\lambda t}\right]_0^{\infty}$$

(B1.27)

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