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Enhancing Transient Performance of Microgeneration-dense Low Voltage Distribution Networks

By

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ABSRACT

In addition to other measures such as energy saving, the adoption of microgeneration driven by renewable and low carbon energy resources is expected to have the potential to reduce losses associated with producing and delivering electricity, combat climate change and fuel poverty, and improve the overall system performance. However, incorporating a substantial volume of microgeneration within a system that is not designed for such a paradigm could lead to conflicts in the operating strategies of the new and existing centralised generation technologies. So it becomes vital for such substantial amounts of microgeneration among other decentralised resources to be controlled in the way that local constraints are mitigated and their aggregated response supports the wider system. In addition, the characteristic behaviour of connected microgeneration requires to be understood under different system conditions to ascertain measures of risk and resilience, and to ensure the benefits of microgeneration to be delivered.

Therefore, this thesis provides three main valuable contributions to future attainment of sustainable power systems. Firstly, a new conceptual control structure for a system incorporating a high penetration of microgeneration and dynamic load is developed. Secondly, the resilience level of the host distribution network as well as the resilience levels of microgeneration during large transient disturbances is evaluated and quantified. Thirdly, a technical solution that can support enhanced transient stability of a large penetration of LV connected microgeneration is introduced and demonstrated.

A control system structure concept based on “a cell concept” is introduced to manage the spread of heavy volumes of distributed energy resources (DERs) including microgeneration such that the useful features of DER units in support of the wider system can be exploited, and the threats to system performance presented by significant connection of passive and unpredictable DERs can be mitigated. The structure also provides simpler and better coordinated communication with DERs by allowing the inputs from DERs and groups of cells to be transferred as collective actions when it moves from a local to a wider system level.

The anticipated transient performance problems surrounding the integration of microgeneration on a large basis within a typical urban distribution network are addressed. Three areas of studies are tackled; the increased fault level due to the presence of microgeneration, the collective impact of LV connected microgeneration on traditional LV protection performance, and the system fault ride through capabilities of LV connected microgeneration interfaced by different technologies. The possible local impacts of unnecessary disconnection of large amount of microgeneration on the performance of the host distribution network are also quantified.

The thesis proposes a network solution based on using resistive-type superconducting fault current limiters (RSFCLs) to prevent the impact of local transient disturbances from expanding and enhance the fault ride through capabilities of a high penetration of microgeneration connected to low voltage distribution networks. A new mathematical approach is developed within the thesis to identify at which condition RSFCL can be used as a significant device to maintain the transient stability of large numbers of LV connected microgeneration. The approach is based on equation solution to determine the minimum required value of the resistive element of RSFCL to maintain microgeneration transient stability, and at the same time additional headroom against switchgear short-circuit ratings is provided. Remote disturbances or a failure to clear remote faults quickly are shown to no longer result in complete unnecessary disconnection of substantial amounts of microgeneration.

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List of symbols

I_{mf}	The peak value of the ac short circuit current
I_{ms}	The steady state fault current
α	The initial system voltage angle
$\theta^{'}$	The impedance angle prior to the short circuit
θ	The short circuit impedance angle
X_l	The reactance between the sources and the fault point
R	The resistance between the sources and the fault point
τ	The decay time constant of the DC component
C	The voltage correction factor
$X_d^{'}$	The transient impedance
X_d	The steady state impedance
Z_s	Equivalent short circuit impedance
R_s	Resistance of the grid source
X_s	Reactance of the grid source
P_L	The load real power
P_o	The rated real power per phase
V_L	The load voltage
V_o	The rated load voltage (RMS, L-G)
a	The voltage index for real power
K_{pf}	The frequency index for real power
Q_L	The equivalent load reactive power
Q_o	The rated reactive power per phase
b	The voltage index for reactive power
K_{qf}	The frequency index for reactive power
Δf	The frequency deviation $(f - f_o)$
f	The measured frequency
f_o	The reference frequency (i.e. 50Hz)
ω_r	The asynchronous machine rotor angular velocity (rad/s)
ω_s	The stator angular velocity (rad/s)
s	The per unit slip speed of a asynchronous machine rotor
ψ	The flux linking of the winding indicated by subscript
R_s	The stator phase resistance of asynchronous machine
p	The differential operator d/dt

V_s	The single phase ac source
R_m, R_a	The main and auxiliary resistances
X_m, X_a	The main and auxiliary reactances
i_m	The current in the main winding
i_a	The current in the auxiliary windings
N	The ratio of the number of the auxiliary/main turns
V_{ds}, V_{dr}	d-axis stator and rotor voltages
V_{qs}, V_{qr}	q-axis stator and rotor voltages
R_{ms}, R_{as}	main winding and auxiliary winding stator resistance
R_{mr}, R_{ar}	main winding and auxiliary winding rotor resistance
ψ_{ds}, ψ_{dr}	d-axis stator and rotor flux linkage components
ψ_{qs}, ψ_{qr}	q-axis stator and rotor flux linkage components
ω_r	electrical angular velocity
P	The air density
A	The area swept by the propellers
V	The average wind speed
Rfcl	The FCL resistance
Vs	The system RMS voltage
ΔT	The maximum permissible temperature rise
Δt	The fault duration
ρ, th, and *w*	The resistivity, thickness and width of the superconductor
Cp	The effective specific heat of the superconductor
Vg	The grid voltage
Vth	The retained voltage at the microgeneration terminals
Rg, Xg	The resistance and the reactance of the grid source
Rfcl	The developed resistance of the fault current limiter
$R_{fcl\,\min}$	The minimum value of the resistance element of RSFCL
T_e	The developed electrical machine torque
T_m	The mechanical torque
S_{cr}	Maximum slip (i.e. critical slip)
X_m	The machine magnetization reactance
$T_d^{''}$	Sub-transient time constant
$T_d^{'}$	Transient time constant
T_a	The periodic time constant
$T_s^{''}$	The sub-transient stator time constant
σ	The total leakage coeffieceint
$T_r^{''}$	The sub-transient rotor time constant

List of abbreviations

AC	Advisory Council of the technology platform for the electricity Networks of the future in Europe
BERR	Department for Business Enterprise & Regulatory Reform
CHP	Combined Heat and Power
DECC	The UK Department of Energy and Climate Change
DTI	the Department of Trade and Industry of the UK
DG	Distributed Generation
DOE	Department of Energy of US
DSM	Demand side management
DLTDS	Distribution long term development statement
ETP	the European Technology Platform
EC	European Commission
EHV	Extremely High Voltage
EIA	the Energy Information Administration US
ETS	Emissions Trading Schemes
ETP	European Technology Platform Smart Grids
FCL	Fault Current Limiter
FiT	Feed-in Tariffs
GSP	Grid Supply Point
GHG	Greenhouse gas
HDPS	Highly Distributed Power Systems
HV	High Voltage
IEC	the International Electrotechnical Commission
IEA	International Energy Agency
IPRI	the Electric Power Research Institute
LV	Low voltage
MV	Medium Voltage
OC	Over Current
PV	Photovoltaic
PCC	the Point of Common Coupling
RSFCL	Resistive Superconducting Fault Current Limiter
RPS	The Renewable Portfolio Standards
RMU	Ring Main Units
RES	Renewable Energy Sources
SFCL	Superconducting Fault Current Limiter
TSO	Transmission System Operator
UKGDS	UK generic distribution system

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Chapter One: Introduction

1.1 Background

Traditional power systems are undergoing a significant transformation and face numbers of issues such as; the possible rapid increase in the global demand where the demand is expected to reach 60% increase in the next 30 years compared to the current demand [1.1], the international growing awareness of the environmental impacts due to large-scale thermal generating plants, and the international concern over the limitation of global primary energy sources. It is expected that the remaining recoverable oil resources for example will represent only 60 years of production according to the World Energy Technology Outlook- 2050 [1.1][1.2]. In addition to these issues, there is also an increasing attention on reliability and security of power systems to minimise the frequent of the recent major blackouts occurred at different parts of the world in the last decade while dealing with aging infrastructure [1.3][1.4][1.5].

To deal with such challenges, traditional power systems would expect to experience numbers of changes. The major aspects that may influence the shape of the changes are: the connection of renewable and low carbon sources to the existing power systems, and the deployment of efficiency measures within the systems for saving energy. For example, it is expected that a wider usage of renewable and low carbon energy generation can be integrated at distribution networks and at electricity use points in order to reduce the reliance upon the large power plants, providing more reserve capacity, and potentially reducing carbon emission and providing some ancillary services that can support the system. Also the level of improving the efficiency across all power system sectors including production, transmission, distribution, and consumption may be required so losses can be reduced and saving in energy can be obtained [1.1].

In addition, at consumers' points, the change in the load response from only passive to more active, the connection of small scale embedded resources such as microgeneration, and carbon-lean transportation could limit the energy waste and provide a significant efficiency improvement [1.6]. Also the heat generated by decentralised electricity production can be used for space and water heating [1.6]. The potential exists for plug-in Electric Vehicles to offer spinning reserves and some other ancillary services [1.7].

Significant international attention has been given to setting targets to provide a significant amount of the electricity generation from renewable and highly efficient energy sources. For example, the UK and other European governments have set a demanding target to provide considerable amount of their electricity consumption from such forms of energy sources [1.8][1.9]. In addition the renewable portfolio standards (RPS) which is provided by the US Environmental Protection Agency have established requirements for electric utilities and other retail electric providers to serve a specified minimum percentage or absolute amount of customer consumption with eligible sources of renewable electricity [1.10].

The EU has set a target to make the share of renewable energy sources (RES) to provide EU electricity to reach 20% of energy in 2020 and 60% by 2050, and this was already adopted by the EU's climate change legislation in December 2008 [1.11][1.12]. Alongside the EU, the UK government has set mid and long-term national targets which aim to cut CO2 emissions by 26% by 2020 and up to 80% by 2050 compared to 1990 levels, and renewable and low carbon energy sources are expected to significantly contribute to meet these targets [1.13][1.14]. According to the UK Renewable Energy Strategy report which was published in July 2009 by the UK Department of Energy and Climate Change (DECC) [1.15], the UK needs to meet 15% of its total energy by RES by 2020 to meet the country 2020 target of carbon reduction. For long term, the study commissioned by the Department of Trade and Industry (DTI) of the UK from the Energy Saving Trust has suggested that 30-40% of the UK’s electricity demands should be met through microgeneration technologies connected to distribution networks by 2050 to meet the UK’s 2050 target [1.16].

However, existing distribution power systems are designed and viewed as a passive portion of the grid system with very limited automation and controllability especially at lower voltages. So far, their main task has been to deliver the available electricity from the generation and transmission systems to the electricity users without expecting any reverse power flow and participation from the users to the system operation. Therefore, increasing the volume of connected microgeneration and increased deployment of energy efficiency measures which can be called distributed energy resources (DERs) to curb carbon emissions and conserve energy resources, will change the reaction of the distribution systems to the wider system, and hence impact the operational structure of the traditional power systems. The system generation capacity will comprise of centralised generation and high densities of distributed generation including microgeneration. A new picture of many active loads supplied by many sources (i.e. including centralised and decentralised generation) will emerge, in contrast to the traditional systems with many passive loads supplied by few sources.

New decentralised generation such as microgeneration which are normally consumer-led rather than centrally planned, may lead to conflicts in the operating strategies of the new and existing centralised generation technologies. For example, exporting power from the distribution to the transmission system may result in the transmission system operators having less control of generation dispatch when the export is taking place. Therefore, it becomes vital for substantial amounts of microgeneration among other decentralised resources to be controlled in the way they will benefit the consumers and their aggregated response will support the wider system. This may require a rethink of a new system structure and operation strategies that would facilitate the transition from the conventional power systems to more efficient highly distributed power systems which are composed of many sources supplying many active loads.

There are numbers of visions that have been developed recently to describe the future changes in power systems, and facilitate the transformation to more decentralised power systems that can perform better. One example is the “IntelliGrid” vision which has been created by the Electric Power Research Institute’s (EPRI’s) for future North America power grids to support the 21st century economy in the state with extreme benefits in reliability, capacity, and advanced customer services [1.17]. Another example is the “SmartGrid” vision which is developed by European Commission - Smart Grids

Technology Platform for the Europe future electricity networks for year 2020 and beyond [1.18]. These visions are based on the characteristics of a future power grid and what the grid should accommodate and offer to meet the future policy objectives. At the moment the visions do not adequately provide recommendations for a physical system structure that can clearly show how the future changes (i.e. DERs) can be fitted in distribution networks, and the controls of the networks can be structured in the way that the benefits from local generation and active demand can be maximised. Therefore, one issue that has not been addressed is the requirement for a flexible system structure concept that facilitates the utilisation of local generation and controllable demand to provide both benefits for consumers and system operation.

In addition, there is an issue of understanding the performance of a system incorporating a large population of DERs including microgeneration under different system conditions to ascertain measures of risk and resilience. A number of previous studies have investigated the technical issues surrounding the connection of a large number of microgenerators in small areas of distribution networks. The studies such as those reported in [1.19] and [1.20], amongst others as in [1.21] and [1.22] were primarily aimed at addressing steady or pseudo-steady-state conditions. The transient performance of distribution systems incorporated with a large penetration of LV connected microgeneration under fault conditions has not received much attention as its important merits.

During fault conditions both microgeneration and the host distribution network are under stress and each of them has a different impact on the performance of the other. A high penetration of LV connected microgeneration may impact the host network by providing a new source of short-circuit current. The source will contribute to the network fault level, and if the network short-circuit rating which normally consists of three categories with different time scales; sub-transient, transient, and steady state is exceeded, then damage to the network equipments may result. In addition, the impact of the new source of short-circuit current may impact the main performance criteria of the host network protection schemes, where traditional schemes have been designed with no consideration of adding generation at distribution level, and the fault source is always considered as upstream to the fault. If the protection main criteria are impacted due to microgeneration integration, then lower reliability, lower sensitivity, and even reduction in power quality by lowering the protection selectivity may result [1.23]. Therefore, understanding the influence of a high density of LV connected microgeneration on the host network performance under fault conditions is vital.

The protection performance of the host distribution network during fault conditions (i.e. how fast the fault would be cleared) will influence significantly the capability of microgeneration to remain connected following system transient disturbances. System transient disturbances can be caused by different events such as losing large amount of generation or loads, or due to a fault on the system. All these events may impact the transient stability of the system, but disturbances caused by faults are normally more severe compared to the others where the affected areas will experiences large voltage dips. Transient stability issues at distribution level were formerly insignificant before microgeneration began to be connected at low voltages. The connection of a large number of microgenerators to LV systems may alter their transient behaviour. This may become a significant issue because of the following reasons; one is the nature of the microgeneration with very small inertia and poor inherent damping compared to large machines. This in turn will increase highly the sensitivity of the microgeneration to faults on the system including remote faults. The other reason is the performance of the host distribution networks which may not support the fault ride through capabilities of microgeneration. For example, protection schemes at distribution level are normally based on coordinating the operating times of the protective devices, where downstream elements will respond to faults faster than upstream. So for some remote faults, upstream protection devices may clear the faults within a time not small enough to support the transient stability of microgeneration at downstream.

Therefore, this thesis offers two main valuable areas of contributions to support future achievement of sustainable power systems: one is the proposal of a conceptual system structure which can facilitate the active utilisation of local distributed energy resources by which the overall system operation can be improved and local system constraints are mitigated. The other is a technical work that provides an understanding of how such a system with a high penetration of microgeneration will behave under fault conditions and what can be done to improve the performance of such a system under transient disturbance caused by a fault on the hosted system. Within the technical work the resilience level of the host distribution network as well as the resilience levels of LV connected microgeneration during large transient disturbance is quantified. Furthermore, a network focused technical solution that can support enhanced transient stability of a large penetration of LV connected microgeneration is introduced and demonstrated.

The thesis proposes a "cell" concept as one of the solutions that can help to manage the spread of heavy volumes of distributed energy resources (DERs) including microgeneration such that benefits are maximised and the host system is supported under different operating conditions. The cell concept that has been developed in this thesis is different from the Danish cell that has been introduced, and based on the value of islanding and black start of active distribution networks [1.24]. The benefits of a system structure based on the cell concept developed in this thesis can be divided into two main facets. One is the possibility of exploiting the useful features of DER units in support of the wider system. This could help mitigate the threats to system performance presented by negative impacts caused by significant connection of DERs such as the impact on the local system voltage profile, the system fault level, and the system protection performance. The other is simpler and better coordinated communication with DERs by building the system in hierarchical structure and allowing the inputs from DERs and groups of cells to be transferred as collective actions when it moves from the consumer level to wider system level.

In addition, to achieve safe operation and in order to avoid stressing the network, the thesis studies the sources of the technical problems that could emerge when typical distribution networks are incorporated with large numbers of small scale microgeneration and the system is operating under fault conditions. Based on the output of the studies practical means to mitigate the problems are introduced in the thesis. Two areas of studies are considered in the thesis from two different angles. One studies the potential impact of integrating a high penetration of LV connected microgeneration on the performance of the host distribution network during transient fault conditions. This includes the contribution to the fault level of the host distribution networks made by integrated microgeneration, and the impact on the performance of traditional LV protection schemes. The other angle is by understanding the impact of the performance of the host distribution network on the transient performance of the connected microgeneration when the system is under the stress of faults. The possible local impacts of losing large amount of microgeneration on the performance of the host distribution networks are also investigated.

In order to cope with problems surrounding the local distribution system under fault conditions with the presence of a high penetration of LV connected microgeneration, and prevent the local disturbances from expanding, the thesis proposes the use of resistive-type superconducting fault current limiters (RSFCL) as a remedial measure that provides useful inputs for both the network performance and the microgeneration units during large transient disturbances. One input is mitigating the problems associated to the microgeneration transient stability issue, and the other is as a measure that can manage the fault level contribution made by microgeneration, and it helps avoiding the alternative costly solutions such as upgrading equipment or reconfiguring distribution networks.

Existing RSFCLs are designed mainly for fault current limitation purposes of a system with one source (i.e. mains) of fault currents without giving any consideration to the limiters capability to improve the system transient performance from the design perspective [1.25][1.26]. Therefore, the thesis in addition to other contributions develops a new analytical mathematical approach that can identify at which condition RSFCL can provide both additional headroom against distribution system switchgears short-circuit, and improved resilience level of a large penetration of LV connected microgeneration. The approach can be used to determine the minimum required value of the resistive element of RSFCL by which the transient stability of LV connected microgeneration can be maintained regardless the fault critical clearance time of the machines as an added function of RSFCL to its main function (i.e. limiting fault current).

The approach is validated by conducting informative transient studies by using detailed models of a small microwind turbine interfaced directly within residential dwellings by a single-phase induction generator, a transient model of RSFCL, and a typical LV distribution network with residential loads. The obtained results from the approach are considered acceptable, and the advantages of the analytical method outstrip the observed disadvantages.

1.2 Summary of the thesis main contributions

- A new system control structure based on a cell concept that can provide a flexible physical structure for managing a system incorporating a high penetration of microgeneration and dynamic loads in response to numbers of particular objectives such that benefits are maximised and the host system is supported under different operating conditions is proposed. The concept is based on a hierarchical structure that can form the host distribution networks as aggregated or further subdivided in order to exploit the useful features of DERs in support of the wider system, and mitigate local constraints. In addition, the cell concept gives an indication of who can control the grid at different voltage levels based on the cells hierarchical boundaries. The proposed cell concept functions are driven by numbers of allocated objectives that can provide numbers of useful contributions for delivering the “Smart Grid” objectives, where other alternative concepts with limited objectives such as “Danish Cell” is driven only by the value of islanding and black start operation [1.24].

- The impact of microgeneration performance on a local performance of a typical LV distribution network during fault conditions is assessed, and the level of the problems is evaluated. The increase in the fault level of a typical UK urban distribution network example due to the connection of a different penetration of LV connected microgeneration is quantified. Also at which locations of an urban MV/LV distribution network and at which penetration of microgeneration the increased fault level may become a problem is identified. Furthermore, the influence of a high population of LV connected microgeneration on the main low voltage protection schemes criteria is quantified. This considers the impact of microgeneration presence on the correct operation of LV protection (i.e.

reliability, when to operate and when not to operate), and the LV protection graded setting (coordination or selectivity).

- The conditions under which circumstances that LV connected microgeneration will be unnecessarily tripped in response to realistic distribution network faults and when they can survive disturbances based on detailed transient models and informative transient studies are specified. The inherent capability and response of grid-connected microgenerators to maintain stability during and after clearing of both transient local and remote faults on the host system is quantified against different fault locations, typical fault clearance times and generator/prime mover technologies. The impacts of simultaneous unnecessary disconnection and deliberate reconnection of substantial amount of LV connected microgeneration interfaced by rotating machines on the host distribution systems performance are outlined. This can widen the knowledge and be considered as an added input to numbers of studies were primarily aimed at addressing steady conditions and did not explore the transient response to be expected from microgeneration.

- A technical solution by using the transient characteristics of a resistive-type superconducting fault current limiter (RSFCL) to enhance the transient stability of a large penetration of LV connected microgeneration and at the same time providing an additional headroom for distribution system fault level is introduced. This would help to improve the resilience level of active distribution networks and hence help to remove the barriers against the spread of microgeneration in the future. A new analytical approach that has a perceptible feasibility for identifying the minimum required resistance that needs to be reached by a resistive-type superconducting fault current limiter (RSFCL) to ensure the improvement of transient stability of LV connected microgeneration is introduced and validated. The approach is based on equation solution rather than on trial-and-error simulation studies, and therefore no longer dependent on digital transient simulation programs and detailed microgeneration transient models to identify the required characteristics of RSFCL to improve microgeneration ride through faults. Solution speed is therefore significantly improved, reducing time required for each investigation. The approach can also give an indication about the suitable RSFCL for different distribution systems based on the system parameters.

1.3 Thesis layout

Chapter two outlines major challenges and issues that are facing the current electric power systems. The major expected changes in future power systems from energy perspective are also discussed. A number of forward looking scenarios those considering the implementation of a high penetration of microgeneration in the future are also discussed within the chapter in order to project future changes in power systems. Within chapter two, a new system structure concept based on a cell concept is developed as means of delivering the objectives of decentralised future power systems. In addition, in order to understand the behavioural characteristics of active distribution networks and based on literatures, the most emerging technical issues due the presence of a high penetration of LV connected microgeneration during fault conditions that require further investigation are clearly outlined.

Chapter three investigates the factors that are more likely to influence the prospective fault level of a typical distribution network incorporating a high penetration of microgeneration. Based on these factors, detailed studies are conducted to test the impact of LV connected microgeneration with different penetration on fault levels of a typical urban distribution network. Two sizes of microgeneration with different penetration are included; domestic and commercial sizes. An aggregated model of different penetration of microgeneration with a careful consideration of the impact of the impedances of the cables between microgenerators connection points which have an impact on fault contribution is developed and used for the fault level investigations.

In chapter four the microgeneration integration impacts on LV protection performance are investigated in detail by using a typical MV/LV distribution network accommodating 100% penetration of microgeneration with respect to the local loads. The studies are conducted in terms of the influence on two emerging areas. One is the reduction in the reach that can be caused by a large penetration of microgeneration which can impact the sensitivity of the low voltage protection schemes. The other is the impact of the reverse fault current provided by LV connected microgeneration on the low voltage protection performance, which can lead to incorrect operation of low voltage protection that can be result due to the impact on the selectivity of the protection.

Chapter five contains the issues surrounding the transient stability of microgeneration using small rotating AC machines in response to representative network transients. An introduction to the transient stability issue is given, followed by outlining why microgeneration transient stability is an important area to consider. A set of microgenerators transient models with different generator/prime mover technologies is developed to be used as part of the transient studies. The impact of different fault locations, typical fault clearance times, and generator/prime mover technologies on the ability of microgenerators to maintain stability when the system is subject to different local and remote faults is investigated in details. In addition, in order to examine the consequence of transient instability of microgeneration, the voltage step changes due to the simultaneous disconnection and reconnection of a large number of microgenerators within a small area of LV distribution network are also evaluated in the chapter.

Chapter six investigates the advantages of the usage of the transient characteristics of RSFCL as a remedial measure to improve the transient performance of large amount of LV connected microgeneration. The main operation principles of RSFCL are also given. In addition, a new analytical method that can maintain large amount of single-phase grid-excited induction microgenerators regardless the machines critical fault clearance times is introduced, and the effectiveness of the method is tested. The test is accomplished by determining the minimum required resistance parameter of RSFCL device that ensures the microgeneration fault ride through capabilities by using the proposed analytical approach which is based on equation solution. The results are validated by detailed transient stability studies conducted by digital simulation programs including detailed microgeneration transient models.

The conclusions and future work based on the work presented in the thesis are drawn in chapter seven.

1.4 List of Publications

The following papers were published during the course of this research:

1 **A.S. Emhemed**, R. M. Tumilty, N. Sing, G. M. Burt, & J. McDonald, "Analysis of Transient Stability Enhancement of LV Connected Induction Microgenerators by Using Resistive-Type Fault Current Limiters", IEEE Transactions on Power Systems, Vol. 25, No.2, pp. 885-895, May 2010.

2 **A.S. Emhemed**, R.M. Tumilty, and G.M. Burt, "Supporting transient stability in future highly distributed power systems", PAC World Conference, Dublin, 21-24 June 2010.

3 **A.S. Emhemed**, R. M. Tumilty, N. Sing, B. M. Burt, & J. McDonald, "Improving the Transient Performance of a High Penetration of LV Connected Microgeneration", IEEE/PES General Meeting, 2009 IEEE, Calgary, Canada, 26-30 July 2009.

4 **A.S. Emhemed**, R. M. Tumilty, G. Burt, & S. Galloway, N. Sing , "Improving the Transient Performance of LV Connected Microgeneration within Highly Distributed Power Systems (HDPS)", 1st International Conference on Sustainable Power Generation and Supply, Nanjing, China. April 2009.

5 **Emhemed, A.S**.; Tumilty, R.M.; Burt, G.M.; McDonald, "Transient performance analysis of low voltage connected microgeneration"; Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE 20-24 July 2008.

6 **Emhemed, A.S**.; Tumilty, R.M.; Burt, G.M.; McDonald, J.R, "Transient performance analysis of single-phase induction generators for microgeneration applications", 4th IET Conference on Power Electronics, Machines and Drives, York, UK. PEMD 2008, pp. 345 – 349, 2-4 April 2008.

7 **A.S. Emhemed**, R.M. Tumilty, O. Anaya-Lara, G.M. Burt, J.R. McDonald, "Impacts of high penetration of single-phase distributed energy resources on the

protection of LV distribution networks", 42nd International Universities Power Engineering Conference, UPEC 2007, Brighton, pp. 223 – 227, 4-6 Sept. 2007.

8 R.M. Tumilty, **A.S. Emhemed**, O. Anaya-Lara, G.M. Burt, J.R. McDonald, "Adaptive Unit Based MV Protection for Actively Managed Distribution Networks", IEEE –RVP, Acapulco, Mexico July 2007.

9 Adel Hamad Rafa, Olimpo Anaya-Lara, Ryan Tumilty, **Abdullah Emhemed**, Gustavo Quinonez-Varela, Graeme Burt and James R. McDonald, "Stability Assessment of Microgeneration Systems", IEEE –RVP, Acapulco, Mexico July 2007.

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11 R.M. Tumilty, **A.S. Emhemed**, Adel Rafa, O. Anaya-Lara, G.M. Burt, "Microgeneration Transient Stability Investigation Report". July 2007, DTI/UGEN/TR/2007-001, DTI/ UK centre for sustainable electricity & distributed generation.

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Chapter Two: Moving towards decentralised power systems

2.1 Introduction

This chapter discusses and outlines the major challenges and issues that are facing traditional power systems, followed by evaluating the major future changes from energy perspective that electric power systems may experience in order meet the policy objectives and overcome the issues impacting traditional power systems. The chapter also explores the differences and the similarities between numbers of different visions of decentralised future power systems driven by different factors and opportunities. A new system structure based on a cell concept is developed as means of delivering the objectives of decentralised future power systems, and the most emerging technical areas during fault conditions require further investigation in terms of integrating large amount of microgeneration are outlined in order to assess the behavioural characteristics of the cell concept.

2.2 Traditional power systems

Traditional power systems are normally based on large remote power plants producing most of the required electric power, and then the power is transferred toward the users over long transmission lines. This paradigm is sketched as in Figure 2- 1, where the large power plants are connected through a set of step-up transformers to meshed and interconnected transmission networks. Transmissions networks are then stepped down and connected to distribution systems where the electricity is distributed and used. Transmission networks are commonly meshed to provide more paths for power transfer as well as low impedance enabling larger power flow. In addition, transmission systems play significant roles in increasing system reliability, improving the quality of supply, and enabling the operators to deal with different system contingencies such as lines outages, lost generation, or unexpected change in the demand [2.1]. To achieve such functions, transmission systems are integrated with other complementary equipments to provide good levels of controllability and automation, and ancillary services to be provided from the generation side.

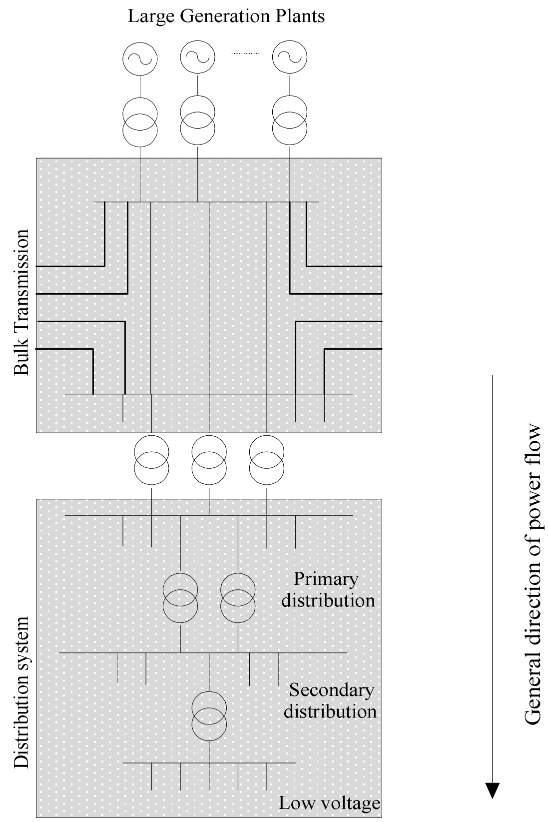

Figure 2- 1: Traditional power system networks

In contrast to meshed transmission networks, distribution networks are mainly radial in nature, and for example in the UK they are connected to transmission level at 132/33kV substations in Scotland and 275/132kV substations in England and Wales [2.2]. Their voltages are reduced to 33kV and 11kV and the power is transferred by 11kV feeders to be carried close to the users (i.e. industrial, commercial, residential, and transportation). The voltage will be further reduced to 0.415kV (UK voltage) at residential and small commercial load points. Distribution systems are usually classified as three different forms, urban, suburban, and rural networks. In urban networks, underground cables are widely used with short lengths to provide electricity for high load densities in urban areas. In rural areas, overhead lines are more common to be used and much longer, while suburban distribution networks use a combination of underground and overhead lines to carry and deliver power within suburban areas.

2.2.1 Characteristics of traditional power systems

At the generation level, the traditional power systems are widely based on central power generation. The generated electric power flows in different directions within transmission systems, and further losses of the generated power will be incurred in the transmission and distribution networks before the power is delivered to users [2.3].

Traditional power systems are operated and controlled centrally, and distribution systems have very limited levels of controllability and automation compared to transmission systems. This may lead to some parts of distribution systems to be restored manually, and their contribution to the wider system operation is limited. For example, due to the lack of communications between the utilities and users, the consumers in traditional power systems have very limited capability to response to the system changes and system needs during different operating conditions. The utilities and operators of distribution networks do not have a full access to control the equipments at consumers' sides by which better efficiency of network utilization can be achieved by having more control, however, there may be a limit how much control consumers would be willing to surrender to suppliers. Also the electric appliances do not have the capabilities to response to the system needs and provide some support from technical perspective. Systems with such characteristics may not be sufficient to help to the meet the EU and UK targets with regard to climate change. Radical changes in each sector of existing power system will be required in order to meet the low carbon targets, and particularly at distribution systems [2.4]. More active engagement of the electricity end users such as playing parts in generating and managing local energy is required. This may lead to radically changes in the characteristics of the existing distribution system. The impact of these changes is discussed in more detail section (2.3).

2.2.2 Challenges and issues facing traditional power systems

According to [2.5] the global electricity consumption for 2020 will exceed 27,000 terawatt-hours (TWh) compared to 15,400 TWh consumed in 2000. This is predicted because of the increase in the global population which is expected to reach 7.5 billion people by 2020 compared to 6.1 billion in 2000 [2.5]. Also another source the "World Energy Technology Outlook- 2050", provided in 2006 by community research of the

European Commission (EC) [2.6], outlined that global demand is expected to reach a 60% increase in the next 30 years compared to the current demand, and the current global generation capacity and power reserve will not be able to meet such dramatic demand increase. For instance, over the next two decades, the UK will need large investment in new generation capacity to replace the closing coal, oil and nuclear power stations, and to meet expected increases in electricity demand [2.7]. The energy analysis conducted in 2007 by Redpoint Energy Limited and Energy Strategies Limited expected that 22.5GW of the UK existing power stations may close by 2020 [2.8].

Building new transmission and distribution networks may be very expensive, and at the same time may increase the complexity of the systems, and reduce the overall efficiency since more lines will lead to more losses. In addition, the rapid increase in the demand could sometimes not be met by building more transmission and distribution infrastructures. “The Smart Grid: An Introduction” report which has been published by the U.S. Department of Energy’s (DOE) Office [2.9], has outlined that since 1982, growth in peak demand in the U.S. has exceeded transmission growth by almost 25% every year. Also the same report has found out that approximately the average power outage affected 15% more consumers from 1996-2000 than from 1991-1995. From a cost point of view, and according to (IEA), the estimated investment for upgrading the transmission and distribution networks in Europe alone to meet the increase in demand by 2030 will approximately reach €500 billion, and the global investment required to meet the increase in global demand for the same time scale could be $16 trillion [2.10].

Based on literature reviews numbers of challenges and issues that are facing traditional power systems are discussed below in terms of environmental, security of energy supply, and operating issues.

I- Environmental issues

There is a high concern over the world about climate change due to (GHG) emissions. According to the fourth assessment report from Intergovernmental Panel on Climate Change (EU action against climate change) [2.11], the temperature rise is accelerating and the sea level rose nearly twice as fast as between 1993 and 2003 as during the previous three decades and the changes were due to man-made emissions of GHG.

Climate change due to GHG emission is a global problem where the source of the problem comes from different parts of the world, but the impact would affect the whole planet. It is believed that developed countries are mainly responsible for the current high levels of GHG emissions as a result of more than 150 years of industrial activity. Therefore, there was an international agreement on tackling climate change which is called the "Kyoto Protocol" [2.12]. It has put large responsibilities with different levels on the shoulders of developed nations to reduce GHG emissions by 2012. However, many countries have committed long-term CO2 cut targets beyond Kyoto. For example, the EU and other developed countries have set targets to reduce the global GHG emission by 30% by 2020, and by 60-80% by 2050 in respect to 1990 [2.11]. The EU has made an independent commitment to cut its emission to at least 20% (30% if international agreement is reached) by 2020 compared to 1990 level, and increasing use of renewable to meet 20% of the EU total energy by 2020 [2.11]. In parallel to the EU, the UK government has set mid and long-term national targets which aim to cut CO2 emissions by 26% by 2020 and up to 80% by 2050 compared to 1990 levels [2.13][2.14]. The table below summarises the global carbon reduction targets.

Set by	2020 (carbon reduction target)	2050 (carbon reduction target)
Global	30%	60-80%
EU	20% (30% if international agreement is reached)	60%
UK	26%	80%

Table 1: The global carbon reduction targets

The climate researchers believe the only way to limit the increase in the carbon emission is to halve the GHG emission, and without environmental remedial measures global carbon emission will increase by 57% to 2030 [2.15]. Traditional power systems are considered as one of the sources that contribute to the climate change problems. For example, large carbon based power plants emit GHG which in turn will harmfully impact climate change. In addition the International Energy Agency (IEA) statistics indicate that 16% increase from 1990 to 2005 in global CO2 emissions caused by the energy use alone [2.10]. Taking the UK as an individual example, the UK’s electricity generation sector accounts for about one third of the UK’s total carbon emissions [2.7], and approximately 25% of the country greenhouse gas emissions caused by the heat and electricity usage at residential sector [2.16][2.17]. Therefore, generation and other power system sectors such as transmission, distribution and domestic as well as transport have a significant impact on the climate change, and if the right measures are applied to these sectors, they would play a significant role in reducing GHG emissions, and reserve more energy primary resources. For example, GHGs emissions can be reduced from power systems sectors by using low carbon generation technologies such as wider use of renewables and thermal generation plants equipped with carbon capture and storage (CCS), and the technologies such as combined heat and power (CHP) that can offer improved efficiency at domestic sector of the power system, and energy saving measure [2.6].

Based on the EU commitments to cut GHG emissions, in addition to Emissions Trading Schemes (ETS) to control pollution by economic incentives, two measures were proposed in 2008 by EU nations and they were added to the December 2008 EU's climate change legislation in order to reduce the GHG emissions released from power systems. One is the share of renewable energy sources (RES) should reach 20% of energy in 2020, and the other is the energy saving should be made by which the consumption would be 20% less compared to the base-line scenario without energy saving in 2020 [2.18][2.19][2.20]. For long term, in 2009 there was a discussion on increasing the figures to 60% RES and 35% energy saving by 2050 [2.18][2.21].

II- Security of primary energy supply issues

There is a big concern on the limitation of global fossil fuel resources. Experts expect the remaining recoverable oil resources represent only 60 years of production [2.6], and from 2015 global demand for oil will outstrip supply [2.15]. Because of the high increase in energy demand and the limitation in traditional primary energy resources, the days of cheap oil in the medium and long term are over [2.15]. The trend towards more expensive oil is driven by the rapidly increasing appetite for economic growth particularly in developing countries [2.15]. According to the International Energy Agency (IEA), China and India alone will account for 40% of the future increase in energy usage, and 84% of the increase in the demand will be met by fossil fuels [2.15][2.22]. With these forecasts and figures the security of primary energy supply therefore is a serious issue especially for those nations relying on imported energy primary sources. For instance, in the EU the reliance on imports of gas is expected to jump from 57% to 84% by 2030, and of oil from 82% to 93% [2.11].

It seems that there is a serious need for moving into more efficient power systems that can save energy wastage, and offer fuel-mix energy sources. The world energy technology outlook-2050 [2.6] has stated that using energy in more efficient way will play a very significant part in saving primary energy resources for the future. The report also expects that when renewable and nuclear energy sources benefits from sustained development, 30% of the world energy supply could be provided by non fossil fuel sources by 2050.

III- Operational issues

In the last decade, numbers of blackouts were experienced across different parts of the world, and particularly in 2003 North America and some parts of Europe experienced their worst power failures [2.9]. The event in North America affected more than 50 millions of people, and tripped more than 400 transmission lines and 531 generating units [2.23]. Also in the same year, up to four millions customers in Denmark and Sweden lost power [2.23]. Few months later a cascading outage left most of Italy without power [2.23].

The main reasons of these major blackouts according to the paper [2.23] were identified by the IEEE PES Power System Dynamic Performance Committee and concluded that it was equipments failures, followed by inadequate and improper control responses to limit and minimise the problem. The US-Canada Power Systems Outage Task Force final report on the August 2003 blackout [2.23][2.24] reported that the primary sources of the US-Canada blackout were due to numbers of computer failures occurred on the energy management system of one of the control centres, which led to a lack of understanding of the actual system behaviour and needs. This was followed by losing numbers of units heavy loaded by reactive power, and due to tree contact a few hours later, numbers of transmission lines were tripped. This caused overloading on other remaining lines as shown in Figure 2- 2 resulting in cascading loss of lines and generating units which left millions of people in the state to be in dark [2.23].

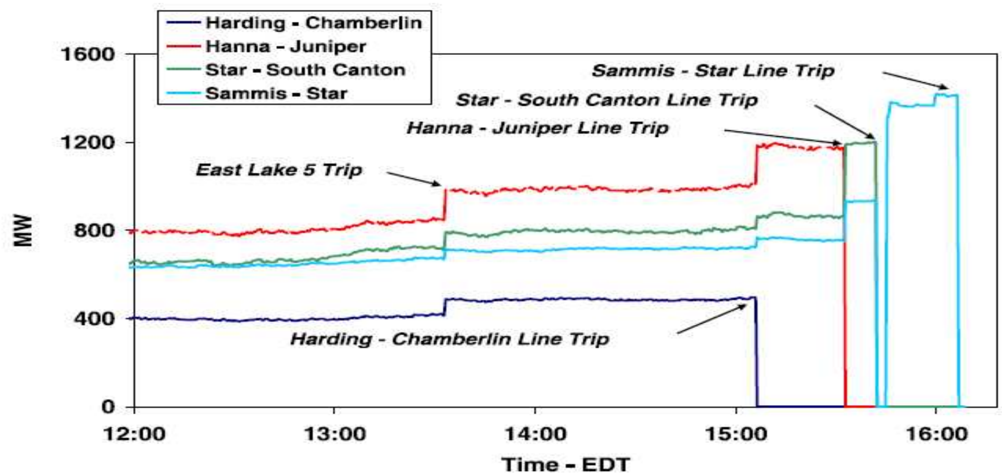

Figure 2- 2: Cascading tripping in US/Canada transmission lines systems in 2003 [2.24]

In Sweden and Denmark, the event started from losing one nuclear generation unit due to failure in a feed-water valve, followed by nearby double busbar fault tripped four lines at the substations. This N-5 contingency caused another trip of 1.8GW power plant [2.25]. This led to an overloaded circuit between the two countries, and the line tripped. The generation was not enough to meet the demand in southern Sweden, so cascading events continued and left millions of people without power.

In Italy problems also started with a single fault causing tripping of the line between Italy and Switzerland, and the automatic breaker refused to reclose the line [2.25]. The country started losing synchronism with the rest of Europe. When the country is electrically isolated, the generation deficit led to large drop in the system frequency as shown in Figure 2- 3, and there was inadequate control of frequency to prevent generation from tripping. This led to the collapse of the entire Italian system except of Sardinia [2.26].

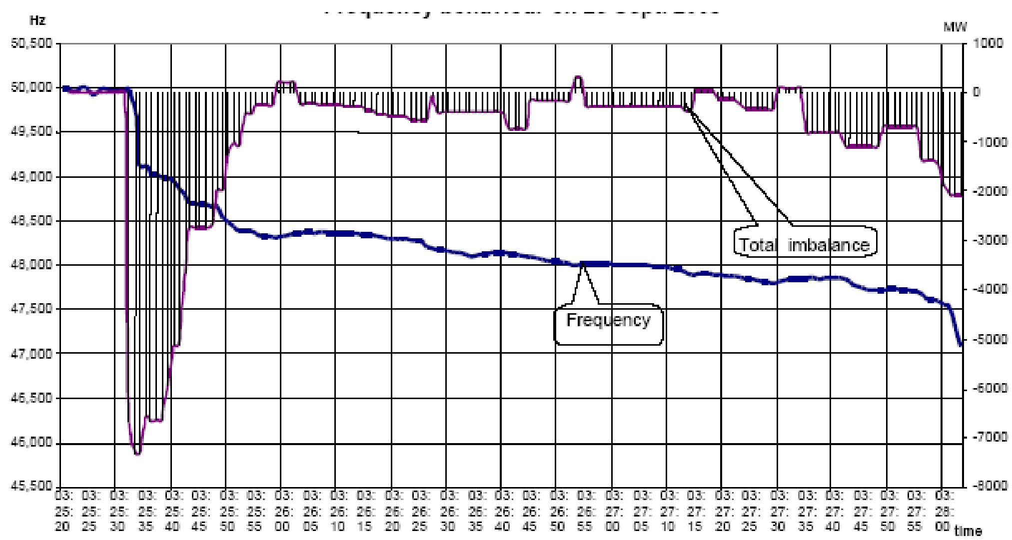

Figure 2- 3: Frequency profile during Italy 2003 blackout [2.26]

Another serious event left more than 15 million of European households without electricity in 2006 was the grid disturbances that impacted most of the European countries transmission grids on 4th of November 2006. According the technical analysis report provided by the European Network of Transmission System Operators for Electricity committee (ENTSO-E) [2.27], there was tripping of several high-voltage lines due to manual disconnection of the double-circuit 380 kV without undertaking sufficient counter measurements to reduce the power flow of neighbouring lines in Northern Germany which led to system splitting, and inducing a severe frequency drop that caused an interruption of supply for wide area of Europe.

UK also experienced a partial blackout on May 27th 2008. The event occurred due to unexpected trip of large amount of generation (i.e. almost 2GW) which in turn led to the maximum secured loss at that day to be exceeded and the low frequency load disconnection schemes to be initiated and affected about 550,000 of consumers. The figure below shows the impact of the event on the UK system frequency, and the loss of total generation and load [2.28].

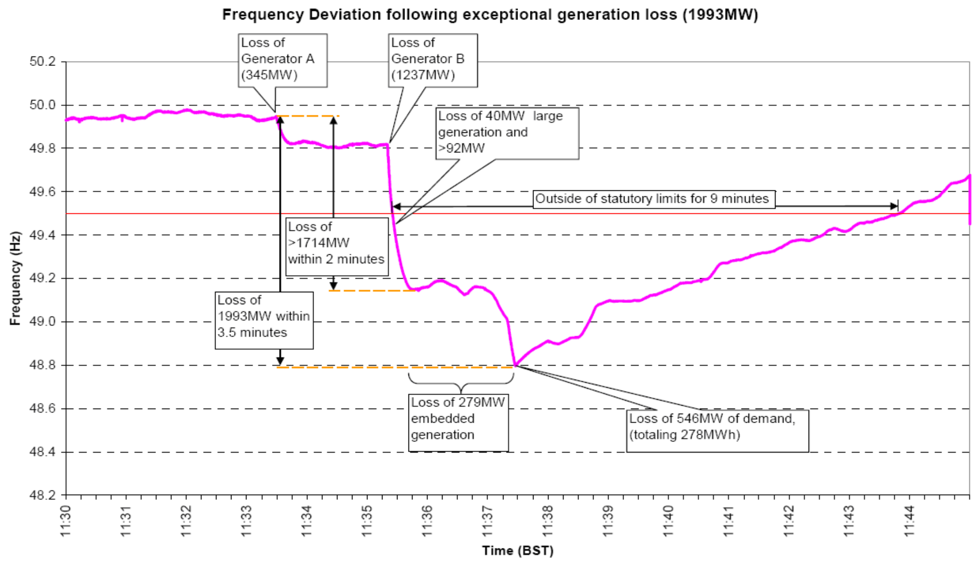

Figure 2- 4: Frequency response following loss of generation during May 27th 2008 UK partial blackout [2.28]

From above events have occurred in USA, some countries of the EU, and the UK, it can be evidently seen that there have been recently numbers of blackouts impacted millions of people across different areas of the world. Most of the above blackouts were initiated with equipment failures, or human errors due to the lack of information about the situation of the affected system prior to the system failure as happened in 2006 blackout in Europe as explained above. Another factor contributing to the spread of the blackouts was the inappropriate control actions that were taken to limit the cascades of the events. Therefore, the reliance on centralised control system would lead massive number consumers to lose electricity in case of a single failure in the main central control room. In order to build a securer system with low carbon emission, making better use of energy, and at the same time minimise the hours of the power cut more decentralised control structure as proposed in this thesis will be required. Such requirement is discussed in more detail in the rest of this chapter.

2.3 Future changes in electric power systems

Moving to a low-carbon environment, managing energy security of supply risks, and potentially reducing the cost of the electrical infrastructure, whilst at the same time improving the reliability of power systems and reducing the widespread of blackouts has motivated an increased interest in the integration of more energy saving measures (i.e. using energy more efficiently) and wider generation mix sources. Such measures have the potential to make further cuts in the carbon emissions and contribute to the security of energy supplies by reducing the reliance on imported energy and ensuring the maximum use of the energy resources through greater energy efficiency [2.7].

The diversity in the energy mix makes the risk of security of primary energy supply to be shared across a range of sources and technologies and reduces the reliance on a single energy source such as fossil fuels or on a single technology type such as large plants interfaced by large synchronous machines [2.7]. The generation mix includes renewable and the adoption of low-carbon technologies, such as carbon capture. This in turn would open up the possibility of moving to more decentralised low carbon energy systems. The decentralised systems will be composed of generation mix including centralised and local generation, and the use of the energy saving measures to improve the efficiency of power generation, transmission, distribution, electricity use, buildings, and shifting toward more environmental transport systems. Local generation and energy saving measures will also offer the flexibility to accommodate variations in demand at different times of the day and of the year [2.7]. A significant growth of local generation that can be connected at distribution systems, energy saving measures, and carbon lean transport will represent a considerable change in traditional distribution systems, and they will have a key role to play in decentralised power systems. How such a range of changes may impact the electricity supply industry is discussed in more detail as follows:

2.3.1 Distributed Generation

Distributed generation (DG) term is referred to generation units that can be connected to distribution networks across different voltage levels rather than to the high voltage transmission grids [2.29]. Distributed generation units provide means of utilising renewable and low carbon energy resources. The units are not always connected at the electricity use points. For example DGs which are driven by renewable energy sources need to be located close to the localised energy resources which can be available at remote areas from the consumers. If DG units are connected to LV distribution networks and are used in the context of generation of power at domestic scale they can take advantage of reducing the capital and operating costs, and can be termed as "microgeneration" [2.30]. Initially DGs were mostly used for shaving peak power or providing power where electricity is not available. However, within future power system changes, DGs including microgeneration technologies can provide further useful inputs to the system. Their useful inputs are summarised as follows.

A- The potential benefits of distributed generation and microgeneration [2.11][2.29] [2.31]

- More efficient use of renewable and fossil fuel: using DGs driven by renewable and low carbon energy sources have the potential to reduce carbon emissions and the demand for imported gas or oil as primary energy source for large plants.
- The heat generated by decentralised electricity production can be used for space and water heating.
- Improved flexibility: decentralised energy system will respond more readily to technological change.
- Increased numbers of energy producers/suppliers: decentralised systems by producing power locally could lead to more market participations, potentially increasing competition and customer choices.
- Raised energy awareness: the production of electricity and heat more locally by DGs will help to increase the awareness of energy production and consumption potentially resulting in more efficient use of energy. It is claimed that this will make the public co-producer of climate change solutions rather than passive consumers of energy.
- Enhanced network reliability and resilience: DGs can provide local active and reactive power which can be used to meet the local demand and the same time supporting the wider system performance such as reduced line losses, and improved voltage profile. This would also relieve transmission and distribution congestion, and offer lower operating cost due to peak shaving.

- DGs in some applications can provide local black-start functions and reduce the power cut periods by supporting consumers under conditions of mains failure.
- Another alternative arrangement to support the increase in growing demand: DGs can provide new opportunities for increasing the diversity and the efficiency of the power system.

B- Distributed generation technologies

There are numbers of DGs technologies which can be identified by the technologies used to interface the unit to the system or by the fuel used to drive the unit. DG technologies from energy perspective include renewable and low carbon devices (fossil-fuelled) are listed below:

I- Electricity generation technologies

Wind power

Wind power is a clean, renewable source of energy which produces no carbon emissions or waste products. The most common wind turbine is three blades mounted on horizontal axes, and driving a generator directly or through a gear box. DGs driven by wind power can be onshore of offshore, and the total of the wind farms could provide total electric power up to 1GW [2.32]. The wind speed is uncontrollable source, and this in turn will make DGs driven by wind to have different electrical characteristics to conventional synchronous generators. Wind power turbines are interfaced to the grid directly by induction machines or by using power electronics interface such as inverters and converts. Wind generation makes a significant contribution to the energy supply system and it is leading the renewable generating technology in many countries [2.32].

Photovoltaic

Photovoltaic or PV generates electricity from sunlight. The PV cells are connected together and encapsulated, usually behind glass, to form a module or panel and any number of modules can be connected together. The electricity is generated when the semi-conducting materials of the PV cells are exposed to the sunlight [2.33]. The PV cells convert the sunlight energy into direct current (DC), and then the DC current is converted into alternative current (AC) when connected to the grid. This technology has the advantage of being very effectively integrated into the structure of buildings [2.30].

Hydro-power

Distributed generation hydro powers are technologies that involving utilising naturally flowing water on hilly lands, or in rivers and streams to generate electricity. Hydro power can also be obtained from a reservoir that discharges water back into the main river. The electricity produced by such technologies depends on the amount of the water and the speed of the flow. From the technical perspective such DGs are normally interfaced to the grid by synchronous machines.

Fuel cells

A fuel cell combines hydrogen with oxygen in chemical processes to produce electricity. Unlike technologies which "burn" fuel, with fuel cells the conversion takes place electrochemically without combustion. Fuel cells can be run on a wide variety of fuels, and importantly, fuel cells make fuels last longer [2.34]. When fuel cells run on pure hydrogen fuel no carbon or other toxic emissions are produced, and this can therefore help to tackle environmental issues [2.34].

II- Heat generation technologies

Distributed generation can be also used to provide space and/or water heating. There are numbers of examples of such DG technologies. One example is solar water heating technologies which use the heat of the sun to produce hot water. Another example is biomass technologies can provide space or water heating from burning wood and non-wood fuels. The biomass fuels are derived from forestry products, energy crops and waste wood products [2.35].

III- Combined heat and power (CHP)

Combined heat and power (CHP) refers to technologies that provide electrical power as well as thermal energy from a single fuel source. Hence the waste heat from generation process can be used as a heat source rather than released to the environment. The two main types CHP technologies are reciprocating and Stirling engines. DGs based on CHP technologies can be interfaced directly to the grid by synchronous generators or indirectly by using power electronics.

IV- Microgeneration

Microgeneration units tend to be, by their nature smaller compare to large distributed generation, and they are defined in the Energy act 2004 as: *"a source of electrical energy and all associated interface equipment, rated to and include 16A per phase, single or multi phase 230/400V ac and designed to operate in parallel with a public low voltage distribution Network"* [2.36][2.37]. Microgeneration technologies are also defined in Microgeneration strategy which is published by the Department of Trade and Industry (DTI) of the UK to produce less than 50kW of electricity or less than 45kW of heat [2.38]. In the UK microgeneration implementation is considered as an essential part within different UK's low carbon building programmes that would help to reach zero carbon buildings [2.39].

Similar to larger distribution generation, microgeneration may include some technologies that can generate only heat, or only electricity, or combined heat and power. According to the range of technologies defined the DTI microgeneration Strategy [2.38], and the Micropower Limited which has a significant interest in developing the small-scale generation, the most common type of microgeneration technologies that have received recently large attention from energy and technology perspective are summarised below [2.40].

- Micro-wind where building mounted turbines are now starting to come onto the market [2.29].
- Solar PV with range of 1-3 kW as a typical power output for a domestic installation.
- Micro-hydro power
- Solar water heating to provide the heat for domestic use where $4m^2$ collection area would provide 50-70% of a typical homes' annual hot water requirement.
- Heat pumps which use the warmth stored in the ground to heat fluid circulating through pipes, a heat exchanger extracts the heat and then a compression cycle raises the temperature to supply hot water for heating purposes.

- Biomass stoves and boilers
- Micro-CHP which can provide around 5 kW offering around 10-12kW of thermal output. A typical domestic sized micro-CHP unit will deliver the same comfort levels as a modern boiler, whilst reducing the CO2 emissions of a typical house by 25% per year.
- Small scale fuel cells are in a range of sizes from about ½ kW upwards

2.3.2 Local demand and deployment of smart meter

The domestic sector has been identified in many researches as an important part of power systems that will play a significant role in CO2 emission reduction, and energy saving. For example in the UK, the housing stock is responsible for around 27% of all carbon emissions in the country according to the White Paper 2007 [2.7]. In a typical British home, three-quarters of carbon dioxide emissions come from the energy used for heating and providing hot water and a fifth from lighting and appliances [2.7]. In addition, the UK Energy Saving Trust as it is reported in [2.7] has estimated that individuals are responsible for around 40% of the UK's energy use and carbon dioxide emissions, and at home over £900 million per year is wasted by leaving appliances on when not in use.

Therefore, using less energy by improving the energy efficiency at domestic sector and the efficiency of the products and the insulation of the buildings will reduce energy bills and helping individuals to be more aware of the importance of their actions to reduce carbon emissions and climate change [2.7]. Using the energy in more efficient way by the consumers may require demand management which in turn can be used to shift the demand away from peak periods, and savings by reducing the need for investment in new energy infrastructure to meet peak demand can be offered. From technical perspective such advantages may be reached by using advanced demand management techniques that allow the consumers, energy suppliers, and network operators to monitor and manage the use of energy. One important element that can significantly help for demand side management is a smart meter, which can be installed at consumers' homes in order to provide real time displays of the energy use, and potentially help the households to manage their energy use.

The smart meter will also allow communication between the consumers, the energy supplier and perhaps the network operator [2.41]. This can help readings to be taken remotely and ensuring all bills are accurate, and providing sufficient information about the situation of the network at consumers' points for the network operator. Provision of energy use information will put energy user in a better position to save energy, the energy suppliers in a better position to incentives the users to use less energy overall and shift the demand at peak periods in response to time of use tariffs, and the operators to operate the system more efficient based on the visibility of local networks that smart meters can provide [2.41]. So, smart meters would be very important enabling technologies that will facilitate the integration of more local generation and the adoption of saving energy measures. The EU target for roll-out of smart metering is 80% of consumers within EU to be equipped with Smart Metering Systems by 2020 [2.42]. Within the UK, the aim in long term is to roll-out the smart metering to all the UK consumers in the way that the consumers, suppliers, network operators and other market participants gain benefits, and at the same time the environmental and policy targets can be delivered [2.43]. The UK policy forecasts the replacement of 47 million of the residential traditional meters in the UK by smart meters by year 2020 [2.43]. So, by deploying demand side management measures, consumers can play more active role in energy systems.

2.3.3 Transport sector

On the consumer side, the potential impact of the transport sector is significant and can be highly anticipated [2.44]. Transport is expected to be one of the fastest growing sectors in the future, and in the UK as an example, the transport accounts for around a quarter of UK domestic energy use and greenhouse gas emissions [2.7]. In addition to the environmental impacts of transport, the transport sector depends heavily on oil, and this in turn may have a potential impact the security of energy supply. In addition, the potential impact of plug-in Electric Vehicles from technical perspective would be highly anticipated where spinning reserves and ancillary services can be offered if appropriate plugs are provided [2.45]. For example, according to the Energy Information Administration, U.S department of Transportation, potential impacts of plug-in electrical vehicles to the U.S. grid can be significant. The number of the cars in the state is more than 250 million, and if such numbers are changed by electric vehicles, then total energy to charge such numbers will be 3840GWs on the average of 15kW per vehicles, while the total current generation capacity of the state is around 986GW [2.44]. This indicates that integrating electric vehicles would lead to a considerable change in the power systems.

For this sector to reduce its carbon emissions impacts and to provide a significant contribution to energy saving, a carbon lean transportation is needed [2.7]. For example, the UK Government has been working to reduce the carbon emissions from transport by: reducing the carbon content of fuel; reducing the carbon emissions of vehicles; encouraging moves towards more environmentally friendly transport and, where appropriate, using emissions trading [2.7].

In spite of the importance of this sector to reduce the carbon emissions and contribute to energy saving, the Stern Review report as mentioned in [2.7] has stated that this sector is one of the most expensive sectors to cut emissions, and the welfare costs of reducing demand for travel are high. The report also stated that transport sector will be among the last sectors to bring its emissions down below current levels.

2.3.4 Policy objectives

Governments also have an important role to play to encourage the deployments of save energy measures and the uptake of local generation. The governments can provide support and assistance to utilities and individuals to be more active and contribute to carbon emissions reduction. This will require the regulatory framework to be in place to deliver improvements to the buildings, products and services [2.7].

A significant international attention has been given to setting targets to provide a significant amount of the electricity generation from renewable and highly efficient energy sources. The global carbon reduction targets were listed previously in Table 1 in section 2.2.2. The UK government has taken a number of steps to promote more decentralised energy measures. For example, according to the 2007 white paper [2.7] the changes to the Renewables Obligation have been made in order to support the uptake of more renewable and CHP technologies to achieve 10% of renewable generation by 2010, and 20% by 2020, and the recovery of energy from waste and some types of microgeneration technologies.

In addition to Renewable Obligation, the UK government has published a new policy mechanism called "Feed-in Tariffs" (FiT) to provide financial incentive measures to encourage the adoption of renewable and low carbon energy by individuals and communities in order to support the UK future energy and climate change targets [2.46]. The Tariffs encourage the consumers to be more self-sufficient in energy, and help them to be rewarded for the power that they generate for local use or to be exported to the grid. The reward can be made within the FiT schemes by three different ways [2.46]. One is the generation Tariffs where the owner of the local generator can earn a fixed income for every kWh of electricity generated and used locally within the property. The other is the export Tariffs, where the owner can earn an additional fixed income for every kWh of electricity generated locally and sent back to the grid. The third is the bit the owner still buys from the supplier. This is based on in case of the generated local power is not enough for the local use, the consumer who has installed renewable source can buy electricity from the supplier at normal rate that is less than those do not install local renewable and low carbon microgeneration. It seems that the FiT scheme for the UK will have the potential to act as a driver for an increased uptake of renewable energy systems and changing the way to think about better use of energy [2.47].

The EU and UK governments have taken numbers of actions to meet their policy objectives by supporting individuals and communities to gain greater availability of energy saving measures, and access to connect local generation. Numbers of the actions are summarised below [2.7].

- Improving the awareness of climate change and security of energy supply issues by providing information on energy use and enabling individuals to have access to see their carbon footprint through an on-line CO2 calculator.
- Setting out the standards for buildings and communities, and products that can make homes and communities zero or low carbon through higher use of energy efficiency and low carbon and renewable energy sources.

- Encouraging energy suppliers to provide electricity displays such as smart meters for the customers in order to provide the needed information for saving energy.
- Requesting Energy Performance Certificates to provide information on the energy performance of buildings and the actions that can be taken to improve that performance and reduce energy waste.
- Removing barriers of the installation of local generation by providing more flexible market and licensing arrangements.
- Potentially rewarding energy generated by householders through local generation.

2.3.5 Future looking network scenarios

The potential for improved power system sustainability in the future to be realised, a massive uptake of decentralised generation and energy saving measures may be required. However, there are still many uncertainties about the picture of the power systems in the future where it is difficult to know for example, which mix of power generation and energy saving technologies will be the most appropriate for delivering the goals of low carbon and more reliable power systems. This can be difficult because the changes in different power systems at different regions are driven by different factors and opportunities. Therefore, there are numbers of forward looking network scenarios which have recently been created by academic consortia, government agencies and trade associations to give an estimate for future energy capacity. One example is, the scenarios that have been developed within the UK against numbers of externalities and factors to predict the generation capacity share between fossil and non fossil-fuelled power generation of the UK system to meet the 2050 UK target [2.51][2.52] and [2.53]. This section discusses two scenarios; one is SuperGen 2050 Scenarios [2.54], and the other is Ofgem LENS project scenarios [2.55].

Within SuperGen 2050 Scenarios six scenarios; strong optimism, business as usual, economic downturn, green plus, technological restriction, and central direction have been developed against a set of technical, economic, environmental and regulatory attitudes. It has been concluded within the worst case scenario “Economic Downturn” which represents a case of adverse economic events with the lack of demand growth and no promotion for demand side management, the generation capacity would be around 55GW. 20-30% of the generation would be met by renewable, and microgeneration connected at domestic side would account for about 10% of generation. On the other hand, when strong economic growth scenario is considered which can lead to advance in technologies, the renewable generation would account for 60-70% of the total generation capacity 145GW, with 35% of electricity provided by microgeneration. The allocation of renewable would jump to almost 90% power production of generation total capacity of 110GW for environmental most important scenario, and microgeneration would represent 20% of the produced electricity (i.e. about 10GW).

The Ofgem LENS project scenarios [2.55] have concluded that when the environmental concern is strong throughout every level of society, and the carbon price to all sectors and become extremely high, and the DG are widely deployed, the total installed generation capacity at distribution systems only would represent almost 50% of the UK 2050 generation capacity which is predicted to reach almost 115GW. The microgeneration at itself would account for 23.2 GW [2.55].

From the above scenarios, a massive uptake of distributed generation including microgeneration is required in order to maximise the reduction in carbon emission, and since most of the distributed generation as discussed earlier are based on renewable and low carbon technologies the higher penetration is added the better contribution to the security of energy supply is obtained. The scenarios also shows a high figure between 10-20GW of the 2050 UK energy capacity can be met by microgeneration only. This figure can show the important roles that empowering consumers can play in meeting the energy future targets.

Therefore, given the support for microgeneration technologies within the 2007 UK government energy white paper [2.7] and the wider scenario based projections, the issue of microgeneration is expected to be of growing interest within the industry as generation technologies mature and become more affordable. For example, the studies commissioned by the Department of Trade and Industry (DTI) of the UK from the Energy Saving Trust have suggested that 30-40% of the UK's electricity demand should be met through microgeneration technologies by 2050 in order to meet the UK 2050 targets, with combined heat and power (CHP) leading the way, followed by micro-wind and photovoltaic (PV) [2.38].

From the technical perspective, the introduction of the European standard EN50438 [2.56], which specifies the technical requirements for the connection of microgeneration in parallel with public low-voltage distribution networks, and the engineering recommendation documents in the UK for small sources connection G83/1 [2.57] are all further evidences of some utilities' preparation for microgeneration connection. Therefore, the case studies considered in this thesis is based on an extensive uptake of microgeneration in order to significantly provide useful contribution to local and wider system.

2.3.6 Potential impacts of future changes in current power systems

Increasing the level of integrated renewable and low carbon energy resources across already established power systems and increased energy efficiency in production and consumption behaviour to curb GHG emissions and conserve energy resources will bring power grids to situations have never been in before. New decentralised generation such as microgeneration are normally consumer-led rather than centrally planned, and this in turn may result in conflicting operating strategies between the new and existing centralised generation technologies.

In addition, traditional distribution power systems are designed and viewed as a passive portion with very limited automation and controllability especially at lower voltages, and empowering the local distribution systems by increasing the volume of connected microgeneration, and activating the system by increased deployment of energy efficiency, will emerge a new picture of many active loads supplied by many sources. Such transition will impact the response of distribution systems to the wider system, and hence impact the operational strategies of the traditional power systems.

It is believed that most of primary enabling technologies that could be required to initiate the move to future power grids are almost available now [2.58]. The technical solutions may be costly, but there is a hope with the advance in the technology in the future the cost will decline. The remaining challenge is how to fit such technologies in an efficient structure that facilitates the compatibility between the new technologies and the established power systems as well as with the future integrated technologies.

Therefore, it becomes vital for substantial amounts of microgeneration among other decentralised resources to be controlled in the way that the local and wider system to be supported. This will require a new control structure to avoid the incompatible and limited performance with greater cost due to the new changes, and avoid higher investment risks. In addition, the system with new changes must cope with different contingencies and the connected decentralised generation must overcome numbers such contingencies, and stay connected as long as possible so their benefits to the system can be realised. This will require understanding of the performance of a system incorporating a large population of DERs including microgeneration under different system conditions to ascertain measures of risk and resilience.

The next section (2.3.7) discusses in detail numbers of future visions of power systems that have been developed recently by different groups in order to facilitate the transformation to more decentralised power systems that can offer better reliability and security, and better efficiency and support environmental issues. Based on the literature review from other visions, the section also proposes a new conceptual system structure to answer one of the research questions, how to fit many energy sources and many active controllable loads within the grid and tie such technologies by which the system operation is improved and local constraints are mitigated. Section (2.5) outlines the technical issues need to be tackled in order to understand the behavioural characteristics of a system incorporating a high penetration of small scale local generation.

2.3.7 Different visions of future decentralised power systems

According to the report on Smart Power for the 21st Century provided by Electric Power Research Institute (EPRI) [2.58], "*the existing grid should be modernised not by randomly gathering a group of interesting technologies and calling it modern, but rather by first building a vision and the framework that enables that vision*". So, building a conceptual vision can be used as a road map that can facilitate the integration of distributed energy resources within the existing power systems. Conceptual visions are normally driven by objectives as well as the available and future opportunities that may emerge during the movement towards decentralised power systems [2.15].

To explore the similarities and complementarities between different developed visions those are all aiming to facilitate the feasibility of better future power grids, three visions created by different regions; the European Commission's (EC) SmartGrid approach, The Electric Power Research Institute's (EPRI's) IntelliGrid approach, and Highly Distributed Power Systems (HDPS) are investigated. These visions are mainly based on the characteristics of a future power grid and what the future grid should offer to meet the policy objectives.

I- The Electric Power Research Institute's (EPRI's) IntelliGrid vision

The Electric Power Research Institute's (EPRI's) has created IntelliGrid vision which can provide a technical foundation to link power systems and integrated energy sources with communications and advanced control to create a highly automated and resilient power delivery system [2.58]. The vision has been created for future North America power grids to be more self-healing systems that can automatically control power flows and operate in more efficient ways and minimise the risks caused by faults. The project believes that such functionality would help to avoid events such as August 2003 widespread blackouts incident at north-eastern of the U.S. and at south-eastern of Canada, which made the security for power supply to become a matter of very great concern in the U.S. [2.45].

IntelliGrid also believes that most of the North American power systems seem to work against any comprehensive grid upgrade, and all the work must be coordinated across the hundreds of companies and stakeholders [2.59]. The suitable way of building the vision of the future grid is by planning carefully and integratively, and incorporating flexibility by starting small and building on successes [2.59]. So start from small spots integrated with intelligent equipments such as demand management measures as an example and, as new intelligent systems and existing systems interconnected over time, more intelligence on the grid will appear and intelligent grid will eventually emerge (i.e. it is not a sudden transformation) [2.59].

The approach has stressed that the improvement of energy efficiency at large power plants and at demand side is a key role that will greatly accelerate the creation of more efficient power systems, and provide more saving in primary energy resources [2.58]. This was justified by the importance of the security of supply issue in the U.S power systems. Also the U.S has a variety of rich resources of primary energy. According to the Energy Information Administration (EIA) the official Energy Electricity of the U.S., the U.S. electricity production mainly depends on fossil fuels, with coal and nuclear leading by 52% and 21% respectively, and the natural gas comes after with 13%. The oil represents only 3% of the total energy sources [2.60]. "The Smart Grid: An Introduction" report published by the U.S. DOE Office [2.9] has stated that if the current U.S. grid were just 5% more efficient, the energy saving would equate to eliminate the fuel and GHG emission of 53million cars in the U.S. Consequently, the IntelliGrid vision has recommended that the changes in power systems should start at improving the efficiency of large power plants, and the use of energy at consumers' side, and then empowering the consumers by connecting local generation. Consequently, saving energy is seen in the U.S modern grid vision as the most effective way of improving energy security.

By integrating the U.S. traditional centralised power systems with advanced operational strategies, saving energy measures, demand response, distributed energy resources, and networked distribution systems [2.61], the vision of the modern grid in the U.S. is set to meet the following six main objectives of the 21st century U.S. power systems: the grid needs to be more reliable, more secure, more economic, more efficient, more environmentally friendly, and safer [2.61]. The characteristics of the vision describe the feature of the grid in terms of functionality. The table below contains the characteristics of the U.S modern grid vision and U.S. traditional grids, and the key aspect driving the U.S. modern grid vision:

Today's grid	characteristics	Modern grid
Responds to prevent further damage. Focus is on protection of assets following system faults.	Self-heals	Automatically detects and responds to actual and emerging transmission and distribution problems. Focus is on prevention.
Consumers are uninformed and non-participative with the power system.	Motivates to include the consumers	Informed, involved and active consumers. Broad penetration of Demand Response.
Vulnerable to malicious acts of terror and natural disasters	Resists attack	Resilient to attack and natural disasters with rapid restoration capabilities.
Focused more on outages rather than power quality problems.	Provides better power quality	Power quality issues identified and resolved prior to manifestation.
Relatively small number of large generating plants.	Accommodates all generation and storage options	Very large numbers of diverse distributed generation and storage devices deployed to complement the large generating plants.
Not well integrated with each other. Transmission congestion separates buyers and sellers.	Enables markets	Well integrated nationwide and integrated with reliability coordinators. Minimal transmission congestion and constraints.
Minimal integration of limited operational data with Asset Management processes and technologies. maintenance	Optimizes assets and operates efficiently	Greatly expanded sensing and measurement of grid conditions. Grid technologies deeply integrated with asset management processes to most effectively manage assets and costs.

Table 2: Comparison between traditional grid and the modern grid vision in the U.S. [2.61]

II- EU's SmartGrid vision

In the EU, a new approach SmartGrid vision is developed by the EC for the Europe future electricity networks. It was set up by the European Technology Platform (ETP) in 2005 to create a common vision for the European networks for year 2020 and beyond [2.62]. The main objective of the approach is to facilitate the transformation from the current Europe power networks to better EU future power networks by integrating the latest technologies, providing efficient and competitive energy market, supporting regulations and policy, and complete integration of distributed energy resources in order to make the EU future power networks to have the following key features [2.62]:

- Flexible: Meeting consumers' needs whilst responding to the changes and challenges ahead.
- Accessible: ensuring connection access to the users, particularly for renewable and high efficiency local generation.

- Reliable: improving security and quality of supply.
- Economic: providing best value through innovation, efficient energy management and competition and regulation.

The ETP has stressed that the movement forward to reaching the future EU power grid functions requires the EU grid to be incorporated by an appropriate information and communication technologies (ICT), activating the participation of end users by applying more intelligent demand and supply management [2.62]. The EU vision is more distributed and decentralised grid focused, where demand control and a high penetration of distributed renewable and low carbon generation are expected to be significantly installed at distribution networks in the future. This is driven by two main factors. One is the high dependency of the EU on external import of primary energy primary due to the limitation in the EU local primary energy resources. The second factor is, the energy related policy decisions are influenced largely by the commitments to local and international environmental targets such as Kyoto and post Kyoto protocol. There is an additional factor which is the level of public awareness of energy consumption issues which is relatively stronger than in the U.S. as explained in [2.45][2.63].

Comparing the two above future power grid visions, a wide range of similarities can be seen. Both visions rely highly on integrating new information, communication, and intelligent technologies into the existing power grids to support the transition towards decentralised systems that can create more affordable and reliable power grids. However, the EU vision is more environmental driven supported by a strong link to the security of primary energy supply, where the EU countries import about 57% of their primary energy from abroad [2.11]. While in the U.S. efforts are driven by Environmental Protection Agency recommendation, and U.S. has rich energy resources compared to the EU [2.45]. Therefore, the U.S. future energy policies related to energy issues focus more on supporting clean coal technologies, demand side management (DSM), and distributed generation seen as secondary focus, while EU policies focus more on use of distributed renewable and low carbon sources and efficiency measures to shape the development of the EU future power systems [2.45].

III- Highly Distributed Power System (HDPS) vision

Highly Distributed Power System is a system that is incorporated with a significant penetration of microgeneration and dynamic loads, in the way that the loads become an active and supplied by centralised generation and a wide range of decentralised generation. The HDPS concept can be summarised by the statement “many active loads supplied by many sources”.

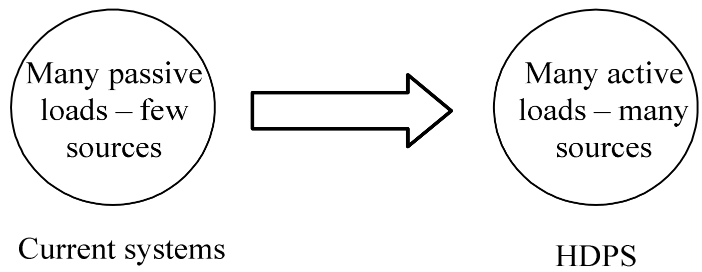

Figure 2- 5: Moving towards HDPS

From characteristics point of view, HDPS mainly focuses on creating solutions for future power systems incorporated highly with distributed energy resources (DERs) which can largely help in tackling climate change and fuel poverty as well as improving the reliability and resilience of the whole system by adopting sufficient energy control strategies. Based on HDPS scenarios [2.51], the DERs including renewable and low carbon microgeneration, demand side management, and electric vehicles require to be significantly installed in order for future power system help to meet the UK 2050 target. This means within HDPS the local distribution networks receive most of the changes by accommodating large volume of microgeneration as well as energy saving measures. The local generation and active demand are the key elements in the structure, operation, and the control of the HDPS.

The above three visions are mainly based on the characteristics of decentralised future power systems, and they do not adequately convey the level of detail necessary to provide a clear system structure that can support the incorporation of large numbers of DERs, and how they can be fitted and managed. Therefore, there is a need for a neat structure that can facilitate the active management of DERs in order to avoid any passive operation of such devices and resulting in system operational problems. In addition, managing DERs actively can bring benefits for DERs owners as well as system operators [2.64]. Therefore, a new structure concept which is called a cell for a system with many sources supplying many active loads is proposed and discussed in comparison with other system structure concepts in the next section.

2.4 HDPS Cell concept

The architecture of traditional power systems control is typically based on centralised approaches. Large regions of passive distribution systems are controlled remotely by limited centres with limited participation from the electricity users. When large amount of DERs are connected to different voltage levels of distribution systems, the systems become an active and their operating strategies may be remarkably influenced. This will require a new way of control structure by which the benefits from/to DERs and the host system are maximised as much as possible, and the problems from/to DERs and the host system are minimised as much as possible.

There are numbers of concepts in terms of the system control structure from technical perspective have been proposed by different research. One example is the "Danish Cell" which has been introduced by the Energinet.dk Company and the Transmission System Operator (TSO) of Denmark to be used as a new solution for obtaining an optimal management and active grid utilisation of the large amount of distributed generation present in Western Denmark [2.65].

The background of the Danish Cell approach is based on the creation of a system architecture that allows for a specific part of a distribution network to operate in parallel with the HV system in normal operation, and to independently disconnect from the HV in case of fault situations and switch over to a controlled island operation. In the case of switching to controlled island fails, then the cell is able to carry out a black-start itself and thus transferred to the state of a controlled island operation [2.66]. Each cell would be controlled by main cell controller which is located at the boundary of the cell in order to successfully run the transition between the three states (i.e. cell connected to the grid, islanded cell, and cell black-start). Figure 2- 6 shows the concept of 60kV Danish Cell example, with the main cell controller [2.67]. The main cell controller receiving measurements and information of demands and generation, and sending control signals to generators, load feeders, and main circuit breakers to perform the cell functions [2.67].

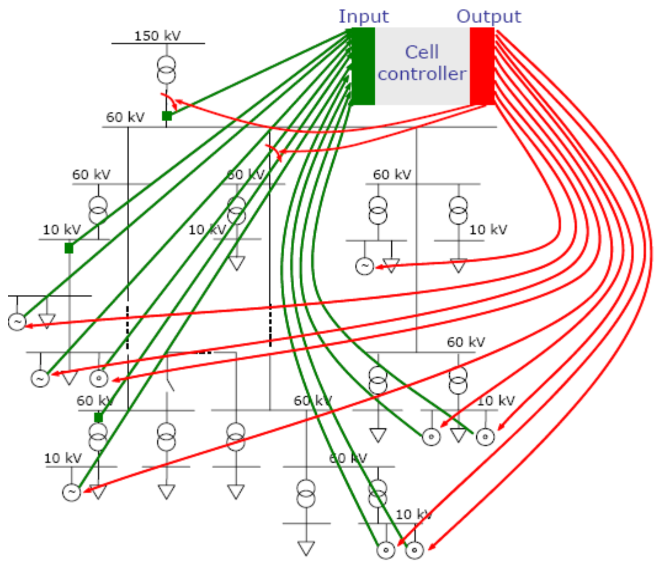

Figure 2- 6: 60kV Danish Cell with main cell controller [2.67].

The main objective of the "Danish cell" is based on the supply of power to the users when distribution network areas with large amount of DGs are unintentionally disconnected from the main grid due to faults. In spite of the importance of such objective, there is a high concern on how to manage and maximise the participation from local generation and active demand to support the system during the grid-connected mode, and at the same time manage the reward of the DERs participation. Also, there is a high concern about minimising the impact of DERs on the performance of the system and the system performance on the DERs during different system operating conditions. Therefore, HDPS cell concept is proposed in this thesis as an alternative concept to exploit the useful features of DER units in supporting the wider system by managing these units more effectively.

2.4.1 HDPS Cell definition

The HDPS cell is based on the concept that distribution networks incorporating large volume of DERs are divided into numbers of multiple manageable areas by which the DERs are controlled to meet particular objectives. Therefore, the cell is created due to the emergence of DERs within distribution system areas, and this makes the DERs as key elements within the cell. The characteristics of the cells depend on their boundaries which can be classified by distribution networks layout based on the allocated objectives that are required from the cell. So, a cell can be demarcated at various levels of distribution networks.

Within the cell two forms of objectives to achieve can be set. One is internal by which the local constraints caused by DERs can be managed within the cell. The other is external by which the DERs collective impacts can be passed to a higher management system to its boundaries (i.e. bigger cell) in order to support the wider system. In addition, the cell also should be capable of being able to operate in conjunctions with other adjacent cells or with higher management systems to the cell to form a bigger cell in a hierarchical structure that will significantly support wider system up to transmission level [2.68].

Figure 2- 7 shows demarcated areas start from LV and electricity users' points up to grid supply point (GSP) of urban distribution networks as an example of a number of cells that are formed in hierarchical structures. The cell hierarchical paradigm will provide flexibility, by passing actions across different cell levels moving toward the system as aggregate actions, and towards the local levels through subdividing structure. At each cell level will be allocated objectives starts from individual consumers up to multi-cell levels as it will be discussed further in section (2.4.3). The Figure 2- 7 also shows the main local elements of the cells that can be used for the system support.

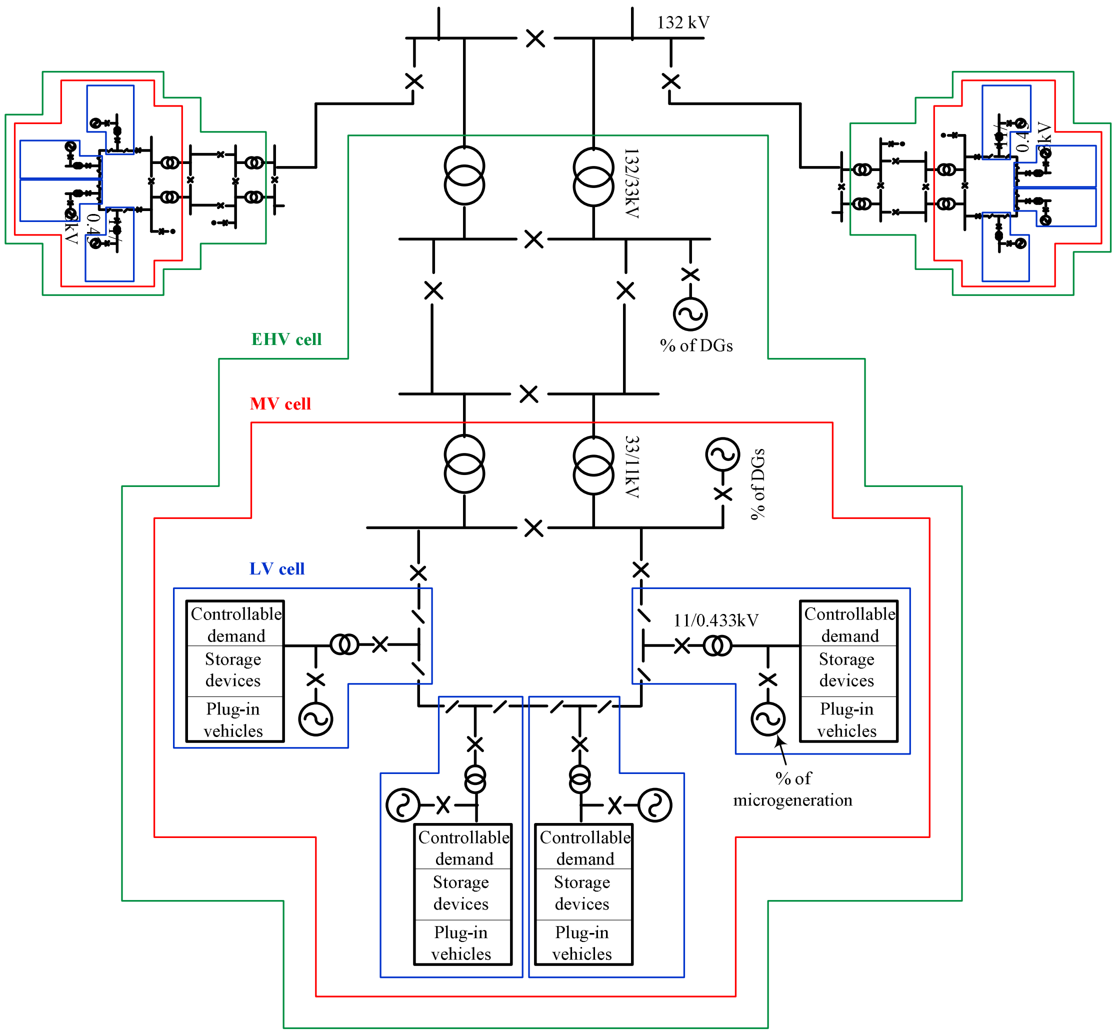

Figure 2- 7: Cell structure examples for urban networks

2.4.2 HDPS Cell objectives

The capability of a cell to perform certain function to meet the cell predetermined objectives can differ according to the size of the cell and the need of the system from the cell. The cell size can be influenced by the density and technologies of DERs incorporated within the cell as well as the cell structure. For example, the cell boundary can be identified at the point that the cell or a group of cells can provide external services to the higher system level. Or the boundary can be identified where the internal constraints can be locally managed. A range of local and external objectives that the cell may achieve are discussed below:

Cell local objectives:

- Effective energy management: integrating demand response with smart appliances by using information provided by smart meter will improve energy usage efficiency, and hence will lead to reduce peak demand.
- Managing local thermal constraints by performing the following functions; zero power export, zero power import, self-sufficiently, constant power import/export, and dispatchable power export [2.69].
- Maintaining local voltages within statutory limits: local active elements of the cell such as controllable local generation and demand, storage, and other local network assets and perhaps other smaller cells if exist can be used within a cell to improve the voltage profile across local distribution buses.
- Supplying power to the users during the loss of the main grid. This will require the cell to be capable of operating in island if distribution networks are disconnected due to faults, and black-start function would be also required.
- Improving reliability and power quality: since large amount of data provided by smart devices, this will increase the distribution automation level which will indeed help in quick and flexible reconfiguration which is in turn will improve the outage restoration time, and improve quality for the users. Also improving the reliability by means of intentional islanding can be obtained in case of system failure.
- Managing local disturbances: due to the increase in the penetration of microgeneration within the cell, the prospective fault level will be increased. This increase should be managed within the cell to avoid any damage could be caused to local equipments.

Cell external objectives

The cell external objectives are system objectives rather than cell level objectives. Some examples of external cell objectives are listed below:

- Support control of system voltage and system frequency
- Control of real and reactive power imports or exports through the cells and higher management systems.

- Control thermal constraints, and the spread of disturbances such as fault level increase and stability problems
- Increase the system reliability
- Minimise the complexity

2.4.3 Control structure of cells

Based on the cells boundaries and their size, the control structure of cells can be mainly built in hierarchical form so the control actions can be further aggregated or subdivided in order to maximise the useful inputs and outputs of each aspect of distribution systems at different voltage levels. The control actions and participation to the system operation can start from a single smart device at consumers' level up to higher management system levels, or from the system level down to device level as shown in Figure 2- 8. Based on distribution networks layout, the control approach within HDPS cells then can be divided into four levels; smart device control level, smart dwelling control level, cell control level, and multi cells control level. At each of these levels there are allocated objectives that the level should meet.

A- Smart device control level

The device control will control the smart device, such as controllable load, microgenerator, and storage and plugged-in electric vehicles within a smart house based on the instructions received from the higher level control. Localised controllers would be required to be installed in home appliances to make it possible for the appliances to be automatically controlled in response to supporting the system operating conditions, and at the same time provide some benefits for the users.

B- Smart dwelling control level

The control schemes at this level will have two main functions: Firstly, making a local decision at customer level based on using local measurement and received control and price signals to meet consumer aims and offer an effective household energy management. For example, the local loads and generation can be controlled by responding to feed-in technical and price signals. The local load and generation could be switched on and off based on low and high rate connection which could be linked to peak shaving. These individual actions can be significant when a high penetration of smart dwellings is present within the cell.

Secondly, responding to requests from local cell level control whenever are required for larger level targets. At this level the smart meter would play a significant role for providing the needed information about the condition of the smart consumer, and coordinating the actions between the consumer's smart devices which can benefit the consumer and support the system operation. At this control level, two directions of power and information between the users and their suppliers can be provided. The information that is provided to the higher control level can be used to take the appropriate action to perform the cell internal objectives based on the available options from the users.

C- Cell control level

The control at this level controls a number of active elements within the cell such as local generation, dynamic loads, energy storage, and other network measures to create the ability of mitigating local constraints and meeting local objectives, and providing a major system-level support. The aggregated corrective action can be extracted from the available collective distributed resources within the cell for local purpose or being exported to wider system level as aggregated actions. For example, the cell distributed resources can be used to maintain voltage regulation and keeping the local voltages within statutory limits. The cell also will enable coordinated control of the all the connected DERs and information provided within a cell to control its elements to provide: ancillary services, peak shaving and shifting, voltage control, system optimisation and reconfiguration, and disturbance management.

D- Multi-cell control level

The control at this level is a multi-level decentralised control that can provide multi-level corrective actions with respect to the host system operating conditions. The control at this level can be considered as an approach to perform administrative tasks to distribute the management and control tasks of numbers of cells in order to provide significant support to wider system in hierarchical structure. For example, system voltage and frequency can be supported by using the local small cells and DERs impacts.

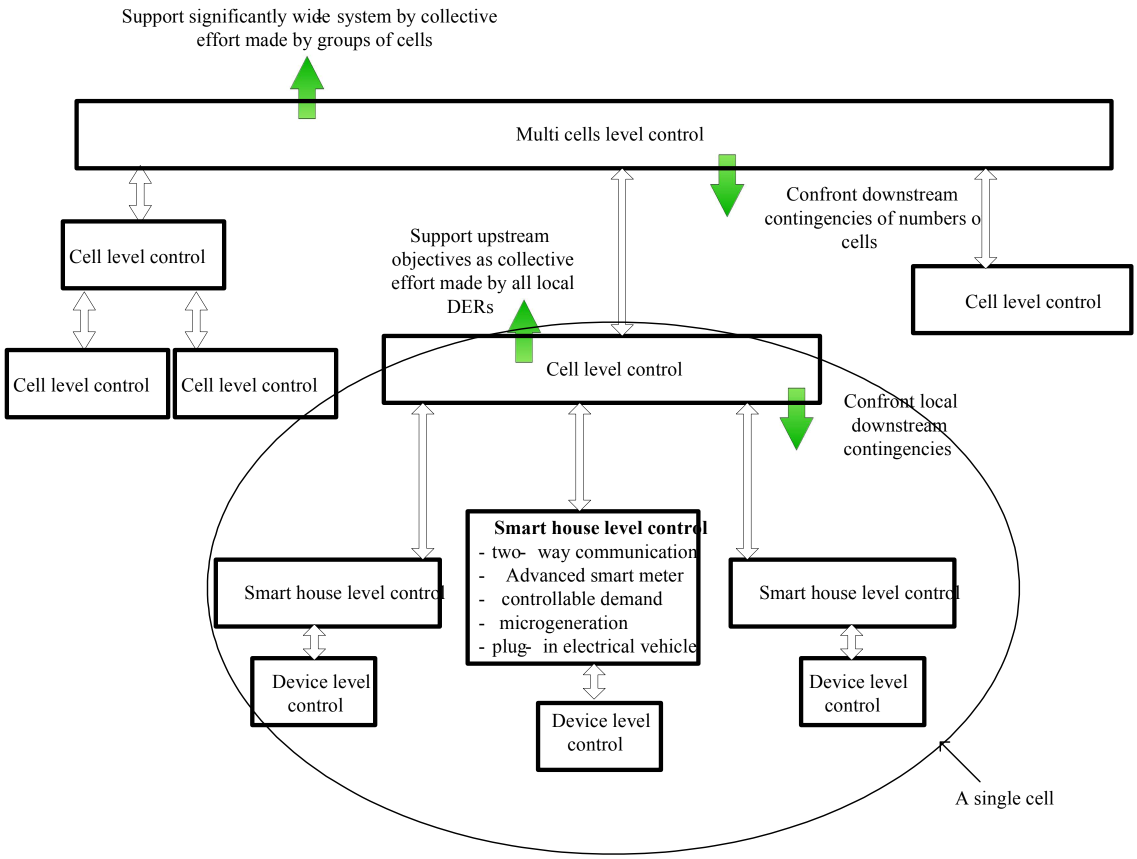

Figure 2- 8: Structure of control levels of HDPS cell concept

The HDPS cell concept based on hierarchical structures can be considered as an effective means to facilitate the utilisation of local DERs, and the possibility of exploiting the useful features of DER units in support of the wider system can be offered by the concept. The HDPS cell structure also provides simpler and better coordinated communication with DERs by building the system in hierarchical structure and allowing the inputs from DERs and groups of cells to be transferred as collective actions when it moves from the consumer level to wider system level.

In addition, the HDPS cell structure gives an indication of who controls the grid and how the grid can be controlled at different voltage levels, and at which level control actions are required based on the allocated internal and external objectives required from the cell to support the wider system. Another contribution can be made by HDPS cell structure is, by identifying the cell objectives in the benefits of the wider system, the appropriate DERs technologies and where can be fit within distribution systems to perform the allocated objectives can be proposed.

Therefore, when HDPS cell is compared with other alternative concepts such as Danish cell, HDPS cell concept is driven by allocated objectives which are normally set to support local and wider systems when a high penetration of distributed energy resources are incorporated. While the Danish cell concept is mainly driven by the value of islanding operation and black-start as main objectives. Also HDPS cell concept is a definite physical structure of active distribution systems rather than a vision based on the characteristic of the system such as SmartGrid and IntilliGrid visions. This means that the HDPS cell concept can be used as a means of delivering these visions.

Based on HDPS cell structure, and on the projection of forward looking power network scenarios discussed earlier in section (2.3.5), substantial amount of microgeneration are expected to be installed in the future, and hence they will become an important element of the cell that can be used to support the cell objectives. The cells performance with such units need to be well studied and well understood under different system operating conditions in order to evaluate measures of risk and resilience levels. This can help to manage the cell local constraints and at the same time prevent the disturbance to be spread to other adjacent cells or to higher system levels. Therefore, the possible technical impact that a high penetration of LV connected microgeneration may have on the performance of LV cells under fault conditions, and stressing practical measures by which these impacts are minimised are discussed in the next section of this chapter.

2.5 Potential technical impacts of LV-connected microgeneration

Traditional distribution systems are radial in nature, and approximately 75% of customers hours power lost are due to faults on distribution networks [2.70]. When large volume of microgeneration connected to LV networks this nature will be impacted and during the fault a number of technical issues may be caused by microgeneration. For example, during fault conditions both microgeneration and the host distribution network are under stress. Microgeneration will provide a new path of fault currents, and the host distribution network has been designed without the existence of such path. From the other angle, the host network performance during faults may significantly influence the fault ride through capabilities of microgeneration.

Most of existing low voltage equipments are designed without consideration of connected microgeneration, therefore the increased fault level caused by microgeneration may lead the equipments to reach their short-circuit ratings, and this can cause damage to the equipments. In addition, the new fault paths provided by microgeneration will provide reverse fault currents, and these currents may impact the LV protection performance, since the design of LV distribution systems protection is largely based on fault with one direction, and the fault source is always seen far from distribution networks.

The following sections summarise the significance of investigating the anticipated transient problems surrounding the integration of microgeneration units on a large basis, and the studies that have been conducted by other research. It is summarised from two points of views; one is the impact of microgeneration units on the host low voltage distribution network performance during fault conditions, and the other is the impact of the host distribution network performance during fault conditions on the transient performance of LV connected microgeneration. Three areas are included; fault level issues, low voltage protection performance issue, and microgeneration transient stability issues.

2.5.1 Fault level issues

Most of traditional distribution networks are radial in nature with only one source and one path of fault currents. Based on this philosophy, the fault current rating of distribution systems equipments is identified, and the equipments are designed. Also, at medium and low voltage distribution networks, the fault contribution of the upstream grid is determined by the impedance of the HV/MV and MV/LV transformers, which is normally chosen to be at its lowest value in order to reduce the losses and at the same time improve the voltage regulations. This may make the short circuit capacity of traditional distribution networks to be close to their design limits [2.71][2.72]. This design has not at all considered the projection of connecting new local generation at distribution networks. So, adding large population of microgeneration to distribution networks will contribute to the system fault level, and this will alter the networks fault level. This is because uncontrolled short circuit can cause numbers of problems such as service outage with associated inconvenience, interruption of essential facilities or vital services, extensive equipment damage, personal injury or fatality, and possible fire damage [2.73]. Therefore, fault levels studies are necessary to ensure that short-circuit ratings of the components are adequate to handle the fault currents available at their locations, and each individual component of existing distribution systems must withstand the prospective fault current when microgeneration are installed.

There are numbers of studies have been conducted to identify whether the areas of distribution networks will be affected by the fault level increase due to the forecast growth in distributed generation. However, regarding to a fault level issue caused by microgeneration, the issue has not received a wide attention, and still no clear answer about whether the fault level due to microgeneration connection would be problem or not. For example, PB power report studies have considered the impact of small-scale single phase generators (i.e. 1.1kW per customer) with penetration up to 100% on LV and MV of a typical UK distribution network fault levels [2.74]. The studies have concluded that the existing LV networks can take up to 100% penetration of small scale microgeneration rating from 1 to 1.1kW, and the only limit was outlined is voltage regulation, and this limit can be overcome by adjusting transformers tap changers or upgrading the transformers. The report has only considered the system fault level issues due to the connection of single-phase microgeneration to domestic premises. The report did not consider microgeneration size that can be connected at commercial levels. For such application, microgeneration can be a three-phase device, and its size can be up to 50kVA.

Another study to tackle fault level issues is the KEMA consulting report for the department of trade and industry of the UK (DTI) to investigate the contribution to UK distribution network fault levels from the connection of distributed generation in short-term period. The output of the studies has indicated that the fault level will not be a problematic in the majority of LV networks, and the only areas are expected to experience fault level issues are the following three cases of the distribution networks [2.75][2.76]:

1- LV networks with a high penetration of distributed generation may require fault level related reinforcement, for instance, where micro CHP is installed in high density urban areas. KEMA has indicated that they do not have experience with networks where large amounts of micro CHP are installed in urban networks [2.75].

2- The increase in power generated from small, medium and large CHP will lead to the increase in fault levels on already densely MV urban 11kV and 33kV networks which currently have the lowest fault level headroom.

3- Isolated 132kV substations where large-scale DG projects connect into rural networks.

The results from the KEMA report [2.76] are based on the contribution to distribution fault level from LV connected distributed generation (DGs) in short-term scenarios, with DGs representing no more than 2.5GW of the UK capacity (i.e. about 3% of the UK peak load). This amount of generation is relatively smaller than the amount of microgeneration that is expected to be installed by 2050 under different scenarios as discussed early in this chapter. The studies also have assumed the fault level will not limit the uptake of distributed generation connected to LV distribution networks where the interface of these generators by power electronics is expected to increase. However, the same studies have stated that in some situations, if distributed generation penetration levels are sufficiently high, it may necessitate network reconfiguration or uprating of equipment. This may occur in the areas with a high density of micro CHP which is more likely to be in urban areas.

Therefore, the impact of LV connected microgeneration with different penetration in respect to the local loads on the fault level of a realistic MV/LV urban distribution network example based on the cell structures is quantified in chapter three of the thesis.

Two sizes of microgeneration are used; domestic and commercial sizes. Microgenerators are modelled in details as an aggregated model with careful consideration of the impact of the impedances of the cables between microgenerators connection points to examine their collective impacts on the fault level of a typical urban distribution networks.

2.5.2 Protection issues

The protection schemes of any power systems including distribution consider a number of requirements such as [2.70].

- Speed (i.e. not too slow which may lead to damage of the equipments and not too fast which may lead to losing selectivity)
- Reliability (i.e. the certainty of a correct operation & the security against incorrect operation)
- Cost (i.e. maximum protection is met at the lowest possible cost)
- Sensitivity (i.e. good capability of detecting faults on the system).

Associated with a traditional distribution system, these protection requirements have been considered for a passive system. When a large number of microgenerators are connected to LV distribution networks, the networks will not be considered anymore as a radial with unidirectional power flow. A new path for short-circuit currents is provided. This may impact the requirements of protection systems of LV distribution networks. If the protection performance is impacted, and it is not properly handled, then lower reliability, lower sensitivity, and even reduction in power quality by lowering the protection selectivity may result [2.77].

Another reason that increases the interest of investigating this area is the nature of the existing protection schemes that protect LV distribution networks. The passive LV feeders are still widely protected by simple overcurrent protection schemes by using fuses blowing schemes for simplicity and cost reasons. Fuses do not have inherent directional properties, where the direction of the current flow is always identified. Adding microgeneration to the LV system may increase or decrease the fault current seen by the LV fuses depending on the fault location, and fuse and microgeneration location. For example, the aggregate contribution from microgeneration to the fault current feeding downstream faults may accelerate the fuse operating time for downstream faults, where the higher fault current will lead to faster fuse operation. Also reverse fault current provided by microgeneration to feed upstream faults may wrongly blow up fuses at the beginning of LV feeders. If any fuse is wrongly operated, the restoration may take some time due to the following the operation which leads to loss of supply until the fuse unit is replaced.

The distribution network protection issues caused by the presence of distributed generation that can be connected at MV side have received a wide area of investigations and studies. However, the impact of a high penetration of small scale microgeneration connected to LV side on LV protection performance has not received much attention. Numbers of researches such as those reported in [2.78] and [2.79] have stressed that the connection of distributed generation to MV may cause traditional protection schemes to become ineffective. In these studies it was concluded that the widespread use of distributed generation created a series of new problems, such as impacting the coordination of overcurrent protection in addition to control of voltage sag magnitude and duration by using overcurrent protective devices [2.80]. The connection of heavy penetration of distributed generation to distribution networks could blind protection devices, or wrongly trip a safe feeder by feeding a fault on an adjacent feeder [2.78]. With the connection of distributed generation, the system coordination could be lost [2.81]. In a case of fault, DGs impact the current contribution to fault, and therefore it impacts the behaviour of network protection [2.81]. When DG is connected, an additional power flow is added from the load side, and therefore opening the main protective device may not assure that the fault is cleared [2.82].

The studies in [2.83] which were carried out to find innovative solutions for protection problems arising in distribution networks in presence of DGs. The studies illustrate the malfunctioning problems that may take place in distribution networks protection schemes in presence of DGs. In particular the following areas were considered; lack of coordination in protection schemes, ineffectiveness of line reclosing after a fault using automatic reclosing devices, undesired islanding and untimely tripping of DG interface protections. In terms of coordination issues, the studies found that if the faulted section is upstream from the protection devices two possibilities can emerge [2.83]:

- Protective devices see the same fault current, and hence coordination can be lost.
- Protective devices see different currents, and coordination can be maintained if the generators that provide a higher contribution to fault currents connected upstream from those with a lower contribution.

So, the remaining research question is, will the collective impact of a large penetration of LV connected microgeneration during fault conditions be strong enough to impact the low voltage protection performance as same as distributed generators do at MV level, or due to their small size the impact will be insignificant?

To answer this question, in chapter four of the thesis more literature review on the work that has been recently conducted in this areas is further discussed, and detailed studies are carried out to outline the protection system problems in LV distribution systems when a high penetration of microgeneration are connected to the LV distribution systems. The influence of microgeneration on LV system protection is analysed, taking into account the impacts on the following requirements of LV protection schemes fuse based: the correct operation (i.e. reliability), the graded setting (coordination or selectivity), and the ability of the protection fault detection (i.e. sensitivity). The results are in favour of identifying whether the LV distribution networks are still sufficiently protected, or some measures will be required.

2.5.3 Microgeneration transient stability issue

The previous two areas discussed the possible potential impacts that microgeneration may have on the host network during fault conditions, and for benefits from microgeneration and support to the host system under transient disturbance to be realised it is also important for these devices to ride-through transient disturbances on the host system. This will require understanding of the resilience level and the transient response of microgeneration during and after the system transient disturbances.

Transient stability studies at distribution system level particularly at LV were formerly insignificant before microgeneration with different sizes and technologies began to be connected to LV feeders. The results that are presented in [2.84] have shown that distributed generation (DGs) at heavy penetration levels will have a significant impact on local distribution systems, and sometimes the bulk transmission system stability may be affected. The low inertia of those generators may increase the weakness of the system. This means the connection of a large number of microgenerators interfaced by low inertia rotating machines into LV distribution network would be more sensitive to faults on the host systems compared to DGs with larger size and better transient response.

Faults on the host system will cause voltage dips, and if the dips are noticed on the terminals of rotating machines connected to distribution networks, transient stability issues may result. This is because the terminals voltage and the rotor speed are intrinsically related, and the rotor speed will increase when the machine terminals voltage decreases due to faults. If instability occurs, sensitive elements such as microgenerators with low inertia and limited controllability can be tripped, and dynamic loads can be stalled if the fault is not cleared quickly. The duration of voltage dips depends on how fast the fault will be cleared by the existing protection.

The distribution network protection schemes are normally based on coordinating the operating times of the protective devices, where downstream elements will respond to faults faster than upstream. This will lead to different operating time dictated by location and type of faults in order to meet protection selectivity purposes. In [2.85] it has been stated that such coordination may lead to operating times of protective devices at the upstream end of a distribution feeder as high as 1.5 sec. Such operating time may not be small enough to maintain the transient stability of connected microgeneration, and thus, the units in an affected area will be disconnected for faults close to upstream protection devices. The impact of losing a single or a few microgenerators following a fault on the system may not be a significant issue except perhaps to individual customers, but the unnecessary disconnection of a large penetration of microgeneration due to remote faults upstream from microgeneration can become problematic. It may have technical, environmental, economic, and social impacts.

From technical perspective, the impact could change the voltage of one phase and may unbalance 3-phase voltages at LV and MV levels through the MV/LV transformers [2.78]. Existing distribution networks are already suffering from voltage unbalance issue due to the random connection of houses to particular phases along a feeder. Another problem could emerge due to unnecessary disconnection is voltage steps which can be seen as a power quality issue, and it is identified in Engineering Recommendation P28 not to exceed a limit of ±3% of the magnitude of the voltage step change occurring from switching operations [2.86]. Also the voltage step changes due to simultaneous reconnection after tripping could result from microgeneration transient instability. In order to avoid delay in reconnection microgeneration, the Engineering Recommendation G83/1 has permitted that if a microgenerator is disconnected from the network, it can be reconnected to the grid after 3 minutes [2.57]. If large numbers of microgenerators are disconnected due to transient instability, this permission could allow considerable numbers of microgenerators to be reconnected almost simultaneously after 3 minutes of disconnection.

In addition, since microgeneration will behave like negative loads, their simultaneous trip can lead to sudden emergence of hidden loads which may initiate the low frequency load disconnection schemes or under voltage protection schemes if nominal voltages or frequency limits are exceeded due to the emergence of hidden loads. Taking 27th May 2008 event in the UK [2.28] as an example, there was unexpected tripping of large amount of distributed generation (i.e. about 279MW connected to the UK distribution systems) which led the maximum secured loss at that day to be exceeded, and the low frequency load disconnection schemes to be initiated and affected about 550,000 of consumers. So if a high penetration of microgeneration is disconnected due to remote faults, then the performance of the system may be impacted adversely by the sudden appearance of the hidden load which may lead to disconnection of consumers.

From social perspective, unnecessary and unplanned disconnection of microgenerators privately owned will be unacceptable, and this can impact customers' interest in considering microgeneration as reliable and sustainable energy sources. From environmental perspective, disconnection of microgeneration would lead to losing their significant contribution to tackling climate change. For example, in the case of significant amount of microgeneration disconnected, the lost local generation amount will be compensated by large power plants. This means more fossil fuels will be used and more losses in transmission and distribution lines will be incurred until microgeneration are reconnected. In addition, within deregulation power market structures, undesirable disconnection of microgeneration driven by consumers' choice may directly lead penalty compensation to the users those lost their generators due to system faults.

Therefore, for a system support under transient disturbances by microgeneration, and for avoidance of any negative impacts that unnecessary disconnection of microgeneration may have on the system performance, there is a need for microgeneration to be able to overcome a number of associated system transient disturbances. This need makes transient stability of LV connected microgeneration to be an emerging area that requires deep studies, and the endurance of microgeneration to ride through remote disturbances to become vital.

To sum up, microgeneration interfaced by rotating machines can be sensitive to transient disturbances on the systems because of the following reasons:

- Microgeneration are machines of small rating with low inertias.
- Microgeneration have limited control capability (the AVRs and speed governors if present have poor dynamic performances).
- Protection philosophy in distribution systems is based on coordination schemes, and this can lead protective devices at upstream end to operate up to few 100s msec. Such operating time may not support the transient stability of LV-connected microgeneration.

So two following research questions emerge in this area:

Q1: How large amount of LV connected microgeneration (i.e. within LV cell) will respond to fault conditions on the system, and what is the compatibility between the existing low voltage distribution protection performance and the capabilities of microgeneration to ride through faults?

Q2: What are the possible innovation solutions and changes that can be implemented to traditional distribution networks in order to provide improved transient stability performance of microgeneration, and the avoidance of negative impacts associated with microgeneration transient stability issues can be reaches?

To answer these two questions, chapter five of the thesis analyses in detail the transient performance of different size and technologies of LV connected microgeneration when different fault conditions are applied to the host distribution network, and the resilience level of microgeneration against different fault locations is quantified. In chapter six, a remedial measure by which microgeneration transient stability can be improved is introduced.

2.6 Computer simulation programme used for thesis studies

The Electro-Magnetic Transients including DC (EMTDC) interfaced by PSCAD computer programme has been used for conducting all the technical work of the thesis. PSCAD/EMTDC can be used for simulating the time domain instantaneous responses to study the electromagnetic transient phenomena, analyze different electrical power systems conditions, and to be used for verification purposes. This tool is a powerful tool that can be used for understanding the behaviour of different electrical systems when the system is subjected to disturbances. Its electric network solutions are based on digital computer solutions in single and multiphase networks. In addition, the tool has a rich spectrum of professionally developed models of different machines, exciters, governors, stabilizers, turbines, and multi-mass tensional shaft model as well as other complementary elements that can be used for power system simulations [2.87]. Also default data of machines and electric branches based on typical data obtained from industry are available with the PSCAD master library.

2.7 Test network selection

A typical HV-LV distribution network for an urban example (i.e. more likely to have higher fault currents) based on an actual urban distribution network has been selected as a test network for investigating the technical issues related to the connection of a high penetration of microgeneration to passive low voltage distribution networks. All the data used for the network model has been derived from information provided within distribution long term development statements (DLTDS) by the distribution network operators (DNOs) and manufacturers of distribution equipments [2.88]. The test network is developed in detail in the next chapter and defined as test network 1 and used for fault level and low voltage protection studies. The same test network with different model details of low voltage networks which is suitable for stability studies are developed in chapter five and defined as test network 2 and used for microgeneration transient stability studies.

2.8 Chapter summary

Environmental issues, security of energy supply issues, emerging competitive power markets, deregulation of electric utilities, and the advance of technologies such as advance communication and smart devices and the exploitation of renewable and low carbon energy resources have stimulated the interest in increasing the numbers of local distributed energy resources (DERs) at distribution systems. Adding a high penetration of DERs including microgeneration to a traditional power system that has not been designed to accommodate such devices will bring a great change to the configuration of such a system.

There are numbers of future power system visions such as IntilliGrid vision, SmartGrid vision, and HDPS vision that have been developed by different researchers to provide a vision of future power systems that can manage the changes that will occur due to the integration of DERs. These visions are based on the characteristics of future power systems and what the systems should offer, and what type of technologies can be implemented to meet certain objectives. However, at the moment these visions do not provide a clear physical structure of how large penetration of DERs can be controlled to gain the benefits that are promised by using DERs. The vast spread of DERs across distribution power systems requires to be controlled within a clear and neat structure in order to maximise the benefits, and minimise the adverse impacts that DERs may have on the system performance.

Within this chapter, a new cell concept was proposed as a means of delivering the objectives of future power system visions by facilitating the exploitation of useful features of local generation and controllable dynamic demand. The concept is based on dividing active distribution networks into manageable areas (i.e. cells) in a hierarchical structure in which the cells can be subdivided into different control levels starts from multi-cell control level down to single device control level. At each control level there are allocated objectives that the cell at that level should meet in order to support itself and the wider system. The structure was proposed in order to provide a system level support by DERs as well as mitigating local constraints on local generation and dynamic demand.

There are other alternative concepts of controlling distributed resources such as “Danish Cell” which is mainly driven by the values of islanding and black-start operation. In contrast, HDPS cell opens access for DERs to provide their maximum contributions of ancillary services to support the local and wider systems under different operating conditions based on the cell allocated objectives. Based on the cell allocated objectives the HDPS cell also provides an indication of who controls the grid at different voltage levels.

For the benefits of DERs including microgeneration to be realised, the behaviour characteristics of a system incorporating a high penetration of these devices is important to be understood under different operating conditions, particularly when the host system experiences transient fault conditions. The host distribution systems must cope with problems emerging due to the presence of large amounts of microgeneration during faults such as increased fault levels and protection problems. Also local generators connected to the host distribution networks must overcome transient disturbances and avoid unnecessary trip. These two areas are widely analysed in the thesis, and solutions are proposed.

By proposing a new cell concept as one of the solutions that can deliver the objectives of future power systems, and understanding the behavioural characteristics of a system with a high penetration of small scale local generation, this thesis offers very valuable contribution to future attainment of sustainable power systems.

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Chapter Three: Fault level analysis of distribution networks with a high penetration of LV connected microgeneration

3.1 Introduction

Unpredictable faults may occur in any part of electric power systems, however, faults occur more frequent on electric distribution networks [3.1]. Faults on the system can introduce large amount of destructive energy of heat and magnetic force into a power system, and calculations always should be made to ensure that short-circuit ratings of the components are adequate to handle the fault currents available at their locations [3.2]. The fault current rating of electrical components within any system mainly refers to two properties as indicated in [3.3]; the amount of absorbed electrical energy by the components during the fault which is equal to the square of the fault current multiplied by the time of the fault duration, and the electromechanical stress that is applied on the system components during the fault. The first property has a thermal impact, and if the impact exceeds a certain limit, then the faulted component will melt down. The second property is an electromechanical force which is produced within the fault current-carrying component, and it is proportional to the square of the instantaneous current flowing and irrespective of the fault duration time [3.3].

Traditional distribution networks have been designed to accommodate prospective fault currents and each individual component of the network are rated to withstand the thermal and mechanical forces emerging during faults. Also, most of distribution networks are already designed close to their maximum short-circuit capacity [3.4]. The design is justified by the cost, where higher rating design leads to higher cost. In addition, the faults at passive distribution networks are always seen as far from the short-circuit sources, and the design did not considered the projection of adding new generation at distribution system levels.

As discussed in previous chapter, adding new generation to distribution networks will provide new sources of fault currents, and the increase of the generation penetration will obviously increase the contribution to the faults. There are numbers of research studies have investigated the impact of distributed generation on distribution networks fault level particularly at MV level. As an example, the study conducted in [3.5] has shown that adding new DGs based on the projection of the UK 2020 scenarios [3.6] to MV networks of an urban example has increased the fault level 2% beyond the design limits. In addition, other studies in [3.7] have examined the impact of adding DG with total amount of 5.5MW to 11kV side of different distribution network topologies, and the type of the network that is more likely to be impacted has been observed is the interconnected distribution network. In terms of the fault level issues at LV distribution networks, the report provided by KEMA for Department of Trade and Industry of the UK has stated that LV distribution networks with a high penetration of distributed generation may require fault level related reinforcement is micro CHP is installed in high density urban areas [3.8][3.9].

Therefore, the work of this chapter investigates whether the increased fault level due to connecting substantial volumes of microgeneration to LV distribution networks will likely impact the fault level of a typical low voltage distribution network or the fault level contributions will be insignificant and should be ignored? In order to answer this question, the chapter investigates the factors that are more likely to influence prospective fault level in a typical distribution network. Based on these factors, the worst fault scenarios are assumed and detailed studies are conducted to test the impact of LV connected microgeneration with different penetration on local distribution networks fault level. Detailed case study based on a typical HV-LV distribution network for densely LV urban examples with low fault level headroom and incorporated with different penetration of commercial and domestic size microgeneration is used. The used network is structured based on the cell structure, the test network is assumed to represent an entity of HV cell from 33kV down to other small LV cells as layers (i.e. RMU) at 400V.

3.2 Factors impacting distribution networks fault levels

For analyzing and studying fault level issues, the characteristics of the faults and the factors that impact the fault levels at distribution systems need to be understood. The characteristics of fault currents can be explained from the general formula of short circuit current profile as expressed in equation (1) [3.10].

$$I = I_{mf} \sin(\omega t + \alpha - \theta) + [I_{ms} \sin(\alpha - \theta') - I_{mf} \sin(\alpha - \theta)]e^{-\frac{1}{\tau}t} \qquad (1)$$

Where I_{mf} is the peak value of the ac short circuit current and it is equal to $\frac{V_g(system\_voltage)}{Z_{cr}(shortcircuit\_impedance)}$

I_{ms} is the steady state fault current.

α is the initial system voltage angle.

θ' is the impedance angle prior to the short circuit.

θ is the short circuit impedance angle and it is equal to $\tan^{-1}(\frac{X_l}{R})$.

X_l is the reactance between the sources and the fault point.

R is the resistance between the sources and the fault point.

τ is the decay time constant of the DC component and it is equal to $\frac{L}{R}$.

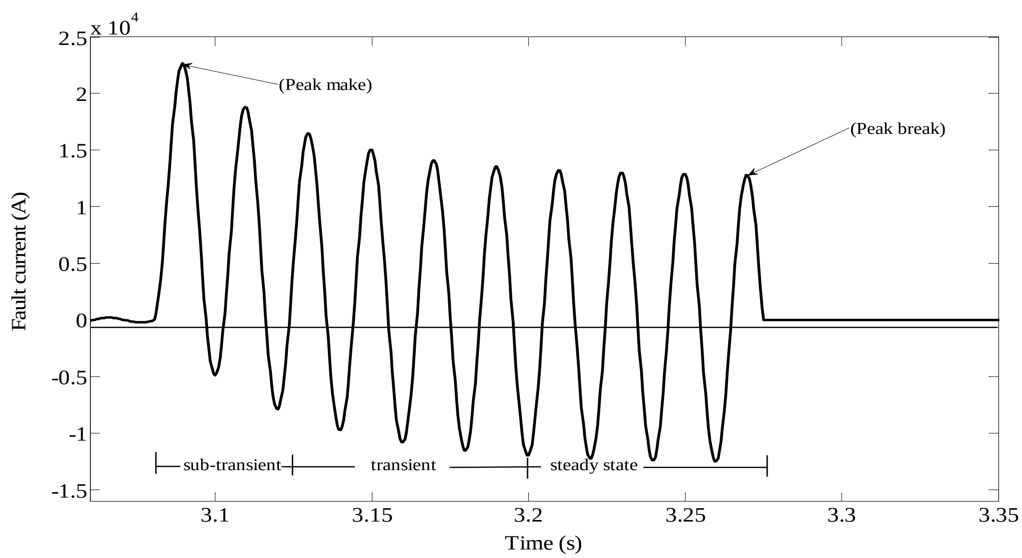

Figure 3- 1: An asymmetrical fault profile

From (1) it can be seen that the short circuit current consists of two components. One is ac and the other is decaying dc which appears due to the presence of the reactance of the system feeders and connected machines. The first highest peak of the fault current within the sub-transient period as shown above in Figure 3- 1 is called “peak make”, and it can reach 2.55 times of the steady state fault current as shown on the same figure within a typical distribution network, and provides asymmetrical fault current until the dc component is eliminated [3.3]. The asymmetrical fault currents peaks decay away to its steady state fault current after few cycles. The rate of the decay depends on the ratio of the system reactance to the system resistance (X/R) as seen at fault points. X/R ratio and the values of fault currents that impact the system fault level are dictated by numbers of factors. The major factors that may impact the fault level issue are discussed as follows:

3.2.1 Distribution Network topologies

At the instant of the fault, the current will rapidly increase to very high values and all the available fault currents will flow into the fault point. The maximum allowed fault current depends on the fault types, fault locations, and the network properties (i.e. impedances between the sources and the fault point). The network properties depend on the network topologies which can be formed as urban, suburban, or rural, and each has its own impacts on the fault profile. Basically, they provide different impedances. Urban distribution networks normally consist of high density of consumers and connected by short feeders, so these types of networks will have the lowest fault level headroom with comparison to other two with longer feeders. Also the short-circuit impedances of MV-LV transformers play very significant role on the magnitude of the fault currents on both sides MV and LV. The contribution from the grid to a fault on LV side will be reduced by the value of these impedances. As result, total impedance between the fault current sources and the fault location is one of the main factors that impact faults profile. The impact will affect both the ac and dc components of the fault profile.

3.2.2 The type and duration of faults

The magnitude of the fault current is impacted by the fault type such as single-phase to earth fault, phase-to-phase fault, phase-to-phase to earth fault, or three-phase to earth fault. Each of these faults has different fault characteristics, however, when short circuit rating of any component is studied the worst possible fault current is assumed, and this can occur when the fault is a solid three-phase short circuit and occurs close to the component. While the thermal impact of fault current depends on its duration. For example, the equipment may withstand a certain short circuit for few seconds, and if the fault lasts longer the equipment will melt. Therefore, the fault current rating will then be specified as a current and time rating.

3.2.3 Types of loads

Normally passive loads have no impact on the fault level, but the dynamic loads such as motors could have an impact on the fault level. Large induction motors can contribute to system fault level, and contribution will decay very rapidly [3.11].

3.2.4 Connected generators

When generators are connected to distribution systems they will contribute to the prospective fault level of the system (i.e. faults from the grid plus faults from connected generators) as shown in Figure 3- 2. Their contributions will depend on their type, size, and penetration. For instance, a contribution from generators that are interfaced directly to the distribution networks by synchronous machines which normally have enough over excitation during the fault may initially provide fault currents as high as 6 times of the generator full-load current [3.12]. Synchronous machines are normally equipped by separated excitation system, so they can supply sustained fault current until the fault is cleared. Equation (2) as given in [3.13] and [3.14] estimates the fault current contribution of the synchronous generators:

$$i(t)=\sqrt{\frac{2}{3}}V_g[(\frac{1}{X_d^{''}}-\frac{1}{X_d^{'}})].e^{(-t/T_d^{''})}+(\frac{1}{X_d^{'}}-\frac{1}{X_d}).e^{(-t/T_d^{'})}+\frac{1}{X_d}]\sin(\omega t+\theta^{'})-\sqrt{\frac{2}{3}}\frac{V_g}{X_d^{''}}\sin(\theta^{'}).e^{(-t/T_a)} \qquad (2)$$

Where $X_d^{''}$ and $X_d^{'}$ are the sub-transient and transient reactances, and $T_d^{''}$ and $T_d^{'}$ are the sub-transient and transient time constant. T_a is the periodic time constant, and $\theta^{'}$ is the impedance angle prior to the short circuit. From equation (2) it can be seen that distributed generation interfaced to the grid by synchronous generators will contribute to fault current during the sub-transient, transient and steady state periods of the short circuit.

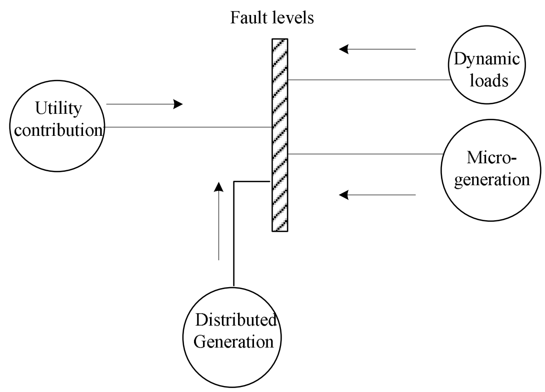

Figure 3- 2: Fault current sources

As for distributed generation interfaced to the grid by induction machines which get their excitation from the mains, their fault level contribution will be limited. This is because in case of three-phase to earth fault, the excitation is completely lost. Therefore, the induction generators will feed the fault within very small time due to the remaining magnetic field in the machine [3.14]. The following formula gives the expected contribution from induction machines to the short circuit current [3.13][3.14].

$$i(t) = \frac{\sqrt{2}V_g}{X_s^{"}}[e^{(-t/T_s^{"})}\sin(\theta^{'}) - (1-\sigma)\sin(\omega_s t + \theta^{'}).e^{(-t/T_r^{"})} \quad (3)$$

Where $X_s^{"}$ is the sub-transient reactance, $T_s^{"}$ is the sub-transient stator time constant. σ is the total leakage coeffieceint, ω_s is the synchronous angular speed, and $T_r^{"}$ is the sub-transient rotor time constant.

It can be seen from the formula (3) that the short circuit will be supplied by induction machines only during sub-transient period. However, the contribution to the short circuit from induction generator during sub-transient period is lower than from synchronous generator with similar rating. The Figure 3- 3 below which is a result of the study that has been conducted in [3.14] to investigate the contribution of synchronous and induction generators to the system fault level shows the difference between the contribution to the fault level by two machines with the same rating and interfaced by different rotating machines (i.e. one by synchronous and the other by induction). Unlike the rotating machines, the fault current provided by converter-connected units is much lower, and it is assumed to range from 1.2 to 1.5 times of the rated current [3.12].

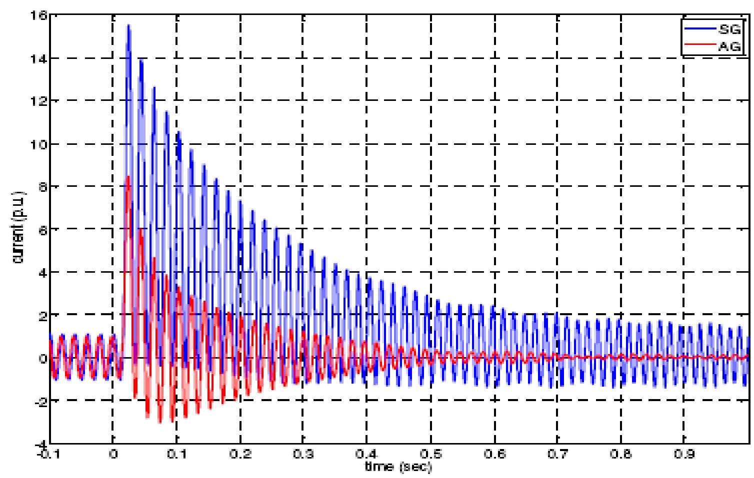

Figure 3- 3: Short circuit contribution from synchronous and induction machine machines during 3-phase bolted fault [3.14]

3.3 Test network and modelling approach

In general fault levels are high in largely interconnected networks with a high density of load, such as industrial areas and city centres. Therefore, a typical UK HV-LV distribution network for an urban example is used as test network for investigating the impact of LV connected microgeneration on distribution network increased fault level. The test network has low fault level headroom based on an actual value taken from a real Scottish urban HV-LV distribution network based on the information provided by the ScottishPower distribution long term development statements (DLTDS) [3.15]. The network supplies a high density of domestic and commercial loads based on the rating of the main transformers of the actual network chosen for the study. A single line diagram as shown in Figure 3- 4 represents the test distribution network used for the fault levels studies. The diagram shows all the short circuits sources and the significant circuit elements that are required for the studies. The network represents one layer of 30kV cell which consists of other small LV cells. Eight LV cells (i.e. from A-H) of LV urban examples as shown in Figure 3- 4 are modelled, and the cell A shown in Figure 3- 5 is modelled in detail. The studies are carried out concentrating specifically on the perspective short-circuit currents at the boundary of each cell (i.e. LV and HV cells) when a high penetration of microgeneration is connected within these cells. The network model is built based on distribution network data derived from information provided within distribution long term development statements (DLTDS) by the distribution network operators (DNOs) and manufacturers of distribution equipments. The test network is labelled as test network 1 in this section and developed as follows:

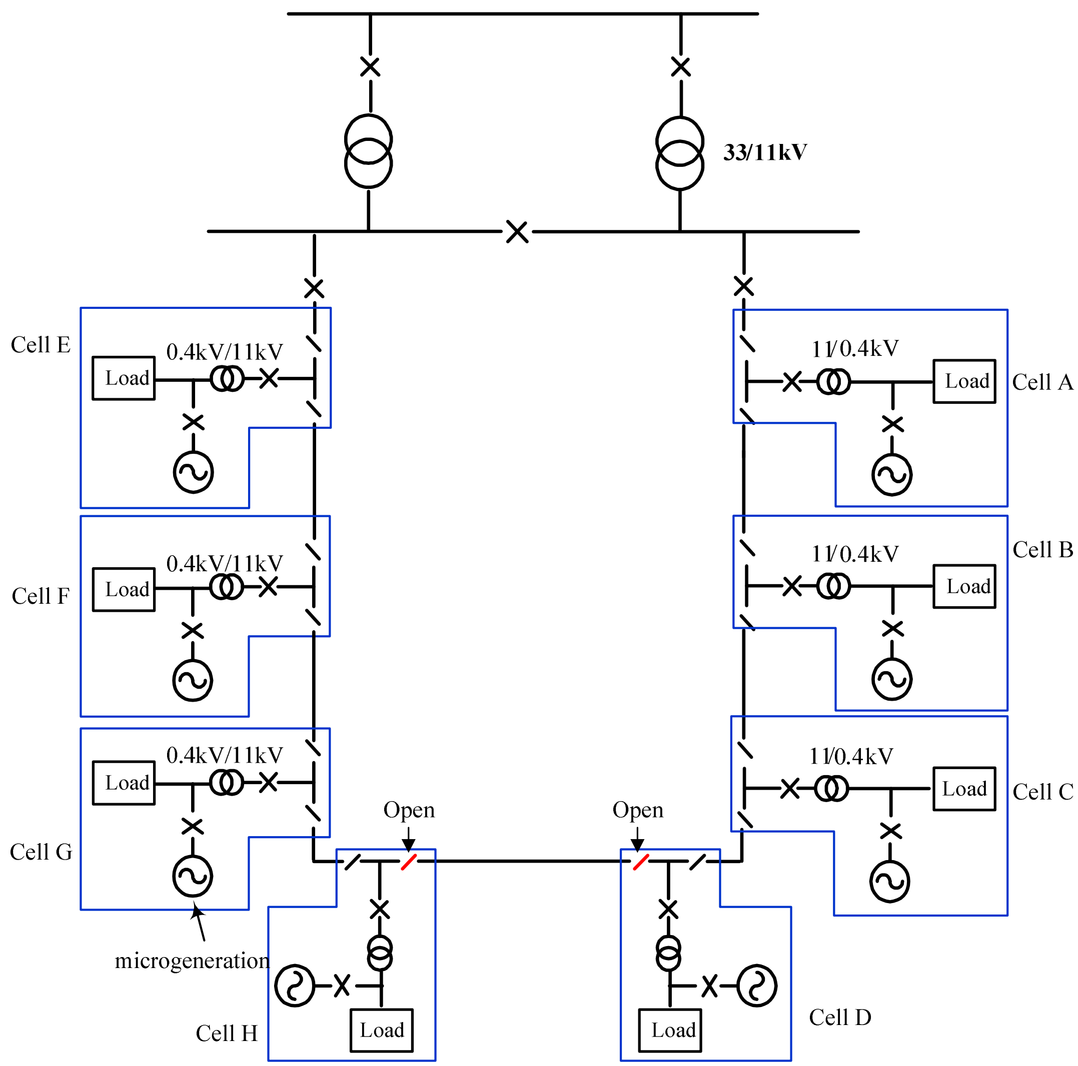

Figure 3- 4: A typical HV-LV urban distribution network

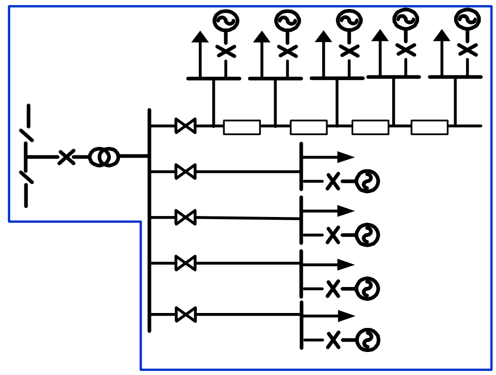

Figure 3- 5: Detailed LV cell (Cell A)

3.3.1 The grid source model

The grid has been modelled by using a three-phase voltage source behind equivalent impedance to provide an appropriate short circuit. The equivalent source impedance is calculated based on the IEC 60909 standard [3.16] where the impact of maximum voltage factor *"Cmax"* is included. *Cmax* is used to determine the maximum short-circuit current with sufficient accuracy that can be provided by the grid, and its value for MV grid is assumed to be equal to 1.1, and it can be multiplied to the nominal voltage when the short-circuit impedance is calculated.

The X/R ratio 9.26 and the short circuit current RMS break 17.67kA represent the real data of the 33kV substation fault level of West George Street substation in Glasgow in Scotland as reported in [3.15] have been used to represent the grid source of the test network. The fault level is calculated by using the system voltage=33kV**Cmax* and the fault level of the test network will be 1110.97MVA. The short circuit impedance, resistance and the reactance of the grid has been calculated from the fault level and X/R ratio, and their values are shown in Table 3.

System voltage	fault level	Short Circuit Current (RMS break)	X/R ratio	Short circuit impedance(Zs)	Resistance of the grid (Rs)	Reactance of the grid (Xs)
33kV	1110.97MVA	17.67kA	9.26	1.186 Ohm	0.127 Ohm	1.18 Ohm

Table 3: Parameters represent grid source of the test network 1

3.3.2 33/11kV primary distribution substation

Two 33/11kV transformers are used to connect the grid to the test MV-LV distribution network with the parameters listed below in Table 4 and taken from ScottishPower DLTDS 2008 [3.15]. Two transformers connected in parallel are commonly used within urban distribution networks for reliability reason. They would provide less impedance between the grid and downstream distribution networks compared to using only one transformer.

Transformer rating	Z% on base 15MVA	X/R	Vector group
15MVA	7.42	15	DY11

Table 4: Parameters of a standard 33/11kV transformer

3.3.3 Medium voltages distribution network feeders

The 11kV distribution cables are used to model the connection between the utility and the consumers, and they have been modelled using parameters provided by manufactures of 185mm^2 aluminium cable [3.17]. Four LV substations (i.e. Ring Main Units RMUs) as shown in Figure 3- 4 are distributed equally across each feeder. The length between each two RMU is 0.25km. This is based on the fact that short cables are used for urban networks with a high density of loads. The following electrical parameters are used to represent each 11kV cable.

Nominal cross-sectional area(mm2)	Impedance at 50Hz ohm/km	Reactance at 50Hz ohm/km	Resistance at 50Hz ohm/km	Cable rating (MVA)
185	0.183	0.080	0.165	6.86

Table 5: Parameters of 11kV cable

3.3.4 11/0.4kV secondary substation

11/0.4kV substations are considered as boundaries of the LV cells for urban examples. The SP DLTDS [3.15] has shown that an LV urban network is typically supplied by utilising standard transformers with sizes 0.5MVA, 0.8MVA, and 1MVA. For area with a high density of load, the larger size is more likely to be used. Therefore, 1MVA

MV/LV transformer has been considered in the test network modelling and its parameters are listed in the table below.

Vector group	X/R	Z%	Transformer rating
DY11	15	4.75	1MVA

Table 6: Parameters of 11/0.4kV transformer

3.3.5 Low voltages distribution network feeders

The 0.4kV feeders are modelled as cables formed of resistance and inductance. All the impedances of the feeders are set according to the IEC 60909 Standard. One of the secondary substation connected feeders is modelled in detail in order to assess the impact of the cable impedances on the fault level contribution from microgeneration. Numbers of loads and microgenerators with different penetration are connected across the cable as shown in Figure 3- 6. The distance between each two customers is chosen to be equal, and it is equal to the total length of the cable divided by the number of the customers. The total length of the LV feeder for the urban example is normally short, and from some examples of real urban networks such as one presented in [3.18] the LV feeders range from 33m to 390m. In the studies of this chapter is chosen to be 200m. The general parameters of LV cable are listed below in Table 7 and are obtained from the case study that has been consider in the PB power report [3.19]. The rest of the other 0.4kV feeders are modelled as a lumped load and a lumped microgeneration connected to the cable with the consideration of the impact of the cable impedances on the lumped models.

Nominal cross-sectional area(mm2)	Continuous rating (kW)	Impedance at 50Hz ohm/km	Reactance at 50Hz ohm/km	Resistance at 50Hz ohm/km
185	230	0.18	0.074	0.164

Table 7: Parameters of 0.4kV cables

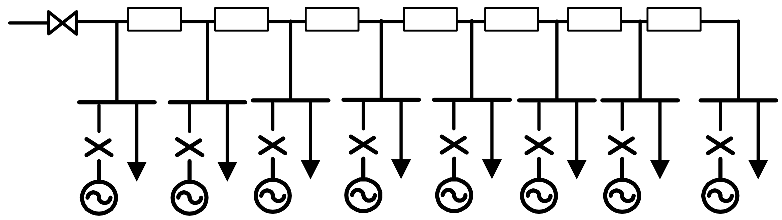

Figure 3- 6: Detailed 0.4kV feeder

3.3.6 The demand model

The demand on the secondary substation has been modelled as high density domestic and commercial loads connected to the urban network. The approximate average consumption of individual domestic and commercial customer is considered to be 1.5kVA and 27kVA respectively. A uniform power factor of 0.95 lagging has been assumed. The loads are uniformly distributed along the feeders, and modelled as three-phase balanced constant kW and kVAr.

The total number of consumers within each LV cell is assumed to be 540 users and distributed across five feeders. Each feeder is 200m, and the total load supplied by each feeder is 162kVA, and the total load over all feeders is 810kVA. This represents 81% of the transformer capacity at the secondary substation. While for the commercial application, each feeder is assumed to supply 6 commercial customers.

3.4 Simulation of LV connected Microgeneration

Two types of microgenerators are modelled. One is a single-phase generator with small size 1.5kW typically of those deployed at domestic properties (i.e. 230V), and the other is a three-phase microgenerator with two different sizes 16.5kVA and 30kVA typically of those deployed at commercial properties. The commercial size microgeneration examples are taken from practical examples provided by manufactures [3.20]. In both cases it is assumed that the microgeneration are interfaced by synchronous machines, and this is because such type of machines will contribute to the fault level more significantly compared to other technologies as it has been explained previously in section 3.2.4.

Therefore, the microgenerator at domestic level is modelled as a voltage source behind an impedance, and this impedance is adjusted to provide 6 times of the full load current during solid three-phase to ground fault at the terminal of the microgenerator. The commercial size microgenerator is also modelled as a voltage source behind an impedance to represent a microgenerator interfaced by a synchronous machine to the network, and the values of transient impedance Xd' and steady state impedance Xd are taken from typical information supplied by manufacturers for the following commercial size microgeneration 16.5kVA, and 30kVA as in Table 8.

Prime rating kVA	Standby kVA	Reactance (Ω)	Full load current (A)	Short-circuit current(A)
16.5	18	Xd'=1.33	25.98	173.238=6.66 times of full load current
30	33.0	Xd'=0.587	47.63	386.94=8.12 times of full load current

Table 8: Performance data of 16.5 and 30kVA three-phase generators [3.20]

In some fault level studies such as in [3.21] the LV connected microgeneration have been modelled as current sources which will supply the same fault current. But this will not give accurate results that will reflect the actual infeed from microgeneration to the fault. Because the microgenerator at the end of the feeder will contribute to a remote fault at the main LV bus less than the upstream microgeneration. How significant the difference between modelling the microgenerator as current or voltage depends on the length of the cable, for example for long cables this might be an issue. This can be simply noticed where each microgenerator will not provide the same current contribution to the fault at the beginning of the feeder as shown in Figure 3- 7. This is due to the impedances of the cables and the location of microgenerators. In the test networks 2 model, one feeder is modelled in detail, and the microgenerators are assumed to be connected at each consumer point with different penetration. While the other feeders based on the detailed feeder model are precisely modelled as an aggregated microgenerator connected to the secondary of the LV transformer and the difference between the fault current contributed by detailed feeder model and aggregated model is insignificant. The aggregation of microgeneration is conducted as follows.

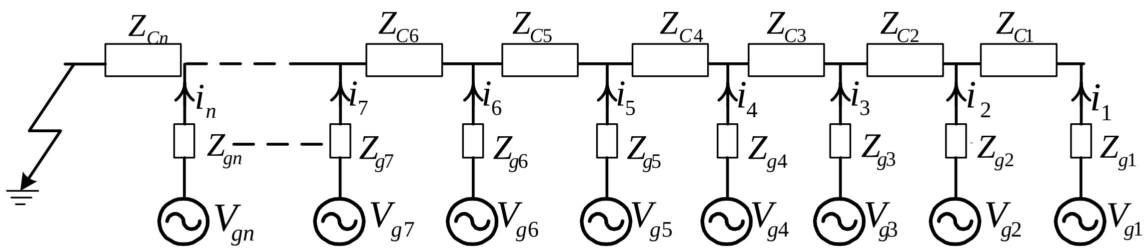

Figure 3- 7: Fault contribution from LV connected microgeneration to 3-phase-to earth fault at the beginning of the LV feeder

By using mesh-analysis and applying Kirchhoff voltage law to each closed loop of the network starting from each microgenerator connecting point to end up at the fault point, the following equations will result.

$$V_{g1} - i_1.(Z_{g1} + Z_{c1}) - (i_1 + i_2).Z_{c2} - (i_1 + i_2 + i_3).Z_{c3} - ..... - (i_1 + i_2 + i_3 + ... + i_n).Z_{cn} = 0 \quad (4)$$

$$V_{g2} - i_2.Z_{g2} - (i_1 + i_2).Z_{c2} - (i_1 + i_2 + i_3).Z_{c3} - .... - (i_1 + i_2 + i_3 + ... + i_n).Z_{cn} = 0 \quad (5)$$

$$V_{g3} - i_3.Z_{g3} - (i_1 + i_2 + i_3).Z_{c3} - (i_1 + i_2 + i_3 + i_4)Z_{c4} - ..... - (i_1 + i_2 + i_3 + ... + i_n).Z_{cn} = 0 \quad (6)$$

$$V_{gn} - i_n.Z_{gn} - (i_1 + i_2 + i_3 + ... + i_{n-1}).Z_{c(n-1)} - (i_1 + i_2 + i_3 + ... + i_n).Z_{cn} = 0 \quad (7)$$

Where *n* is the number of the microgenerators across the feeder. The equations (4), (5), (6), and (7) can be written as follows:

$$\begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ i_n \end{bmatrix} . \begin{bmatrix} (Z_{g1} + Z_{L1} + Z_{L2} + \cdots + Z_{Ln}) & (Z_{L2} + Z_{L3} + \cdots + Z_{Ln}) \cdots\cdots\cdots\cdots & (Z_{Ln}) \\ (Z_{L2} + Z_{L3} + \cdots + Z_{Ln}) & (Z_{g2} + Z_{L2} + Z_{L3} + \cdots Z_{Ln}) \cdots\cdots\cdots & (Z_{Ln}) \\ \vdots & & \vdots \\ \vdots & & \vdots \\ \vdots & & \vdots \\ \vdots & & \vdots \\ (Z_{Ln}) \cdots\cdots\cdots & & (Z_{gn} + Z_{Ln}) \end{bmatrix} = \begin{bmatrix} V_{g1} \\ V_{g2} \\ V_{g3} \\ \vdots \\ \vdots \\ \vdots \\ V_{gn} \end{bmatrix} \quad (8)$$

By assuming the consumers are distributed uniformly across the feeder for simplicity reason, the impedances between the customers will be equal. Also the voltage and the short circuit impedance of each connected microgenerator are set to be equal. Therefore, the following matrix results:

$$\begin{bmatrix} i_1 \\ i_2 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ i_n \end{bmatrix} \cdot \begin{bmatrix} (Z_g + nZ_L) & (n-1)(Z_L) & (n-2)(Z_L)\cdots\cdots\cdots\cdots(Z_l) \\ (n-1)(Z_L) & (Z_g + (n-1)Z_L) & (n-2)(Z_L)\cdots\cdots\cdots\cdots(Z_l) \\ (n-2)(Z_L) & (n-2)(Z_L) & (Z_g + (n-2)Z_L)\cdots\cdots(Z_l) \\ \vdots & \vdots & \ddots \quad \vdots \\ \vdots & \vdots & \ddots \quad \vdots \\ \vdots & \vdots & \ddots \quad \vdots \\ (n-(n-1))(Z_l) & (n-(n-1))(Z_l)\cdots\cdots\cdots\cdots\cdots\cdots & (Z_g + Z_L) \end{bmatrix} = \begin{bmatrix} V_g \\ V_g \\ V_g \\ \vdots \\ \vdots \\ \vdots \\ V_g \end{bmatrix} \tag{9}$$

From these equations the current of each microgenerator is calculated, and the sum of all currents will be the contribution to the short circuit as in equation (10).

$$i_f = i_1 + i_2 + i_3 + ... + i_n \tag{10}$$

Then the total impedance can be calculated from this current and the voltage source behind this impedance as sketched in Figure 3- 8 represents the aggregated microgeneration that will represent all small microgeneration connected to the feeder.

$$Z_f = \frac{V_g}{i_f} = R_f + jX_f \tag{11}$$

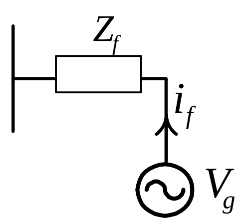

Figure 3- 8: Aggregated microgeneration connected to the LV secondary substation

This representation of the microgeneration will simplify and speed up the simulation of a distribution system incorporated with microgeneration, and at the same time consider the cables impedances impact on the contribution to the fault level from microgenerators connected at different locations. The greater care of the impedances of the cables between the connected consumers as the model approach has described will provide more accurate and conservative results. For example if microgeneration are modelled as current sources or the microgeneration are lumped as one aggregated generator without considering the impact of the impedances between the consumers, the fault level contribution would be higher than when the aggregated microgeneration developed by the approach is considered. This may recommend microgeneration penetration less than the real penetration and hence limitation on the spread of actual microgeneration penetration may be experienced.

3.5 Fault level studies

The available short circuit current that flows into the fault at distribution networks is directly dictated by the short circuit capacity of the grid, connected distributed generation and microgeneration, and connected motors. It is typically independent of the load current. The fault studies in this part are conducted to identify the approximate fault level rise at MV and LV buses of an urban distribution network example due to the connection of different quantities of different size of microgeneration starting from 0% up to 120% of generation penetration with respect to the load. The main objectives of the studies are listed as follows.

- To quantify the increase in the fault level of an urban distribution network example due to the connection of a different penetration of LV connected microgeneration, and identify at which level of microgeneration the increased fault level may become a problem.

- To identify which locations of the distribution network will more likely suffer from the increased fault level.

The following assumptions are assumed during the studies:

- The worst scenarios that will bring the fault contribution to its maximum are considered within the studies. For instance, urban distribution networks with short length feeders and low fault level headroom supplying a high density of users are considered in the studies. This has been considered because based on the literature such type of networks are more likely to suffer from fault level issues.
- The faults are always assumed to be bolted three-phase to ground faults.

- The contribution to the short circuit current peak is not considered, and only RMS values of the steady state of the fault current are considered, and because only microgeneration interfaced by synchronous machines will contribute to the steady state fault current, all microgeneration are assumed to be interfaced by a such technology. This has been considered because distribution network components such as breakers and fuses have interrupting and withstand ratings defined as RMS value of symmetrical current [3.3].

When numbers of microgenerators are connected to the LV side, the maximum fault level occurs when solid three-phase to ground fault is applied at the point of common coupling (PCC), where the fault will be the sum of all downstream microgeneration fault contribution and the grid. Therefore, two fault scenarios are applied as shown in Figure 3- 9. Fault 1 is applied at 0.4kV bus of the cell A which is the nearest cell to the primary substation, and all the contributions from the grid and all connected microgeneration across other cells to this fault are examined. The second fault is applied at 11kV bus as shown in Figure 3- 9 in order to investigate the impact of LV connected microgeneration on the fault level at MV distribution level. For each fault scenario, the impact of domestic and commercial size of integrated microgeneration on the fault level with different penetration is examined.

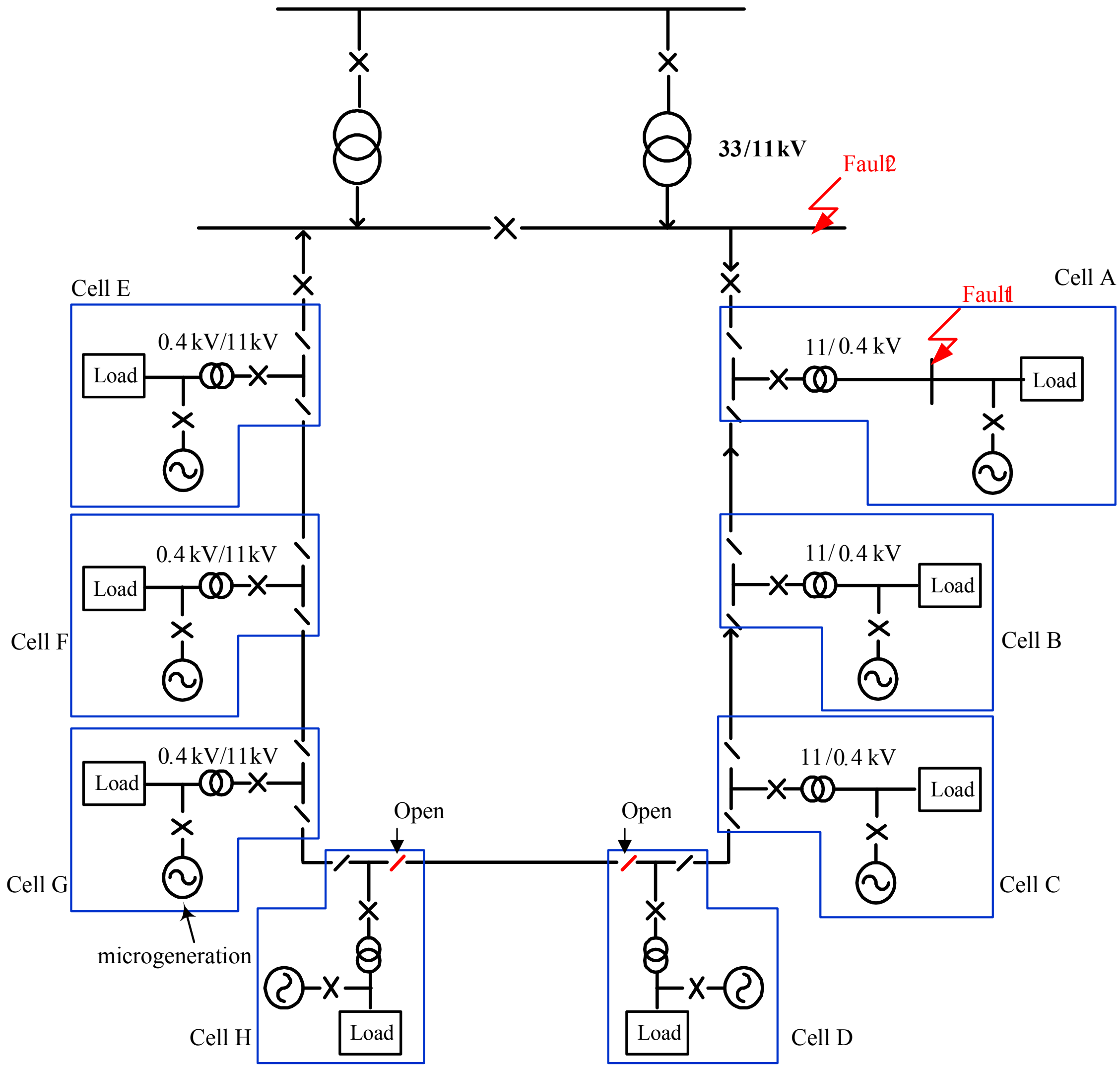

Figure 3- 9: Test urban network example

3.5.1 Fault level at the secondary of the LV substation (0.4kV)

A- Increased fault level due to connection of different penetration of domestic size microgeneration

During this study, it is considered that each customer per each phase connected to LV feeders consumes 1.5kVA. This is based on the average of a typical single house daily profile [3.22]. It is also assumed that each customer owns a single generator which is capable of providing a range of output power from zero up to 120% penetration of the customer load. The generation penetration 0, 20, 40, 60, 100, and 120% in respect to customer loads (i.e. 1.5kVA) are applied. At each case the contribution to the short circuit current and fault level from the additional generation is evaluated. The same penetration is applied to all cells from A-H at the same time, and the impact on the fault level is compared to the approximate typical fault rating of LV equipments which is assumed to be equal to 25MVA.

When there is no microgeneration connected (i.e. 0% microgeneration penetration), the available fault level at 0.4kV bus of the cell A is 18.43MVA. With the increase in the penetration of microgeneration, the fault level at 0.4kV bus will increase. The increased fault level obtained values from the simulation studies for each increase in the microgeneration penetration are tabulated in Table 9.

Microgeneration penetration	0%	20%	40%	60%	80%	100%	120%
Fault current RMS (kA)	26.607	27.95	29.285	30.68	31.85	33.1	34.33
MVA	18.43	19.36	20.29	21.26	22.07	22.93	23.8
increased MVA %	0%	5%	10.1%	15.36%	19.75%	24.42%	29.14%
Cell A contribution	0%	2.83%	6.38%	9.76%	13.29%	16.87%	20.45%

Table 9: The contribution from domestic size LV connected microgeneration with different penetration to the fault level for 3-phase fault at 0.4kV bus

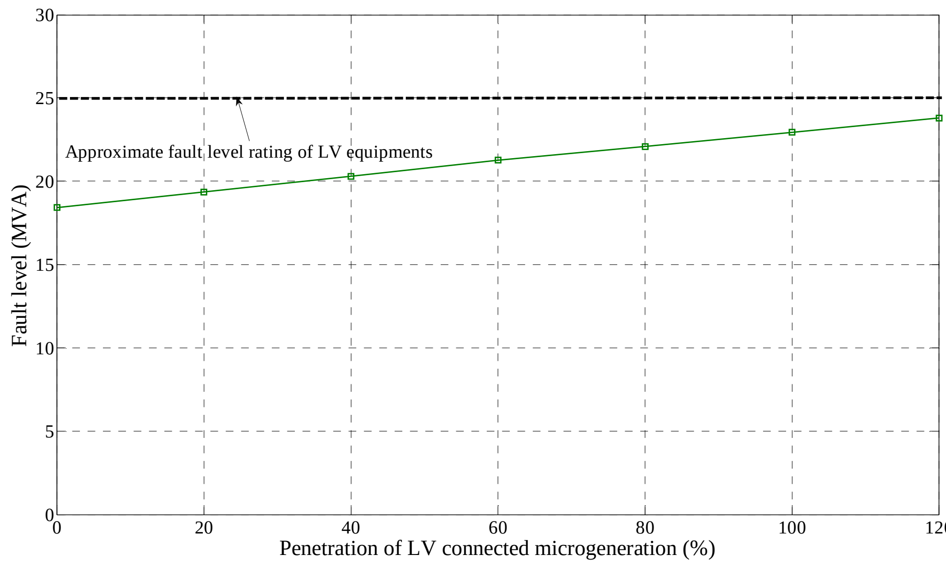

Figure 3- 10: The fault level at 0.4kV bus with and without the connection of domestic size microgeneration

The increase in the fault level at 0.4kV bus of the cell A due to the fault contribution from the all microgeneration added to the LV cells is shown in Figure 3- 10. The figure shows that the increased fault level has not exceeded the approximate typical fault level rating of LV distribution networks (i.e. 25MVA). The network has accommodated the increase in the fault level, and it was capable of taking up to 120% of microgeneration with domestic size 1.5kVA. However, the fault level was brought very close to the equipments short-circuit rating limit. Frome the results in Table 9 it can be observed that the highest fault contribution to fault 1 within the cell A as shown in Figure 3- 9 comes from the cell A local microgeneration. Up to more than 65% of the total fault contribution is made by the local generators of the cell A compared to other adjacent cells, where each 1kVA generation at cell A has contributed 0.004MVA to the fault at 0.4kV bus (i.e. fault 1 on Figure 3- 9). The insignificant contribution from other adjacent cells (B-H) can be justified by the influence of the 11/0.4kV transformers and cables impedances which have played a significant role in limiting the fault contribution from external to local fault within LV cell.

In spite of the increased fault level being accommodated for this study, it can not be generally considered as insignificant issues. This is because for example with 100% penetration which is equal to 810kVA generation per a cell, the increase in the fault level was considerable. It reached more than 20% increase compared to the original prospective fault level. In addition, the remaining fault level headroom is very limited for equipments that have 25MVA short-circuit rating.

The collective fault contribution from all connected microgeneration has added 4.5MVA to the original fault level as shown in Figure 3- 10. Consequently, low voltage distribution networks with fault level headroom less than 4.5MVA will not be able to accommodate 100% penetration of microgeneration with 1.5kVA per microgenerator. This was the impact of 810kVA generation at LV side of each cell which represents 81% of the capacity of 1MVA transformer (i.e. the main MV/LV transformer of each cell). But, because the penetration of microgeneration has been set in respect to the load density in the studies, and the load density is not fixed for all LV distribution networks. For example, a 100% penetration microgeneration in respect to load condition equal to 81% of larger transformer for example 2MVA will be equal to 1620kVA generation. Since each 1kVA increase in microgeneration will contribute 0.004MVA, and the relationship between the microgeneration penetration and the increase in the fault level is almost linear as shown in Figure 3- 10, 1620kVA will cause 6.48MVA increase in the fault level at 0.4kV bus of the network example shown in Figure 3- 9. This will lead the short circuit rating to be exceeded since the fault level headroom is only 4.5MVA. With such condition the network will be incapable of accommodating 100% microgeneration, and the total microgeneration that can be connected will be only 69.44%. Therefore, it may be difficult to state and generalise that LV distribution networks can accommodate 100% penetration of microgeneration at domestic level without causing fault level issue.

The general rules that dictate the limit of microgeneration penetration is the available fault level headroom, and the future investment in reinforcement of the network. For example, if a new transformer is required to be added in order to meet the increase in demand, and the network already accommodated 100% of microgeneration and only

2.07MVA fault level headroom is left, the transformer could not be connected until the penetration of microgeneration is reduced. Generally the penetration of the generation would be higher for higher consumers' density, and thus resulting in higher fault level contribution. This may lead to the LV distribution network with a high density of consumers and low fault level headroom could set-back the spread of microgeneration across the networks.

B- Increased fault level due to connection of commercial size microgeneration

This part of the study considers the impact of a typical commercial microgeneration that can be connected at commercial premises. Two different size of microgeneration have been considered 16.5kVA and 30kVA. The selection of these two size microgeneration is based on the real data provided by manufactures [3.20] which are expected to be more likely connected at commercial level. So during the investigation there was no range of change in the generation output power such as in the pervious studies, where the output power varies from 0 to 120% of each individual microgenerator with respect to the average load. The penetration of the microgeneration is based on the number of the commercial customers. The average 3-phase commercial consumption was assumed to be 27kVA, thus for the used network example where each feeder provides 162kVA, six commercial customers are assumed to be connected to each feeder. It is applied that one commercial size microgenerator is connected per each customer. The commercial size microgeneration obtained data from manufactures as listed above in Table 8 is used to model these generators. Based on the real data taken from [3.20], the 16.5kVA microgenerator provides a short circuit current as high as 6.66 times of the full load current for a fault at its terminal, and the 30kVA microgenerator provides a fault current equal to about 8 times of its full load current. The impact of each of these two microgenerators on the fault level at 0.4kV bus is examined as explained in the coming two sections.

B1- Increased fault level due to connection of different penetration of 16.5kVA microgenerator

In this section, it is assumed that numbers of commercial customers one by one start installing their microgenerators with size 16.5kVA. For each case and based on the number of connected microgenerators, the penetration compared to the total load connected to the 3-phase feeder is calculated, and the fault level contribution is examined. For instance, when 16.5kVA microgenerator is connected to the first, second, third, fourth, fifth, and sixth customer, the generation penetration will be 10.19%, 20.4%, 30.6%, 40.74%, 50.92%, 61.11% respectively of the total consumption across the feeders. The fault level contribution obtained results are listed in the table below.

Microgeneration penetration	0%	10.19%	20.4%	30.6%	40.74%	50.92%	61.11%
Fault current RMS (kA)	26.607	27.44	28.28	29.09	29.88	30.63	31.37
MVA	18.43	19.01	19.59	20.15	20.7	21.22	21.74
increased MVA	0%	3.14%	6.31%	9.36%	12.32%	15.14%	17.93%
Cell A contribution	0%	2.2%	3.9%	5.26%	7.4%	9.4%	11.57%

Table 10: The contribution from 16.5kVA commercial size LV connected microgeneration with different penetration to the fault level for a 3-phase fault at 0.4kV bus

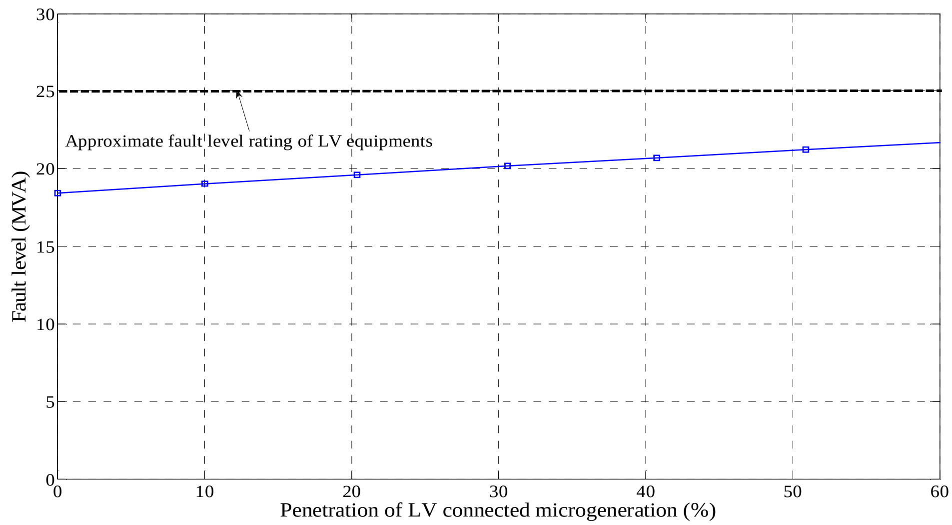

Figure 3- 11: The fault level at 0.4kV bus with and without the connection of 16.5kVA commercial size microgeneration

B2- Increased fault level due to connection of different penetration of 30kVA microgenerator

As for 30kVA microgenerators, and when they are connected to the first, second, third, fourth, fifth, and sixth customer, the generation penetration will be higher than those for 16.5kVA and the penetration are equal to 18.5%, 37.03%, 55.5%, 74%, 92.6%, 111% respectively of the total consumption across the feeders. For each generation penetration the fault level contribution is examined, and the results are listed in Table 11.

Microgeneration penetration	0%	18.5%	37.03%	55.5%	74%	92.6%	111%
Fault current RMS (kA)	26.607	28.51	30.36	32.13	33.96	35.257	36.52
MVA	18.43	19.75	21.03	22.26	23.53	24.43	25.30
increased MVA	0%	7.16%	14.1%	20.8%	27.7%	32.56%	37.3%
Cell A contribution	0%	4.12%	7.9%	12.37%	17.47%	22.5%	27.4%

Table 11: The contribution from 30kVA commercial size LV connected microgeneration with different penetration to the fault level for a 3-phase fault at 0.4kV bus

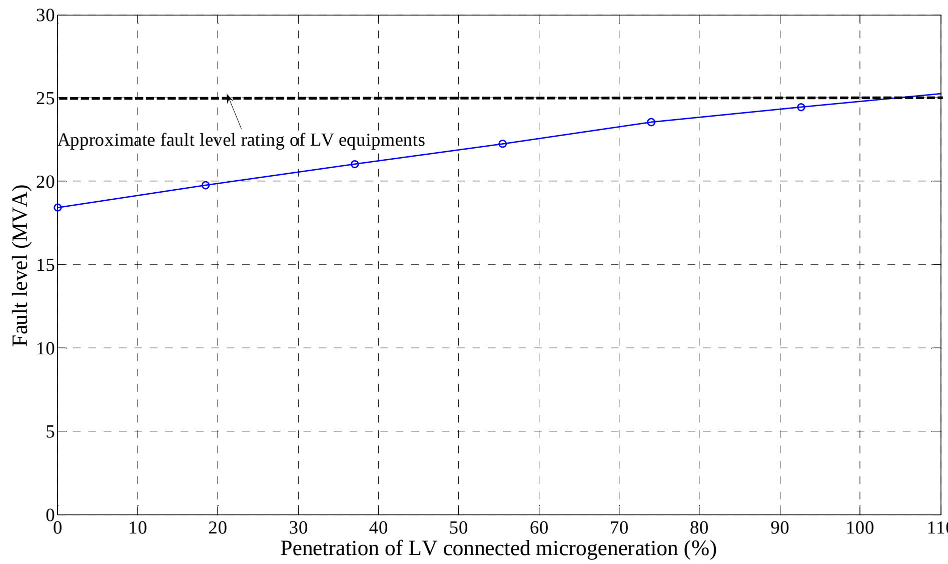

Figure 3- 12: The fault level at 0.4kV bus with and without the connection of 30kVA commercial size microgeneration

The additional fault level from the commercial size microgeneration has caused the overall fault level to be brought very much close to the designed fault level limit of the distribution equipments when the penetration of connected microgeneration has reached 100%. It can be seen from Table 10 and Table 11 that the size of the connected microgenerator is very important factor that will directly impact the fault level contribution. For example, each consumer can connect 16.5kVA microgenerator, and the total increased fault level still can be accommodated, while for bigger size microgenerator (i.e. 30kVA) installing such size for all the customers will bring the fault level very close to the equipments fault rating. For save operation, it is not advisable to operate close to the fault rating limit in order to avoid stressing the network components.

From Table 11 it can be seen that when more than 92.6% of the commercial microgeneration are added, the fault level issue has been experienced, and to avoid that only five of six consumers at maximum can connect microgenerators with size 30kVA. Since there is no specific size of the microgeneration that can be connected to the LV distribution networks particularly at commercial level where microgeneration can size up to 100kVA and they are driven by the consumers choices, the identification of the most appropriate size of microgeneration without impacting the rating of the network become an important issue. This can be identified by how much each 1kVA generation added to LV network will contribute to the fault at PPC point, and based on the available fault level headroom the recommendation can be made after the total generation is calculated. For example, when different penetration of commercial sizes 16.5kVA and 30kVA are applied, each 1kVA for each case has provided 0.0042MVA and 0.00553MVA respectively at PPC point. So for the test network example with a fault level headroom equal to 6.57MVA the maximum microgeneration that can be locally connected without causing fault level issue can be calculated. If the average fault level contribution is around 0.0055MVA provided by each 1kVA generation, the total generation that can be connected to LV is equal to 813kVA generation. Then based on the number of consumer connecting points, the size of microgenerators can be recommended. This is with the consideration of the contribution from other adjacent cells as well.

3.5.2 Fault level at the secondary of the MV substation (11kV bus)

This section investigates the impact of LV connected microgeneration for domestic and commercial application on the fault level at 11kV bus. The main output of the studies in this section is to determine how far the impact of microgeneration fault contribution to upstream faults can go. It also examines the influence of the transformers at LV substations on the fault level contribution to upstream faults.

A- Increased fault level at MV main bus due to the connection of domestic size microgeneration

The same generation penetration that was applied in section 3.5.1 to all eight cells is also used in this section, and the contribution from LV connected microgeneration to upstream fault at MV side is investigated. The output is compared to a typical MV fault level which is equal to 250MVA [3.15].

Microgeneration penetration	0%	20%	40%	60%	80%	100%	120%
Fault current RMS (kA)	8.755	8.932	9.115	9.294	9.471	9.641	9.802
MVA	166.81	170.18	173.66	177.07	180.45	183.69	186.75
increased MVA	0%	2.02%	4.11%	6.15%	8.18%	10.12%	11.96%

Table 12: The contribution from domestic size LV connected microgeneration with different penetration to the fault level for 3-phase fault at 11kV bus

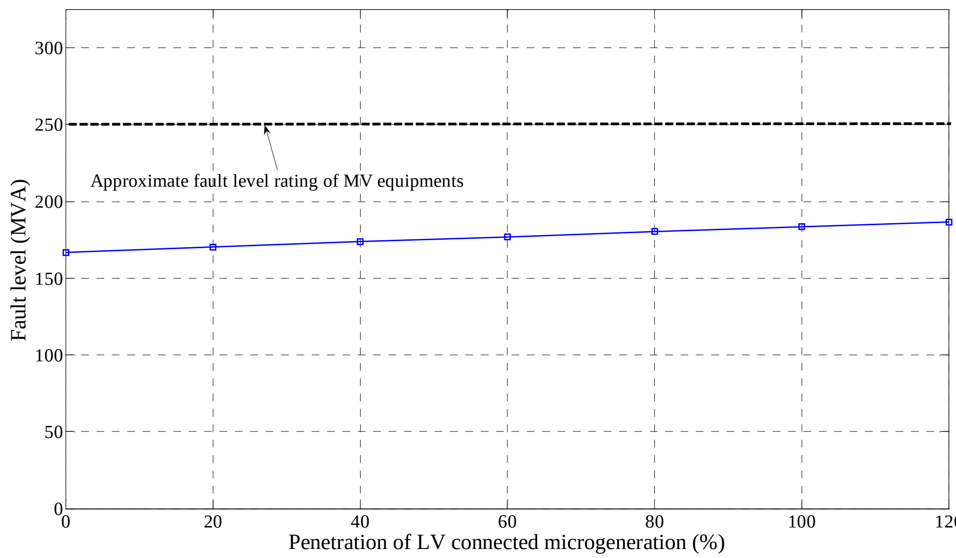

Figure 3- 13: The fault level at 11kV bus with and without the connection of different penetration of domestic size microgeneration

In this case, the increased fault level at MV side on 11kV bus of the test network 1 shown in Figure 3- 9 due to connection of large penetration of microgeneration to low voltage distribution networks has been accommodated, and the results are shown in Figure 3- 13. This is mainly because of two reasons; one is the contribution was limited by the MV/LV transformers impedances where the contribution made by 120% microgeneration penetration was only 11.96% increase. The other is that the fault level headroom at MV distribution networks is generally high compared to LV networks. For example, for the used test network which represents a typical MV distribution network and its data was taken from a real network the available fault level headroom is 100MVA. So it is hard for microgeneration to provide increase in fault level that would exceed the rating limit of MV networks.

B- Increased fault level due to the connection of commercial size microgeneration

The same generation scenarios used in section 3.5.1 in terms of commercial size microgeneration is also used in this section, and the contribution from (i.e. 16.5 and 30kVA) LV connected microgeneration to upstream fault at MV side is investigated.

B1- Increased fault level due to connection of different penetration of 16.5kVA microgenerator

The results added the below table and figure shows the impact of 16.5kVA connected at LV side on the fault level at MV side. It can be seen that the increase in the fault level is insignificant, and due to the large available fault level headroom, the MV equipments would not be affected by the contribution to fault level made by LV connected microgeneration.

Microgeneration penetration	0%	10.19%	20.4%	30.6%	40.74%	50.92%	61.11%
Fault current RMS (kA)	8.755	8.867	8.98	9.091	9.21	9.31	9.42
MVA	166.81	167	171.1	173.21	175.5	177.4	179.5
increased MVA	0%	0.114%	2.6%	3.84%	5.21%	6.35%	7.61%

Table 13: The contribution from 16.5kVA commercial size LV connected microgeneration with different penetration to 3-phase fault at 11kV bus

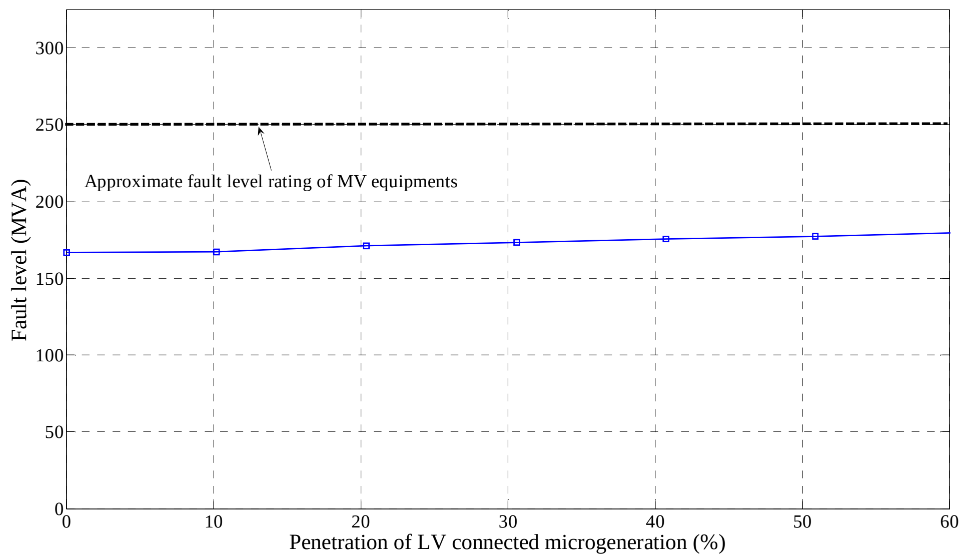

Figure 3- 14: The fault level at 11kV bus with and without the connection of 16.5kVA commercial size microgeneration

B2- Increased fault level at 11kV bus due to the connection of different penetration of 30kVA microgenerator

Microgeneration penetration	0%	18.5%	37.03%	55.5%	74%	92.6%	111%
Fault current RMS (kA)	8.755	9.01	9.255	9.49	9.714	9.92	10.11
MVA	166.81	171.66	176.33	180.81	185.08	189	192.62
increased MVA %	0%	2.91%	5.715	8.39%	10.95%	13.3%	15.47%

Table 14: The contribution from 30kVA commercial size LV connected microgeneration with different penetration to the fault level for a 3-phase fault at 11kV bus

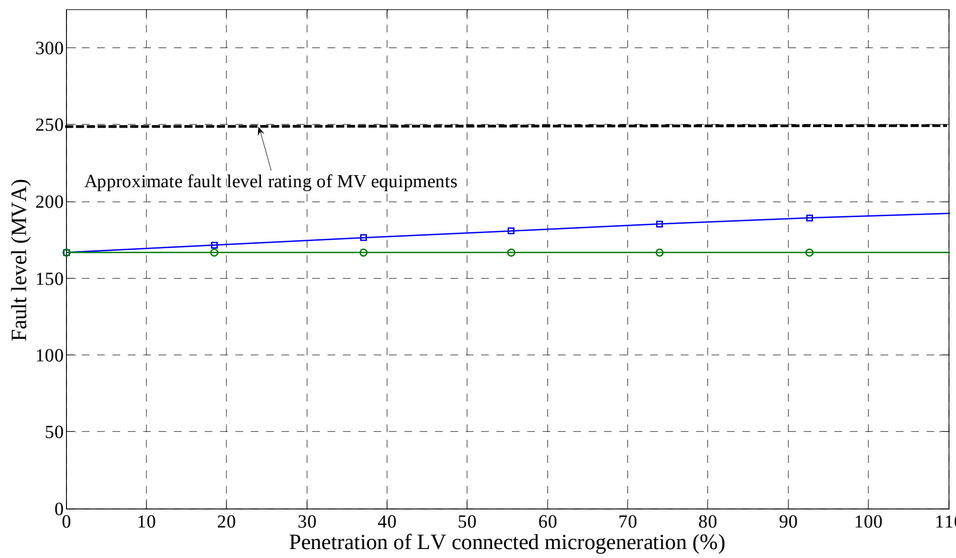

Figure 3- 15: The fault level at 11kV bus with and without the connection of 30kVA commercial size microgeneration

Figure 3-12 and Figure 3- 15 have shown that the contribution to the fault level at 11kV bus made by a high penetration of commercial size will be accommodated.

The results of this chapter have shown that the relationship between the system fault level contribution and the penetration of LV connected microgeneration is linear. The increased fault level is a linear function of the microgeneration penetration. Therefore, by using this relationship, the microgeneration fault level contribution can be simply calculated from equation (12).

$$FL = mPen + FL_0 \qquad (12)$$

Where FL is the increased fault level (MVA), m is the slop of the increased fault level, Pen is the penetration of connected microgeneration (%), and FL_0 is the system fault level without the presence of microgeneration.

Taking the results of increased fault level from Table 10 when 30.6% and 50.92% of microgeneration are added to the system the slop m can be calculated as following:

$$m = \frac{FL_{50.92\%} - FL_{30.6\%}}{50.92\% - 30.6\%} = \frac{21.22 - 20.15}{0.203} = 5.27$$

Thus based on the available fault level headroom of the system, the maximum local generation that can be connected to LV without impacting the fault level rating of the network can be calculated from equation (12). For example when m =5.27 the maximum penetration of microgeneration to be added at LV level can be found as follows:

$$FL_{\max} = mPen_{\max} + FL_0 \tag{13}$$

$$m = \frac{FL_{\max} - FL_{0\%}}{Pen_{\max} - Pen_{0\%}} = \frac{25 - 18.43}{Pen_{\max} - 0} = 5.27$$

$$Pen_{\max} = \frac{25 - 18.43}{5.27} = 126\%$$

3.6 Chapter summary

The results of the case study have shown that the collective fault level contribution from a high penetration up to 100% of domestic size microgeneration connected within a typical LV cell has increased the fault level by 24% of its original value (i.e. 4.5MVA) at 0.4kV bus, and this has brought the test urban network with low fault level headroom very close to its short circuit limits. 65% of the total microgeneration fault contribution caused by the local microgeneration within the faulted LV cell and 35% from the microgeneration within the other adjacent LV cells. When larger microgenerators size (i.e. commercial size) were added to LV side of the test network, the studies have shown that there are some situations where the increased fault level can be an issue. With 100% penetration of commercial size microgeneration, the increased fault level has reached the fault level limit of the network, and caused fault level issues.

On the other hand, the impact of LV connected microgeneration on the fault level for a fault on MV side (i.e. 11kV bus) is insignificant. This is mainly because of two reasons; firstly the contribution is significantly limited by the MV/LV transformers impedances. Secondly, the fault level headroom at MV distribution networks is relatively high compared to LV networks. For example, for the used test network which represents a typical MV distribution network and its data was taken from a typical real network the available fault level headroom is 100MVA. So it is hard for microgeneration to provide increase in fault level that would exceed such limit. So increased fault level due to connection of microgeneration are more likely to be a local issue rather than a wide system issue. So if microgeneration do not cause a local fault level issue, then they are more likely not to cause a wider system fault level issue.

The two fundamental criteria to identify whether integration of a heavy level of microgeneration would alter the LV distribution networks fault level are: (1) the amount of fault level contribution would be provided by the total generation expected to be connected to the network. (2) How much fault level headroom is available before microgeneration are connected. The fault level headrooms are known from the network design, which is already set without the consideration of incorporating new generation at distribution level. By using different microgeneration size that could be connected to domestic and commercial level based on manufacturer data, the results have found that the relationship between the penetration of microgeneration and the contribution to the RMS values of the steady state fault current occurred at 0.4kV bus is linear. Each 1kVA generation added to the local LV will increase the fault level at the LV main bus by 0.0042MVA. Thus based on the available fault level headroom the total generation that can be connected to LV without impacting the fault level rating of the network can be easily worked out. Then the network operator could advise how much local generation can be added to LV networks.

Numbers of studies as mentioned early in this chapter have stated that LV distribution networks can uptake up to 100% penetration of domestic size microgeneration without causing a significant increase in the system fault level. But the results of this chapter have proven different. 100% of commercial size microgeneration has forced the fault level to exceed the nominal limits. In terms of domestic size microgeneration, the test network has just accommodated 100% of domestic microgeneration and the contribution to LV fault level made by such penetration has reached 24% increase of the original fault level, and this is significant and can cause numbers of issues. For example, such significant contribution can lead urban networks which are normally have low available fault level headroom to operate very close to the short circuit rating limits. This can lead to stressing the network components resulting in lower lifetime to be experienced, increasing the requirement for a component with larger short circuit ratings which will be bigger in size and hence increasing the cost of the component and the cost of the space which can be an issue in urban areas. In addition, operating the network close to the rating will obstructing the spread of more microgeneration uptake and DGs at MV level and probably reduce the chance for new investment such ad adding a new transformer at the primary substation for meeting the increase in the demand and operate in parallel with the existing transformers.

Therefore, for safe operation and to avoid setting-back the growth of microgeneration across LV distribution networks there will be a need for managing the increase in the fault level due to microgeneration integration in order to avoid all these issues. Measures such as using fault current limiter or reconfiguring the network could facilitate the spread of microgeneration if other constraints are met.

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Chapter four: The impact of a high penetration of LV connected microgeneration on the protection performance of LV distribution networks

4.1 Introduction

A priority of any supply system is, the system should be well designed and properly maintained in order to limit the number of faults that might occur [4.1]. However, when the cost is considered, it is not practical and cost effective to design a system to withstand all possible system failures, and the alternative is to design a protective system that can quickly detect faults and take required actions within reasonable time [4.2][4.3]. Therefore, use of protection systems is very necessary in electrical power systems. They must be installed to cover all the system in order to detect faults, and restrict them to limited areas and isolate only the faulted parts [4.2]. This in turn will avoid damage and prevent personnel injury, and minimize outages and restoration cost, and enable continuity of service in unfaulted parts of the system. The protection schemes depend on the protected portion, and also on other factors such as voltage level, the complexity and the arrangement of the protected system, and the importance of the protected system. However, the main principles of any protection scheme are the capability of immediately sensing the faults and isolating the impacted equipment, and allowing the rest of the power system to remain in service [4.1].

4.2 Requirements of Electric Power System Protection Schemes

The main criteria by which the performance of a protection system may be measured are listed below [4.1][4.3][4.4]:

1- The speed: speed is required in order to avoid damage to equipment. The protection must operate as it is required. It should not be too slow which may lead to damage of the equipments and not too fast and lead to unwanted operation (i.e. losing selectivity).

2- The reliability: reliability is very important requisite. If a fault occurs the protection should react correctly. The reliability of protection has two elements; the certainty of a correct operation, which is called dependability, and the security against incorrect operation.
3- The selectivity: it is based on disconnecting only faulted sections of the network to isolate the fault and maintain the continuity of supply to other healthy parts. The protection must be able to discriminate between when the operation is required and when it is not, or time delay is required.
4- The cost: a suitable balance between the benefits of protection and the economic cost should be considered. So maximum protection should be at the lowest possible cost.
5- The sensitivity: It is important that the protection has a good capability of detecting faults on the system.

It is difficult to satisfy all the above points at the same time. Thus it is very necessary to compromise the above requirements in order to obtain acceptable performance and optimum protection systems [4.5]. Associated with a traditional distribution system, these protection requirements have been considered for a passive paradigm.

When a high penetration of LV connected microgeneration is integrated into a distribution network, the network will not be seen anymore as a radial with unidirectional power flow. A new path for sort-circuit currents is provided. This path may impact to some level the main performance criteria of protection systems of distribution networks, where the traditional protection has been designed with the absence of such path. If the protection performance is impacted due to microgeneration integration, then lower reliability, lower sensitivity, and even reduction in power quality by lowering the protection selectivity may result [4.6]. Therefore, the investigation of the influence of a high density LV connected microgeneration on the LV protection performance is vital.

In [4.7] it has been reported that the connection of distributed generation to MV may cause traditional protection schemes to become ineffective. This chapter investigates whether the connection of a high population of microgeneration to low voltage level will degrade the protection performance and protection requirements at low voltage level or their impact will be insignificant? The impacts are investigated in details in terms of the influence on the following LV protection requirements; the correct operation (i.e. reliability, when to operate and when not to operate), and the graded setting (coordination or selectivity). The electro-magnetic transient computer simulation programme EMTDC interfaced by PSCAD is used for all the protection studies of this chapter. This is because of numbers of advantages of using this tool as it has been mentioned early in chapter two section (2.6).

The following sections of this chapter include a brief introduction to basic principles of the protection schemes of low voltage distribution networks, followed by a discussion on the expected protection impact due to microgeneration connection and a detailed case study with different fault scenarios to identify the protection issue.

4.3 Protection of low voltage distribution networks

Traditional medium and low voltage distribution systems are considered to be lower importance from the protection complexity perspective [4.2]. This is because of the cost, and they are normally operated in a radial manner, and the direction of the current flow is always known. Distribution network protection does not involve extensive hardware, and the networks are protected by a simple and cheap type of overcurrent protection [4.1]. Compared to other protection schemes, overcurrent protection is more economical and simple, thus they are widely used to protect distribution power systems [4.5].

Low voltage overcurrent protective devices are normally described by inverse time-current characteristics. The fault current flows through overcurrent protection devices, is used to determine the presence of fault conditions, and initiate the protection operation. The speed at which the protection will operate is dictated by the amount of the fault current that will flow through the protective device. The protection operating time decreases as the fault current increases. Based on unidirectional power flow philosophy of traditional distribution systems, the fundamental functions of overcurrent are achieved by coordinating the operating times of protective devices, where downstream elements will respond to faults downstream faster than the upstream devices [4.3].

The devices that are most used for protecting distribution networks are; overcurrent relays, reclosers, sectionalisers, and fuses, and the common schemes to protect LV feeders are overcurrent protection schemes [4.1]. Fuses are a common example of devices that can be used for overcurrent protection. They are normally simple to use, fail safe, their operating characteristics can be graded, and they are relatively cheap compared to other protective devices. Thereby, fuses are extensively used on low voltage systems (415 and 660V) with rating from 2 to 1600Amps [4.1]. Fuses do not have inherent directional properties, and they have been used to protect passive distribution networks where the direction of the current flow is always identified. So the effect of the opposite fault current flow due to microgeneration connection is important to be understood. This will require understanding of the performance of a low voltage distribution network protected by fuses when large amount of microgeneration are connected to the network.

4.3.1 Principles of fuse operation

When the fault current exceeds a predetermined value, the fuse has an element that will be melt by the heat caused by the fault current [4.4]. Fuses are considered as the simplest and most basic of hardware items used in system protection [4.2]. A fuse is also define as in IEC Publication 291: Fuse Definition as *"a device that by the fusing of one or more of its specially designed and proportioned components opens the circuit in which it is inserted by breaking the current when this exceeds a given value for a sufficient time. The fuse comprises all the parts that form the complete device"* [4.8].

The following information is required in order to select a suitable fuse for use at distribution systems [4.1]:

1. Voltage of circuit and insulation level.
2. Type of system (connection arrangements).
3. Maximum short-circuit level of circuit to be protected.
4. Load current.

The above four factors determine the fuse nominal current, voltage and short-circuit capability characteristics. The above factors are normally used to determine the prospective current of the circuit to be protected.

4.3.2 Fuse-fuse co-ordination

In order to achieve the coordination between overcurrent protective devices (i.e. fuses), and the disconnection of the entire feeder is avoided, it is important that their time/current characteristics are chosen to be sufficiently separated, so only device closest to the fault operates firstly to clear the fault. For example, when two fuses protecting the same feeder, the maximum clearance time of downstream fuses should not exceed the 75 per cent of the minimum melting time of the upstream (i.e. back-up) fuse for the same fault level [4.1].

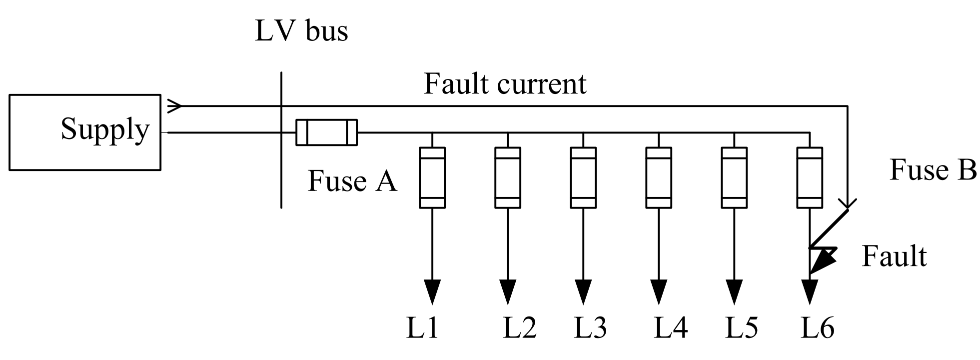

Figure 4- 1: Low voltage feeder protected by two fuses

Fuse B in Figure 4- 1 is the main protection of load 6, and fuse A is a back-up protection to fuse B. So if fuse B for any reason fails to operate then fuse A will disconnect all the feeder resulting in unnecessary disconnection of other loads. Therefore, the total clearing time of fuse B must be smaller than the melting operating time of fuse A. Thus the required energy for melting fuse B is less than that is required for fuse A.

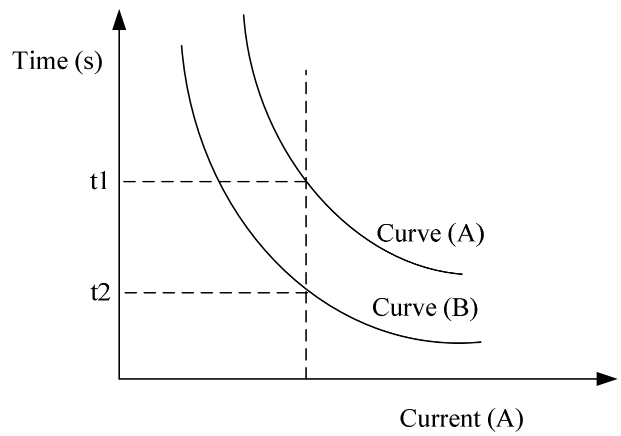

Figure 4- 2 : Time/current characteristics of two fuses protecting the same feeder

The time/current characteristics of LV overcurrent protection devices protecting the same feeder as in Figure 4- 2 are chosen to provide the required discrimination. The fuse with time/current characteristics as shown on curve (B) is more sensitive compared to the fuse with time/current characteristics of curve (A) on the same figure. Thereby, fuse B will be used as main protection and it is normally connected close to the load with lower rating. While fuse A with higher rating compared to fuse B is used as back-up protection and it is connected at upstream towards the source.

4.4 LV protection issues due to a high penetration of LV connected microgeneration

The principles of over current (OC) protection that have been set for protecting a passive distribution network are based on a higher fault current will lead to faster protection operating time. With the movement towards active distribution networks the OC operating principles may be impacted, and may lead to undesirable protection operation, and this is unacceptable [4.9].

The widespread use of distributed generation has led to a series of new problems, such as selective coordination of overcurrent protection in addition to control of voltage sag magnitude and duration by using overcurrent protective devices [4.4]. For example, the studies conducted in [4.10] to identify the issues related to fault level impact in an urban distribution network due to a high penetration of distributed generation have concluded that a number of issues will emerge due to the presence of the DGs. One is when a DG is located between the fault and the feeding substation there is a possibility of delaying the operating time of the relay at the beginning of the feeder or even blocking the relay due to the reduction in the current measured by the relay which is caused by the contribution of the DG to downstream fault. The other issue is when the fault occurring on the adjacent feeder, the reverse fault current provided by the DG will lead to unnecessarily trip of the DG. The same studies have recommended that there is a need for more active protection with advanced communication to be employed to solve such problems [4.10].

In terms of adding a high penetration of microgeneration to low voltage networks, the impact can be different. The microgeneration also will contribute to the downstream faults and provide a reverse fault current for upstream faults, but with different level if compared to larger DGs added to MV networks. Another issue compared to the issues caused by DGs at MV is that LV distribution feeders are widely protected by fuses, and such advanced controls and communication to improve the protection performance as recommended in [4.10] can not be implemented in such devices due their inherent operation. So, the remaining question that this chapter of the thesis intending to answer is, how will a high penetration of small scale microgeneration connected to low voltage networks impact the existing LV protection performance based on fuses?

To answer the above question the microgeneration integration impacts on the LV protection performance are investigated in detail by using the test network 1 developed in chapter three. The studies are conducted in terms of the influence of microgeneration contribution to upstream and downstream faults on the following functions of the LV protection operating time: when to operate and when not to operate which can be reliability issue, and the time delay to operate which can be selectivity issue. The contribution to upstream faults and downstream faults may lead to reduction in the reach or unnecessary tripping of the feeder, therefore these two areas are considered.

4.4.1 Reduction in the reach

For downstream faults as shown on Figure 4- 3, if the aggregated contribution from the connected microgeneration is relatively strong, then it could cause a delay in the fuse operating time, or in the worst case it may lead to a reduction in the reach of fuse A. This may impact the customers connected to the LV feeder.

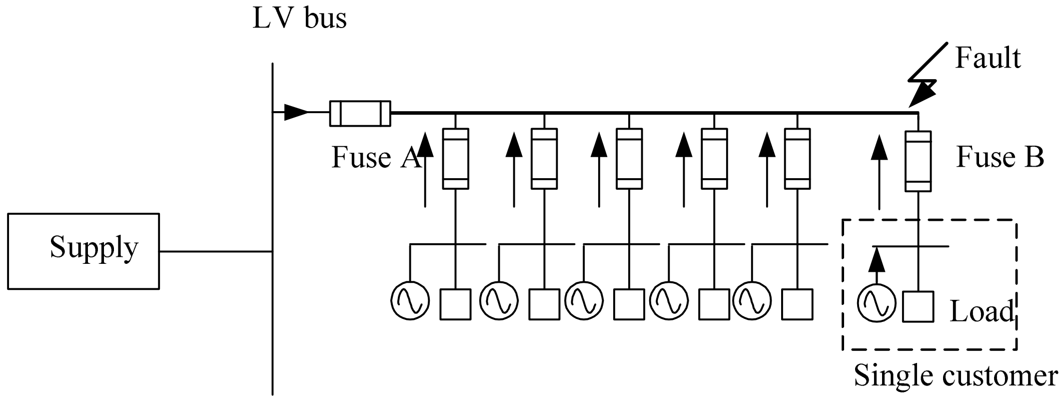

Figure 4- 3: Impact of LV connected microgeneration on the reach of the main LV feeder protection

4.4.2 Unnecessary tripping due to reverse fault current

When a fault as shown in Figure 4- 4 occurs on LV adjacent feeder without adding microgeneration, zero current will flow in fuse A, and only fuse C operates. While for the same fault condition and with the presence of microgeneration, fuse A will experience a reverse fault current as shown on Figure 4- 4. This fault current with a new path is provided by the sum of microgeneration connected across the feeder. Fuses do not have inherent directional properties, so if the reverses fault current exceeds the threshold value of the fuse operating current, the fuse A shown on Figure 4- 4 will start melting and leading to unnecessary disconnection of the feeder. Thereby, less reliability in protection performance may result. Such an impact is definitely not acceptable which may lead to lost revenue through losing microgeneration. Therefore, this issue is investigated within the case study in section (4.5) when the entire local load is met by the local microgeneration (i.e. 100% penetration of microgeneration).

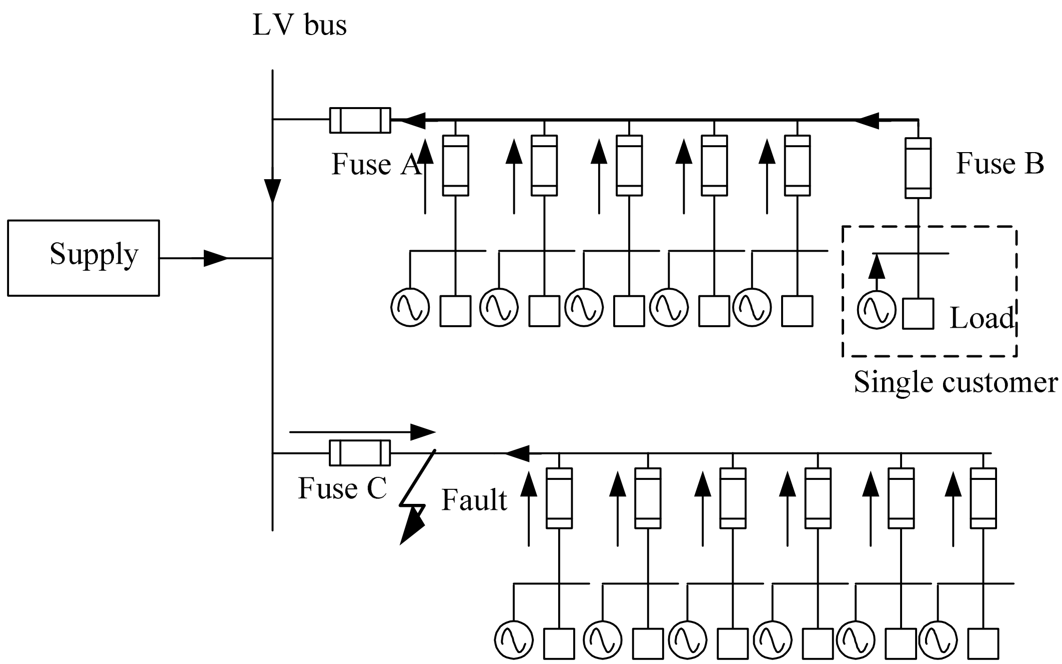

Figure 4- 4: Impact of the LV connected microgeneration on LV protection performance during a fault on adjacent feeder

4.5 Case study

The studies of this chapter are conducted on the same test network 1 developed in chapter three, and only one LV cell (i.e. LV cell A in test network 1 in chapter three) is considered as shown in Figure 4- 8, and the impact of a heavy level of microgeneration integrated within the cell on the performance of LV protection is assessed. Only domestic level microgeneration are used, and the penetration of the microgeneration that have been used for the studies is chosen to meet 100% of the local load as used before in chapter three for fault level studies. This penetration has been chosen because it produced a significant contribution to the short circuit in the fault level studies in chapter three (i.e. 20% increase in the fault level), and such significant contribution is important to be considered within protection studies.

4.5.1 Fuse model

The used fuse model is developed as an overcurrent protection device by using the extremely inverse time-current characteristic model that is available within PSCAD master library, and at the beginning of each LV feeder one fuse is added. The model is based on integrating a function of current F(I) with respect to the time [4.11]. Predetermined value (i.e. pickup) of the fault current is set, and when this value is exceeded, the integration starts positively to represent the start of fuse operating time, and when the integral reaches the pickup value, the fuse becomes completely open. This will give the estimated operating time in milliseconds. The integrator is used to represent the fuse operating time (i.e. pre-arcing time plus arcing time in practice) according to the total clearing time-current characteristic curves of low voltage fuses. The input to the fuse model is a measured current, and the fault current is used to indicate the presence of the fault, and based on its value the operating time is calculated. If the fault current is below the pickup value, then the function F(I) is always negative, and the integrator reset, and hence the fuse will not detect the fault. The developed fuse model by using PSCAD/EMTDC simulation program is shown on the figure below.

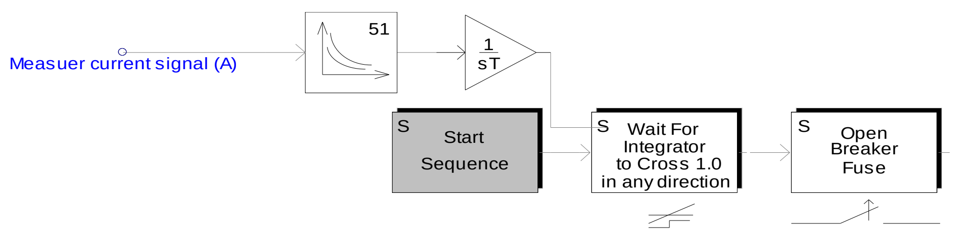

Figure 4- 5: PSCAD/EMTDC developed fuse model

Minimum fusing current is equal to fuse factor multiplied by the current rating. The fuse factor is not fixed, and it depends on other factors such as temperature and fuse breaking capacity [4.12]. The fuse factor can range between 1.25 and 1.6 times of the current rating [4.2]. In the used fuse model, the factor is assumed to be 1.6 times normal current rating, so the pickup current value is equal to 1.6 of the current rating. The low voltage fuse specification has been taken from [4.12] as shown in Figure 4- 6. All the specifications are conformed to standard IEC: 60269-2-1 with breaking capacity 80kA of the fuse links. The upstream fuse A is assumed to be 630A rated fuse.

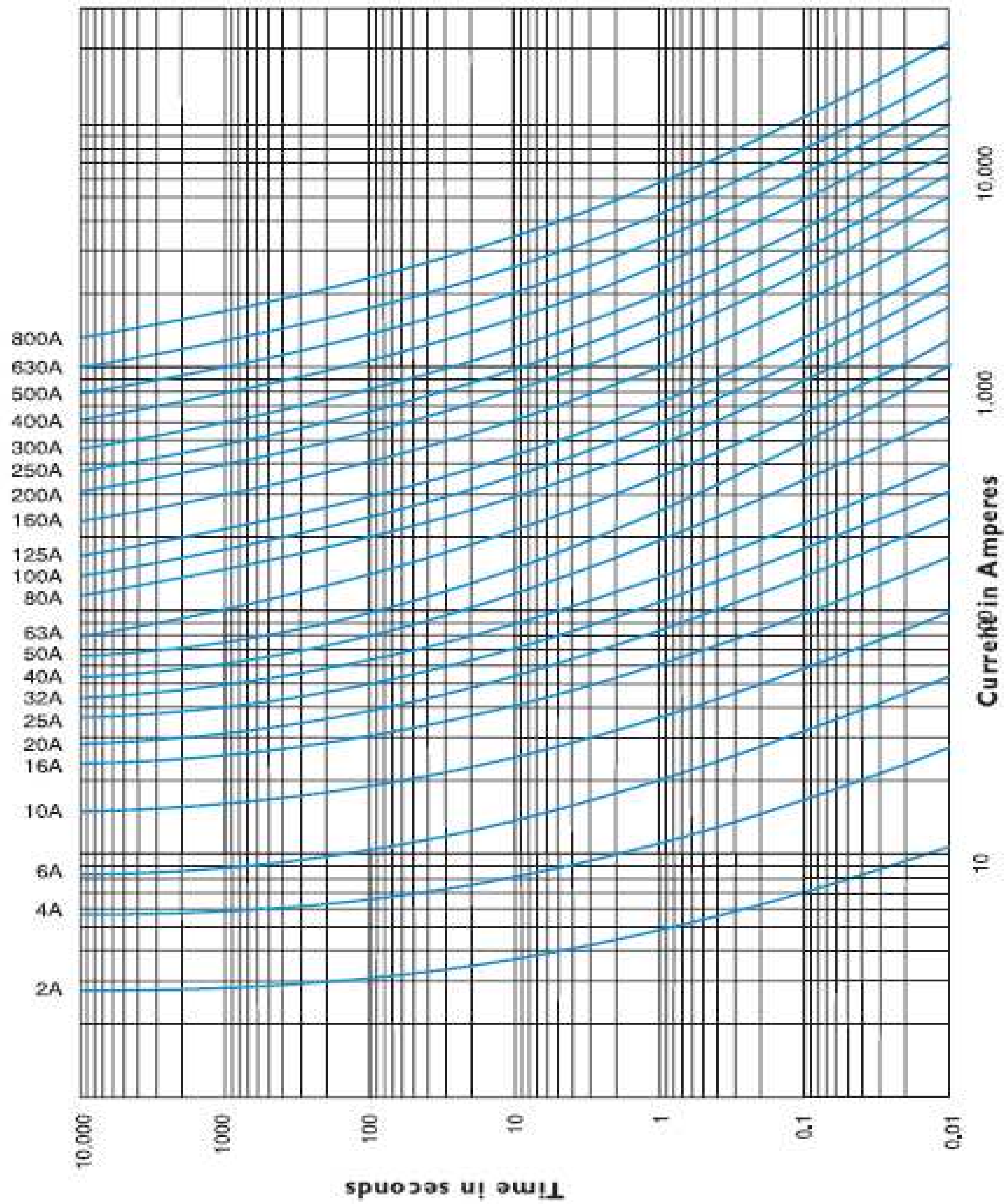

Figure 4- 6: Low voltage fuse specification [4.12]

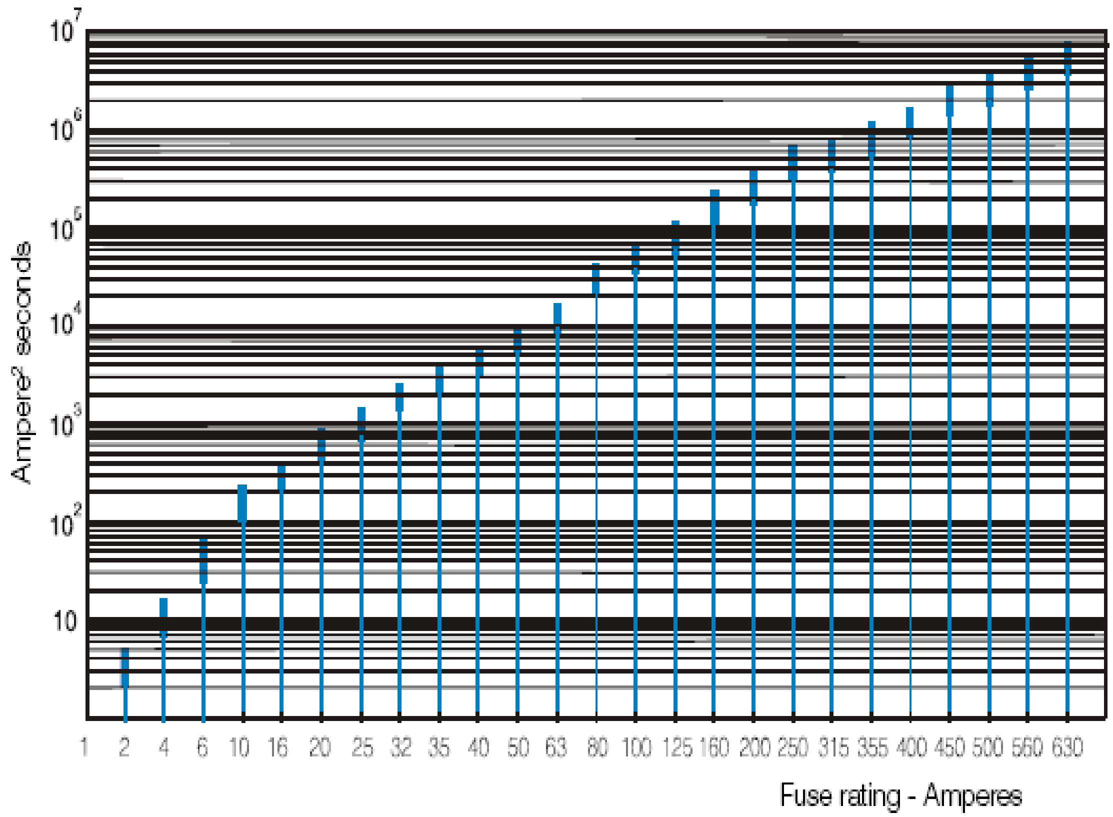

Figure 4- 7: Withstand capacity of most common fuses used for LV protection [4.12]

4.5.2 Protection studies

A- Downstream fault

The impact of aggregated microgeneration on the performance of main fuse (i.e. fuse A) protecting an LV feeder as shown in Figure 4- 8 has been studied. The study has investigated the impact on the reduction in the reach of fuse A, and hence ascertain the impact of microgeneration on LV feeder fuse protection in general. Figure 4- 8 shows the single diagram of the test network. Two scenarios have been considered, the feeder protection performance without adding microgeneration, and the performance with adding a high density of LV connected microgeneration, and the impact on the fuse protection performance is assessed.

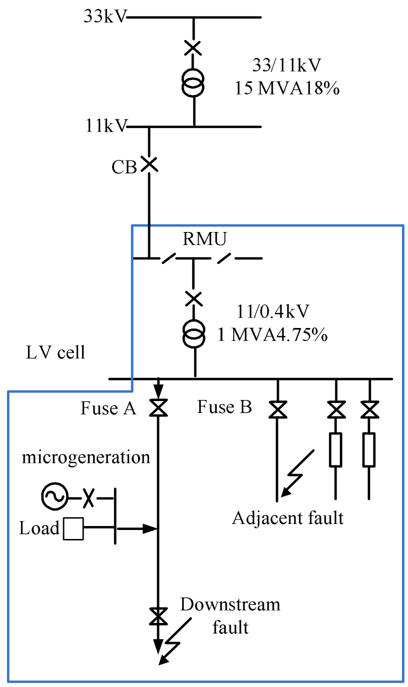

Figure 4- 8: Faulted LV distribution network feeder integrated with a high penetration of microgeneration

A1- LV feeder protection performance without adding microgeneration

A solid three-phase to earth fault was applied at the end of LV feeder, and the performance of the fuse located at the beginning of the feeder was assessed when no microgeneration was added to the network. The figure below shows that the fault current was cleared by the fuse (A) after 73msec, and this values is similar to the typical fuse operating time given in Figure 4- 6 for the fuse630A.

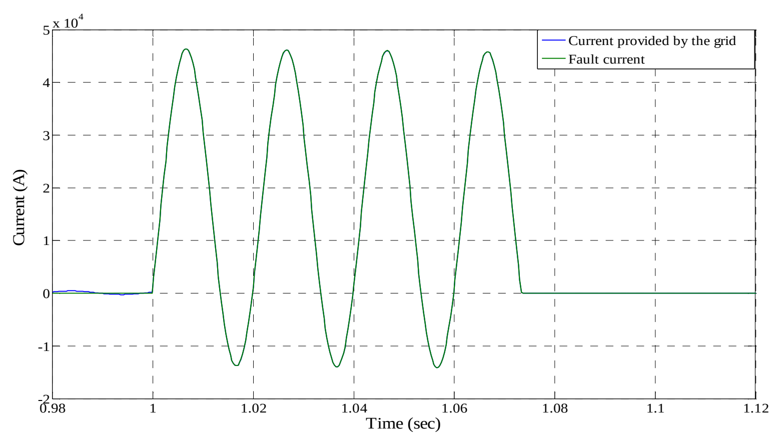

Figure 4- 9: Downstream fault current cleared by upstream fuse

A2- LV feeder protection performance with adding 100% penetration of microgeneration

For the same fault scenario as in section A1, a 100% penetration of microgeneration (i.e. 100% of a single feeder and not of the entire local distribution network) in respect to local load of the feeder has been added and the impact of the aggregated contribution from the microgeneration has been studied. Figure 4- 10 shows that the contribution to the downstream fault is negligible. For example, there is no a reduction in the reach of fuse A or a delay in the fuse operating time. This was because of the relatively small contribution to the fault by the microgeneration which was only 1/19 compared to the strong fault contribution from the grid. The Figure 4- 10 shows that the fuse has cleared the fault in 75msec, and this is just 2ms delayed from the previous studies when no microgeneration was added (i.e. 2.7% delay). This can conclude that adding microgeneration up to 100% penetration to an LV feeder would not cause a reduction in the reach of the protection devices located at the beginning of the feeder during downstream faults, and no failure to operate would be caused.

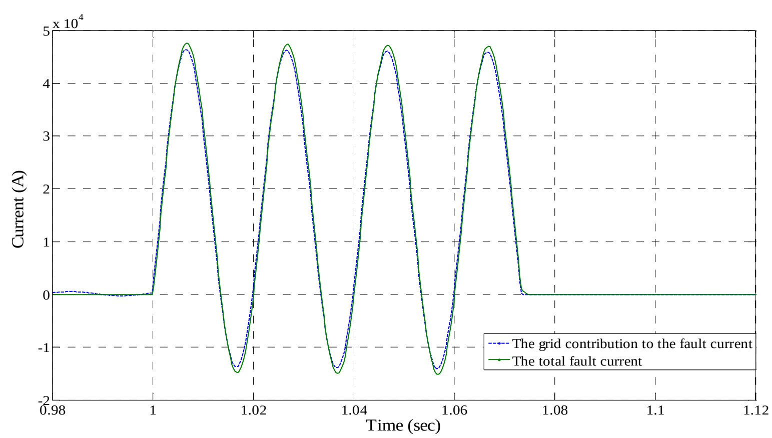

Figure 4- 10: Downstream fault current with the impact of 100% penetration of microgeneration

B- Upstream fault (Reverse fault current impact on LV feeder protection)

B1- Fault on adjacent circuit

A solid three-phase fault was applied on an adjacent feeder as shown in Figure 4- 8, and the impact of the reverse fault current that is provided by a high penetration of LV downstream connected microgeneration on the healthy feeder fuse has been examined.

The results of this section have shown that the main protective device fuse A of feeder 1 as shown in Figure 4- 8 which is the healthy feeder has detected the fault condition. This is because of the resultant reverse fault current which is provided by the local microgeneration connected to the feeder. The results have shown that this reverse current is larger than the fuse pick-up operating current. Figure 4- 11 shows that this current reaches 1.36kA RMS where the fuse pick-up current was set only to 0.63kA. However, fuse A did not operate, and this was because the fault contribution from the grid and from the microgeneration connected to feeder 1 forced fuse B to clear the fault quickly within 76msec before fuse A operates. In the case of fuse B does not operate for any reason, the reverse fault current was enough to operate the fuse A of the healthy feeder after 4.9 sec as shown in Figure 4- 11.

The RMS value as shown in Figure 4- 11 is determined by using the digital RMS meter available within the master library of the PSCAD programme which is based on using a 'moving data window approach' to determine the RMS values for repeating input waveform [4.11]. The approach as summarised in [4.11] is based on sampling the waveform per cycle of the fundamental, and all the samples are continuously buffered, and then moving snapshots of the input signal are produced, and the snapshot boundaries are defined by the present time and the period of the fundamental frequency, and a very smooth RMS output signal is provided.

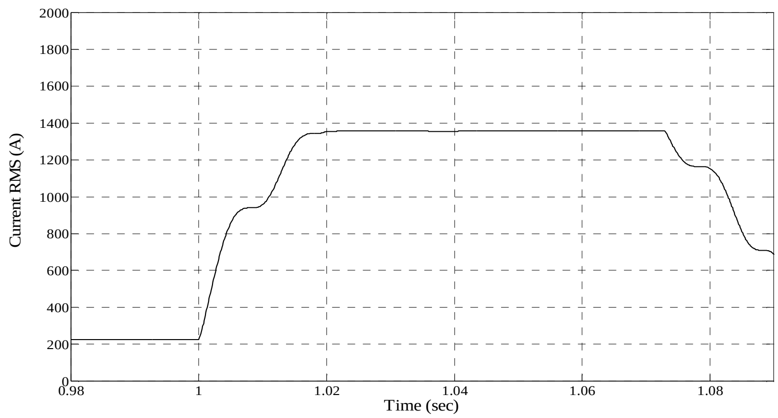

Figure 4- 11: reverse fault current provided by local microgeneration to feed an adjacent fault

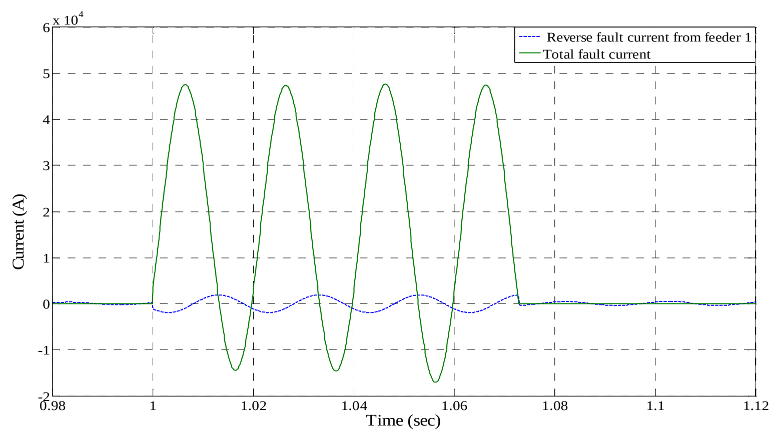

Figure 4- 12: The fault contribution from the grid and from an LV feeder connected microgeneration

B2- Fault on the main LV bus

When a solid three-phase to earth fault is applied at the LV bus as shown on schematic diagram as in Figure 4- 13 the CB on the grid side was opened very quickly. However, the fault was not completely cleared and it was supplied by the local microgeneration until fuse A and B operated after 4.9sec. The reverse current in each feeder has reached 1.36kA as shown on Figure 4- 14. It is normally expected that the downstream connected microgenerators should trip by their own protection before 4.9s. This will lead the downstream consumers to loss their generators even the fault is outside their properties. This can be an issue if the aim is to keep the local generation connected to supply the islanded consumers until the fault is cleared and the consumers are reconnected again to the grid. But if the microgeneration within the affected area are not quickly disconnected, then delay in the restoration time can be caused if a recloser is used to clear temporary faults on distribution systems. In order to avoid reclosing on a fault condition, the restoration action has to wait until the fault is completely cleared. This could take up to few seconds. Such delay would not be desirable within future power network where fast restoration and reducing the power cut time is one of its main objectives, and the delay may impact sensitive equipments connected to the system. Another issue that may be caused by the resultant reverse fault current is the following to the fuse operation which will lead to loss of supply after the reconnection with the grid until the fuse unit is replaced. Such situation does not exist if no microgeneration are added to the LV side. If the reverse current is not strong enough to blow the main fuse of the feeder, the fault will be supplied until the connected microgenerators are tripped by their own protection.

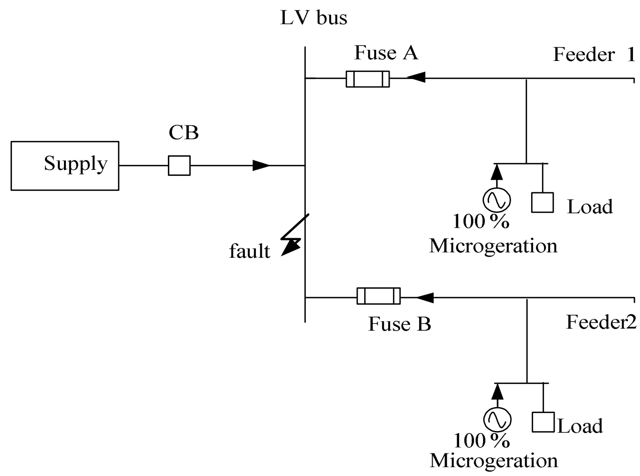

Figure 4- 13: Test LV distribution system with two LV feeders configuration

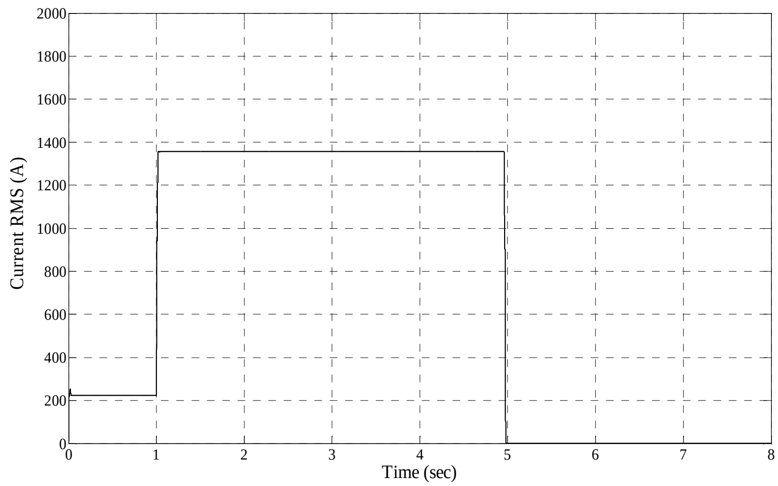

Figure 4- 14: RMS value of the reverse fault current provided by LV feeder connected microgeneration

For such problems associated with reverse fault current provided by downstream microgeneration, the direct answer to overcome these problems would be the disconnection of all microgenerators by their own protection such as under-voltage protection or loss of mains protection. But, would such a solution be acceptable within the intelligent future power system where the sustainability of supply and the ability of privately owned generators to provide local energy needs during the power outage are one of the main system targets? Or better solutions that can stop the infeed to the fault and at the same time keep the microgeneration connected would be better. This could be reached by disconnecting all microgeneration from the main LV feeder and keeping them connected within the houses. This may require an intelligent or complex controller that could detect the disturbance, disconnect the consumers from the faulted feeder, and stabilise the microgenerators within each house or within the area impacted by fault taking the advantage of the load diversity factor, and when the grid is ready, the consumers will be reconnected to the mains.

There are numbers of studies for load/generation balancing during a power cut. For example studies in [4.14] have proposed an algorithm and a model of domestic electricity infrastructure of a house and a microCHP device for producing heat and electricity at the same time with a high efficiency. The results show that with some extra hardware all the appliances in a house can be supplied, however not always at the preferred time. As microgenerators have a limited generation capacity, the most important appliances such as heating and lighting for example can be supplied. The rest of generation capacity can be used for other equipments for reducing the discomfort. Some changes to domestic infrastructure may be necessary for self supporting during power cuts. It is difficult for generation and consumption to be exactly matched, however the results of the simulation of the studies conducted in [4.14] have shown that islanded house operation with micro CHP device is possible without a lot of discomfort.

The following table summarised the protection issues that could be experienced with existing LV protection arrangement due to the presence of large amount of LV connected microgeneration.

Protection issues caused by a high penetration of LV connected microgeneration	
Issues	Cause
1- Issues of selectivity with existing arrangements	The resulted reverse fault current could blow the fuse on the adjacent feeder to the faulted feeder
2- Issues of nuisance extra fuse blowing with existing arrangements	The resulted reverse fault current could be strong enough to unnecessarily blow the healthy feeder fuses
3- Issues of safety with existing arrangement	Low reverse current may not be enough to be cleared, and the fault will be supplied until the connected microgenerators are tripped by their own protection, and this could increase the hazard.
4- undesirable features for future systems	Delay the restoration time: • The following to the fuse operation due to reverse fault current leads to loss of supply after the reconnection to the grid until the fuse unit is replaced. This increases the time of the power cut. • Impacting the operation of reclosers used for quick removal of temporary faults by feeding the fault for few seconds. This may impact sensitive equipments connected to the system

Table 15: Protection issues caused by a high penetration of LV connected microgeneration

4.6 Chapter summary

The protection issues associated with connecting a significant penetration of microgeneration to an LV distribution network protected by LV fuses have been investigated in this chapter. The obtained results have shown that with the existing arrangement of LV protection schemes and based on fault locations, microgeneration can cause numbers of protection issues. The following issues have been outlined: issues of selectivity and nuisance extra fuse blowing, issues of safety, and issues of undesirable features for future systems.

For downstream faults, the high penetration of LV connected microgeneration meeting 100% to the local domestic loads of the test urban distribution network has not impacted the selectivity to clear such faults. However, for upstream faults, the results have shown that when the upstream fault on the main LV bus is cleared from the grid side, there will be still resulted reverse fault current provided by downstream microgeneration. The reverse current has led to blowing the fuse within few seconds when 100% penetration of microgeneration contributed to the upstream fault. Therefore, a healthy feeder can be disconnected due to nuisance fuse blowing.

The minimum amount of microgeneration penetration that can cause the reverse fault current to exceed the fuse threshold current has been found in the simulation studies to be 47% of microgeneration. The reverse current provided by such penetration will require about 15 minutes for blowing the fuse. Therefore, if the microgeneration does not trip during islanding mode, then the level of hazard can be increased by feeding a fault on the system for long period of time. If the amount of microgeneration is less than 47%, the fuse will not detect the fault current and the fault would be supplied until the microgeneration trip by their own protection.

The sustainability of supply and the ability of privately owned generators to provide local energy needs during the power outage are one of future power systems targets. Supplying upstream faults by reverse fault current provided by downstream microgeneration for few seconds may cause a delay in the restoration time, by impacting the fast reconnection of the system by the reclosers used for quick removal of temporary faults. This may impact sensitive equipments connected to the system. If the reverse current caused LV fuses to blow as proved by the result the following to the fuse operation will increase the time of the power cut until the fuse unit is replaced.

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Chapter five: Transient Performance Analysis of LV Connected Microgeneration

5.1 Introduction

To cope with changes during the transition towards decentralised highly distributed power systems incorporating a large volume of microgeneration, it is important for the microgeneration to survive undesirable operating conditions (i.e. such as faults) and avoid unnecessary disconnection. The two previous areas of studies in chapters three and four have dealt with the impact of microgeneration performance on the local distribution network performance during fault conditions. The impacts on the fault level and low voltage protection performance were assessed, and the level of the problems was evaluated.

The reaction of a distribution system to any fault conditions would be very important to all equipment connected at that level. This is because faults on the system will cause a drop in the voltage of the close areas resulting in dynamic loads and connected generators to exhibit stability issues. Therefore, it is also very important to understand the influence of the host distribution networks performance during transient faults on the transient performance of connected microgeneration during and after the faults. Understanding the transient behaviour of microgeneration is useful to examine the resilience level of microgeneration during transient disturbance on the system. In addition, any source of problems that may emerge due to disconnection of a large penetration of microgeneration can be addressed, and practical means to mitigate the problems can be applied.

This chapter presents studies concerning the transient stability of microgeneration using small rotating AC machines in response to representative network transients. The chapter is structured as following: Introduction to the transient stability issue is given in section 5.2, followed by specific consideration in section 5.3 to outline why microgeneration transient stability is an important area to consider. As a result of the shortages of small scale microgeneration transient models, a set of suitable microgenerator transient models with different generator/prime mover technologies have been developed in section 5.4 to be used as part of the transient studies. The models have been built using PSCAD/EMTDC. This tool has been used for the transient stability studies as mentioned before in section (2.6) of chapter two due to its rich library which contains numbers of developed models of different rotating machines and the flexibility of building new models as well as its excellent performance for understanding the transient behaviour of electric power systems under large transient disturbances. Two types of technologies are considered for the studies: a small micro CHP diesel engine driving a three-phase synchronous machine connected within commercial premises; and a small scale microwind turbine interfaced directly within a residential dwelling by a single-phase induction generator. In 5.5 the impact of different fault locations, typical fault clearance times and generator/prime mover technologies on the ability of microgenerators to maintain stability when the cell is subject to disturbance during and after clearing of both local and remote medium voltage faults is investigated in detail. In addition, in order to examine the consequence of transient instability of microgeneration, the voltage step changes due to the simultaneous disconnection and reconnection of a large number of microgenerators within a small area of the network (i.e. cell) have been also evaluated in section 5.5.

5.2 Transient stability of a traditional power system overview

For any given power system there are numbers of operational constraints that should be considered during planning and design of the system. Power system stability issue is seen as one of the major concerns in system operation, and its evaluation basically depends on the understanding of the system behaviour when the system is subjected to a certain disturbance condition [5.1]. The issue is defined by IEEE/CIGRE task force on stability terms and definitions [5.2] as "*the ability of an electric power system, for a given initial operating condition, to regain a state of operating equilibrium after being subjected to a physical disturbance, with most system variables bounded so that practically the entire system remains intact*".

Compared to other different complex phenomena on power systems, power system stability is still believed to be seen as one of the most difficult area to assess and analyse [5.3]. This is because power systems have been moving to more complex and with more growth in interconnections between the systems [5.3]. In addition, the stability phenomenon is expected to present more difficult challenges in the 21st century electric power systems as the systems would operate closer to their stability limits [5.3] due to the increase of the interconnectivity and the potential change in the system characteristics due to the increase in the penetration of decentralised generation.

Power system stability phenomena has different forms, and clear understanding of the stability forms is essential for the satisfactory design and operation of power systems [5.2]. According to IEEE/CIGRE task force on stability terms and definitions [5.2], the power system stability are categorised into three main forms as shown in Figure 5- 1.

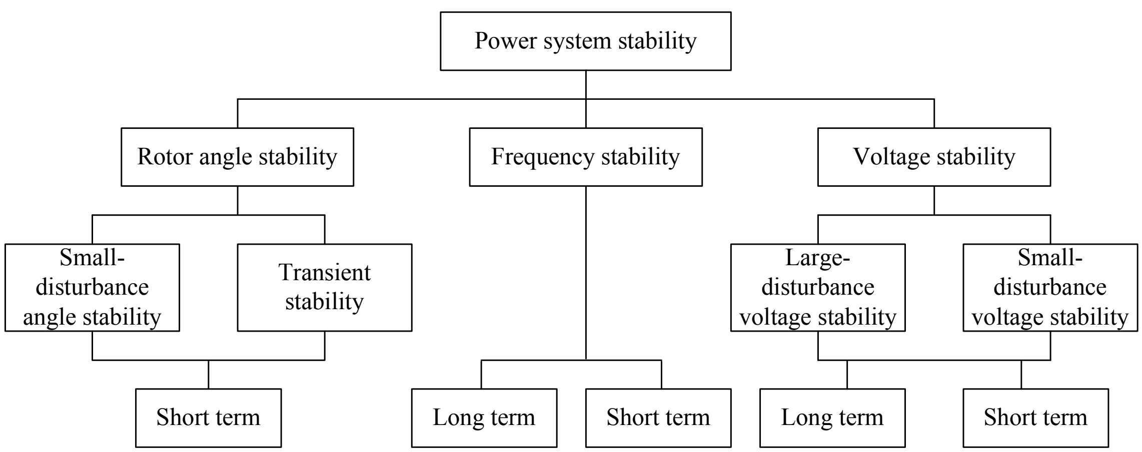


Figure 5- 1: Power system stability classification [5.2].

The voltage and frequency stability could be experienced within short and long terms, but the rotor angle stability can occur only for a short term. The rotor angle stability is divided further into two types; small disturbance angle stability and transient stability. The power system transient stability is one of the most severe limitations compared to other power system operation limitation [5.4]. It is believed that the operation of many power systems could be restricted by transient stability limits [5.4]. Transient stability is generally defined in [5.3] as *"the ability of the system to maintain synchronism when* *subjected to a severe transient disturbance such as faults, sudden loss of generation or loss of a large load".*

The synchronism means that all the system operates at same frequency. Loss of synchronism can happen between a single synchronous machine and the rest of the system or between groups of machines and the wider system. The synchronism may be still maintained among each group after separation from others but the system stiffness may be reduced [5.3]. For a traditional power system, the electricity is mainly generated by large synchronous generators. Therefore, the transient performance of synchronous machines during transient faults plays a significant role to facilitate the stability of the entire system.

5.2.1 Synchronous machine transient stability

To understand the performance of a synchronous machine during transient faults it may be recommended to review the principles operation of the machine. The principles of the machine operation are explained in detail in [5.3] and [5.5], and they are summarised as follows. Under steady-state operation the rotating magnetic field produced by the ac alternative currents in the three-phase windings of the machine stator rotates at the same speed as the rotor with an angular separation between them based on the electrical output power of the generator. This electrical power output is changed by the change in the mechanical torque applied to the rotor, and the frequency of the induced voltage (machine terminals voltage) depends on the speed of the rotor. Therefore, the frequency of electric variables of the stator (i.e. voltages and currents) are synchronised with the rotor mechanical speed (i.e. 3600rpm for 60Hz and 3000rpm for 50Hz). The increase in mechanical torque will lead the rotor to take a new position in respect to rotating magnetic field of the stator. When more machines are connected to each other, the frequency of all the stators voltages must be the same, and the rotors mechanical speed must be synchronised with this frequency, thus the machines can operate in synchronism. So the rotor of any synchronous machine connected to the power system must be in synchronism with the revolving field of the machine stator which is corresponding to system frequency.

During a transient fault on the system, kinetic energy will be gained by the rotor of the faulted synchronous machine. After clearing the fault, if the gained energy is transferred to the system then the machine will experience a period of oscillations and it may return to its stability state after a period of time. But if the kinetic energy is not absorbed by the system after the fault is cleared, then the machine rotor runs at high speed, and this may lead the machine not to maintain the synchronism with the system, and it will be seen as unstable and tripped from the system. Instability of a large machine may influence other generators connected to the system, and lead to consequent cascading events [5.6]. So, the dynamics of a synchronous machine rotor are important criteria for transient stability studies of a traditional power system where most of the large generators are interfaced to the grid by large synchronous generators. The rotor dynamics are described by the well known swing equation as in (14) [5.7].

$$\frac{d^2\delta}{dt^2} = \frac{\omega_s}{2H}(P_m - P_e) \tag{14}$$

Where

ω_s is equal to $2\pi f$ and f is the system frequency

δ is the rotor angle

P_m is the mechanical power supplied by the prime mover

P_e is the electrical power output from the generator = $P_{\max} \sin \delta$

H is the constant of inertia

The stable operation (transient stability margin) of the synchronous generator depends on the acceleration power, which is equal to the difference between the mechanical input power and the electrical output power of the generator during the fault. The acceleration power (Pe-Pm) as shown as accelerating area A1 in Figure 5- 2 has a direct impact on the swing of the rotor angle. The largest value that the rotor angle may reach during the oscillation without losing stability is used to identify the limit of the transient stability margin. One simple approach to identify the maximum power angle is the direct method based on equal-area criterion [5.3]. The method is described as in Figure 5- 2, and it can be used for a single synchronous machine connected to the grid. During $\delta_0 \le \delta \le \delta_{cr}$ the mechanical power Pm is larger than the electric power Pe, and the rotor is accelerating (i.e. within accelerating area A1). During $\delta_{cr} \leq \delta \leq \delta_3$ the electric power Pe is larger than Pm, and thus the rotor is decelerating (i.e. within decelerating area A2). The stability of the machine is maintained if only accelerating area A1 is equal to the decelerating area A2 as shown in Figure 5- 2 [5.3]. If A1 is greater than A2 then δ will be larger than δcr and the machine will loss the synchronism with the system. Therefore, the maximum value of δ that will maint the stability of the machine can be calculated when A1=A2. The duration of the fault stressing the machine is very important factor that impacts the stability of the machine. Based on the maximum value of the rotor angle δcr that can be reached during transient disturbance without losing stability after the faults, the maximum duration of the fault which maintains the stability can be identified. This time is called critical clearing time (CCT) and it has been defined in the IEEE report [5.8] as "*the maximum time between the fault initiation and its clearing such that the power system is transiently stable*".

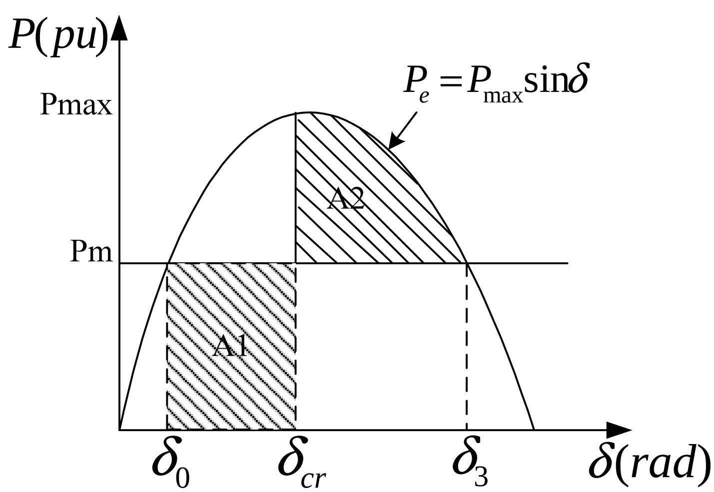


Figure 5- 2: Power angle relationship

5.2.2 Induction machine transient stability

Moving to more complex system structure incorporated with distributed generation which can be interfaced into the grid by different technologies including induction machines, the transient stability of such machines has received further attention [5.9]. The nature of induction generators has increased the interest in using such machines for renewable power generation [5.10].

Unlike a synchronous generator, induction generator is a type of rotating electrical machine that operates at a speed not directly related to the system frequency. The machine requires an external source for its excitation whether the machine is used as generator or as motor. The transient stability analysis of an induction generator as a self excited machine (SEIG) which can operate as a stand alone machine has been widely considered [5.11]. Most of the studies are related to voltage build-up due to the self-excitation and load disturbance conditions [5.12][5.13]. The grid-connected induction machine is excited by reactive power drawn from the grid, and the required electro-magnetic field inside the stator of induction generators depends highly on the voltage of the grid. The machine electro-magnetic torque is proportional to the machine speed and the square of its terminal voltage as in equation (15) [5.14].

$$T_e = KSV_{\mu g}{}^2 \tag{15}$$

T_e is the electromagnetic torque developed inside the machine.

K is a constant depends on the parameters of the machine

S is the slip of the machine

$V_{\mu g}$ is the machine terminal voltage (i.e. nominal voltage of the system)

The dynamic behaviour of the induction machine rotor is governed by the swing equation given below [5.7]:

$$J\frac{d\omega}{dt} = T_m - T_e \tag{16}$$

T_m is the mechanical torque applied to the rotor.

J is the inertia of the machine

ω is the angular rotor speed

The rotor speed of induction machine is not fixed as in a synchronous machine. If the rotor speed is greater than the synchronous speed of the stator which is corresponding to the system frequency the machine will operate as a generator, and if the rotor speed is less than the synchronous speed then the machine will operate as motor. The difference between the rotor speed and the synchronous speed is called the *"slip"*. The transient performance of induction machines is determined by the mathematical relationship between the machine electric torque and the speed [5.5]. When an induction machine is connected to the grid and its speed starts increasing above the synchronous speed, the electromagnetic torque developed inside the machine will increase until a certain value of the rotor speed. If this value is exceeded then the torque collapses and the machine will not behave anymore as generator.

In the event of the fault, a reduction in the machine terminal voltage will occur, and from equation (15) it can be observed that the electromagnetic torque will be reduced. Since the response of mechanical parts to short time faults is relatively slow the mechanical torque T_m as in equation (16) is normally assumed to be constant during the fault. During the fault the acceleration torque will appear due to the decrease in *Te* and this in turn will lead to an increase in the kinetic energy of the machine rotating mass. After the fault is cleared if the speed of the machine exceeds the allowable stability limits, the machine will experience unstable conditions, otherwise the machine rotor speed will be damped after a series of oscillations and the stability is maintained.

5.3 Microgeneration transient stability issue

As power systems are moving towards systems where increasing numbers of householders are generating as well as consuming electricity, there will always be a need to ascertain whether the underlying network can support this change in terms of transient stability or whether some adjustment is required [5.15]. Generating power at distribution systems level will alter the transient behaviour of distribution systems. According to [5.16], various studies conducted by industry and academia have shown that distributed generation could affect negatively the host distribution network in different ways from a stability perspective and on the other hand the performance of the host distribution network would directly impact the capability of the generators to ride through different disturbances.

Transient stability of generators connected at distribution networks particularly at low voltage can be a significant issue because of the following three main reasons.

- The nature of the device (i.e. microgenerator) which has relatively very small inertia (i.e. poor inherent damping), and this in turn will increase highly the sensitivity of the device to most of the faults on the system even remote faults.

- The performance of the host distribution networks which may not support the fault ride through capabilities of microgeneration. This is because existing distribution networks have been designed without any consideration of connected generation to their sides.

- The adverse impact that tripping large numbers of microgeneration due to transient instability may have on the system performance.

The transient stability of microgenerators refers to the capability of the devices to remain connected following transient disturbance. Based on some literatures, the importance of considering the microgeneration transient stability is discussed in further detail as follows.

5.3.1 Microgeneration transient characteristics

When a short-circuit fault occurs on the system, all parts close to the faulted area will experience voltage drops to a certain level. The voltage drops at the terminal of the machines and the rotor speed are intrinsically related. The rotor speed will increase when the machine terminal voltage decreases due to the fault. This will be significant for small size generators connected to LV distribution networks. The transient stability of such generators might be problem if they are interfaced directly by rotating machines (particularly induction) with low inertia [5.6]. The low inertia of those generators may increase the weakness of the distribution system. For illustration, the transient stability of 10kV distribution network with CHP 0.25MW microturbine interfaced by three-phase synchronous generator and 1.5MW and 0.66MW wind turbines interfaced by three-phase induction generators is analysed in [5.6] and [5.16], and the results of the studies have shown that the inertia is the major factor influencing transient stability performance, and there is linear relationship between inertia constant and critical clearance time. For the same remote fault conditions applied on all the three generators, the distributed generator with 0.25MVA size has been found to be the most critical elements due to its lowest inertia, and the generator did not maintain the stability when the duration of the applied fault was larger than 425ms. This will indeed create a need for giving more attention to microgeneration transient performance where the level of controllability is very limited and the inertia is very small due to the small size of units.

In transient stability studies for traditional power systems, the disturbances that are normally believed to be more severe types and lead to maximum acceleration of the generators are short circuits at the machine terminals [5.1]. Such scenario could be important when a large machine is considered within centralised power systems, where losing a large machine due to transient instability may lead to large impact on the system performance as a whole. But, this might be different for small scale generators connected at distribution levels. The fault at the terminal of small scale generator might be less critical than remote faults at the wider system. This is due to two reasons. One is the limitation of the fault by the local protection devices where their design is based on fast operation with lower fault level compared to upstream devices. The other is the generators' protection would respond very quickly to local faults and only limited generators connected very close to the fault would be disconnected. But remote faults may cause unnecessary tripping of large amount of microgeneration.

5.3.2 Host distribution system transient performance

Currently, based on the requirements for connection of distributed generation, the common procedures are to immediately disconnect the generators from the grid if faults occur and the grid is disconnected [5.17]. But as the aggregate distributed generation capacity increases this would not be acceptable any longer and new requirements for distributed generation connection may be needed [5.16]. Also the performance of traditional distribution systems may not be adequate for connected small scale generators to ride through transient faults. For example, from the protection perspective, existing protection schemes in distribution systems are largely based on a unidirectional power flow philosophy. The fundamental functions of the schemes are basically achieved by coordinating the operating times of the protective devices, where downstream elements will respond to faults faster than those upstream. Faults occurring in distribution networks are usually cleared in rather long time [5.6]. The protection coordination at distribution systems may lead to operating times of protective devices at the upstream end of a distribution feeder as high as 1.5 sec [5.18]. Such operating time may typically not be small enough to maintain the transient stability of LV connected microgeneration, and thus, the units in an area will be disconnected for faults close to upstream protection devices.

In addition, protective devices used to protect individual distributed generators would respond to transient disturbances on the system, and they could be a reason for unnecessary disconnection. The results of the studies of transient stability analysis of distribution networks with distributed generation represented in [5.6] have shown that even very short disturbance may lead to the tripping of all small scale distributed generators in the faulted area. In addition, based on the study conducted in [5.6] by comparing the typical used under-voltage protection setting of 0.25MVA distributed generator and the derived CCT-voltage dips of the same generator, the results have shown that in most cases the generator was disconnected before reached its stability margin. The study has also concluded that the present settings of distributed generation under-voltage protection (0.8pu, 200ms) would lead to massive tripping of the units over large areas in case of faults at the transmission level. It was proposed that keeping the generator connected to the grid would provide support to the system, and it was proposed that the fault ride through capabilities could be improved by the adjustment of the generator under-voltage protection according to the CCT-voltage dip curves.

The discussion in the two above paragraphs shows that transient stability of generators connected at distribution level could be an issue due to the sensitivity of distributed generation and the performance of the host network that may not support the fault ride through capabilities of the connected generators. This is based on a review of some studies that have considered the transient stability of distribution networks with distributed generation. The microgeneration would be more sensitive compared to larger distributed generation, and they have not received much attention in terms of their resilience level during fault conditions on the system. Therefore, the impact of protection performance of a typical distribution network on microgeneration transient performance is vital to be understood. The significance of the studies could be motivated if the advantages of improving the transient stability of microgeneration are outlined as well as the negative impacts of losing large amount of microgeneration are predicted.

5.3.3 The impact of losing large amount of microgeneration on the system performance

Numbers of researches such as in [5.19] have concluded that distributed generation at heavy penetration levels will have a significant impact on local distribution systems, and sometimes the bulk transmission system stability may be also affected. After outage of large amount of generators connected at distribution level, there is a possibility of emerging shortage (deficit) of active and/or reactive power, and such situation might lead to cascading events [5.6]. So the collective impact of tripping a large amount of microgeneration on the local network performance is important to be quantified in order to mitigate the problems that uncontrolled microgeneration tripping may cause to the host system.

5.4 Transient models

As a result of the shortages of LV microgeneration transient models, a set of suitable microgenerator transient models with different generator/prime mover technologies have been developed to be used as part of the transient studies in order to assess how LV microgeneration within LV cells will respond to different fault conditions on the system. The models of microgenerators used in this chapter are more suitable for capturing the transient behaviour of the devices compared to those used in chapter 3 and 4, where the amount of the fault current contribution was more important to understand the phenomena. The models for transient studies are commented upon in the following sections.

5.4.1 Test Network

The test network model used for the transient studies is the same as a single LV cell connected to the grid at 33kV that have been modelled in chapter three. The main difference between the LV cell model in chapter three and the LV cell model used in this chapter is the load characteristics model. The model is not assumed as constant loads with constant value as has been modelled in chapter three. The model in the studies of this chapter is characterised as a function in voltage magnitude which is more suitable for stability studies. Therefore, the test system in this chapter is labelled as test system 2, and it is shown as a single line diagram in Figure 5- 3.

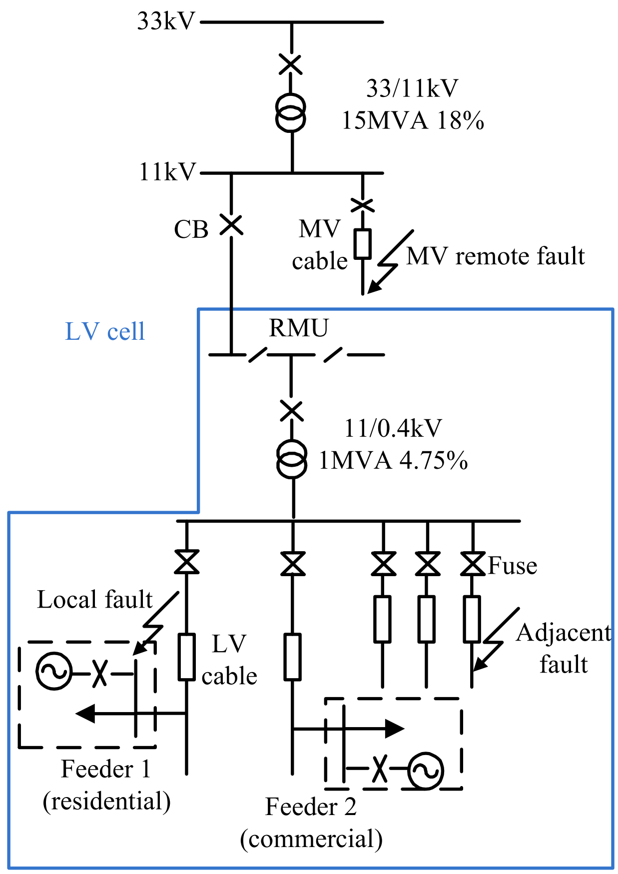


Figure 5- 3: MV-LV distribution network model for transient studies

5.4.2 Demand model

The demand on the secondary substation has been modelled as domestic loads connected to feeder 1 and commercial loads connected to feeder 2 as shown in Figure 5- 3. A uniform power factor of 0.95 lagging has been assumed, and short lengths of connecting cable typical of urban areas are also used.

Since the load characteristics have an important influence on system stability studies, the detailed load models are considered in the simulation. The static well known load model as in expressions (17) and (18) is used in the studies to represent the load [5.3]. The model is characterized as a function of voltage magnitude and frequency, where the load real and reactive powers are considered separately.

$$P_L = P_o \left(\frac{V_L}{V_o}\right)^a (1 + K_{pf} \Delta f) \tag{17}$$

$$Q_L = Q_o \left(\frac{V_L}{V_o}\right)^b (1 + K_{qf} \Delta f) \tag{18}$$

Where, P_L is the load real power, P_o is the rated real power per phase, V_L is the load voltage, V_o is the rated load voltage (RMS, L-G). $a = dP_l / dV_l$ is the voltage index for real power, and $K_{pf} = dP / df$ is the frequency index for real power. While, Q_L is the equivalent load reactive power, Q_o is the rated reactive power per phase, $b = dQ / dV$ is the voltage index for reactive power, $K_{qf} = dQ / df$ is the frequency index for reactive power, and Δf is the frequency deviation $(f - f_o)$ where f is the measured frequency and f_o is the reference frequency (i.e. 50Hz).

When the parameters of this model *a* and *b* are equal to 0, 1, or 2, the model represents constant power, constant current, or constant impedance characteristics respectively [5.3]. However, reference [5.3] has also stated that at low voltages the static models given by the equations above are not realistic, and may lead to computational problems. Therefore, the stability programs usually make provisions for switching the load characteristic to the constant impedance model when the bus voltage falls below a specified value. In the load model used in PSCAD/EMTDC transient stability program [5.20], the parameters a, and b are varied as a function of voltage below a threshold value of bus voltage, the constant power and constant current components are switched to constant impedance representation. The non-linear characteristic of the used load model is effective within ±20% of the rated RMS voltage. Outside this range, the load model reverts to constant impedance. Typically, K_{pf} and K_{qf} range from 0 to 3 and from -2 to 0 respectively [5.3]. In the studies of this chapter this type of load is used because it provides the characteristics of the change in the load including the nonlinear characteristics during the change in the voltage magnitude caused by faults on the system. The default values K_{pf} =0, K_{qf} =0, a=2 and b=2 as given in [5.20] are used, and the load models are assumed as balanced three-phase loads.

5.4.3 Microgenerators Model

Based on the potential benefits that renewable and low carbon driven microgeneration will introduce to the system and to the environment as discussed earlier in chapter two, two types of microgeneration technologies are considered for the studies in this chapter. One is micro CHP driven by reciprocating engine that can be used at commercial level, and the other is a microwind that can be used at residential level. The reciprocating engines such as diesel can have a variety of sizes and run at full power within few seconds and achieve electric efficiency up to 50%, and the efficiency can be increased if the technology is used as CHP [5.21].

The type of the technology that is used to drive the microgeneration has a limited impact on the transient performance of the machine due to the slow response of the mechanical parts during transient period, however, the full detailed dynamic models of a micro CHP driven by a small diesel engine interfaced by a three-phase synchronous machine connected within commercial premises, and a microwind interfaced directly within a residential dwelling by a single-phase induction generator are built and used within the studies.

A- 3-Phase Synchronous Generator with Reciprocating Engine Prime Mover

A complete electromagnetic transient model of a nonsalient pole three-phase synchronous machine has been used for the microgeneration transient studies. The model of the generator is one of the fully developed machine models that are available in PSCAD/EMTDC master library [5.20]. It has been programmed in state variable form using generalized machine theory, and it is based on transforming the stator windings into equivalent commutator windings using the dq0 transformation, and the three-phase rotor windings are transformed into two-phase equivalent winding with additional windings added to each axis.

The block diagram of the complete 3-phase diesel generator that has been used in the studies is given in Figure 5- 4. The figure shows the real and reactive power outer loops that control the output of the machine to give operation at a power factor of 0.95 lagging. This model is used in order to investigate the fault ride through capabilities of a microgenerator that can be connected at commercial levels and evaluate the machine resilience to the fault conditions at different locations on the network.

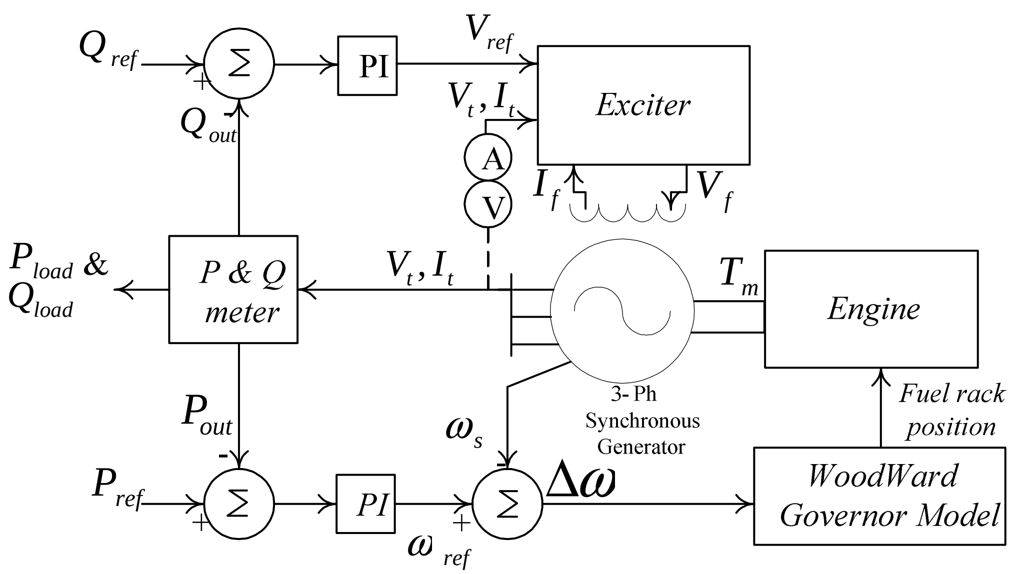


Figure 5- 4: Three-phase synchronous generator model with diesel prime mover [5.22]

The exciter is externally interfaced to the generator model, and an IEEE alternator supplied rectifier excitation system model (AC1A) as sketched in Figure 5- 5 is used to provide field control for the generator [5.23]. This model represents one of the commercially available exciters that are categorised by IEEE.

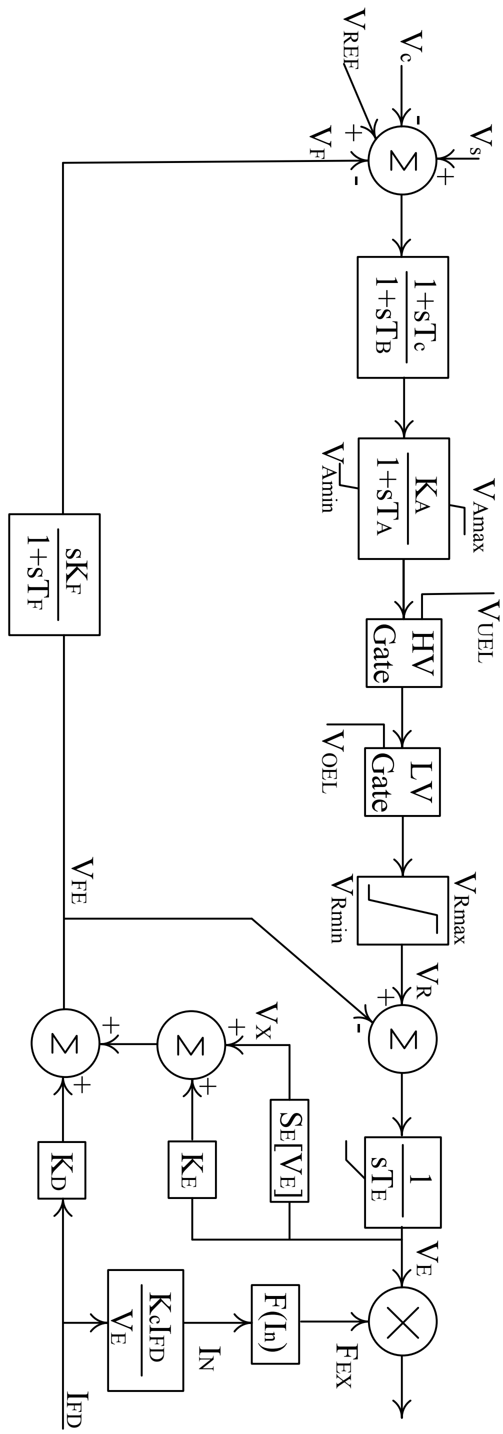


Figure 5- 5: IEEE Alternator Supplied Rectifier Excitation System (AC1A) [5.23].

The reciprocating engine used for the prime mover is shown schematically in Figure 5-6. The widely applied Woodward governor model is used to control a diesel engine model approximated by a delay expressed as an s-domain exponential function. The typical parameters available within the PSCAD/EMTDC library and based on practical data is used for the model, and they are listed in table 23 and 24 in Appendix A [5.22].

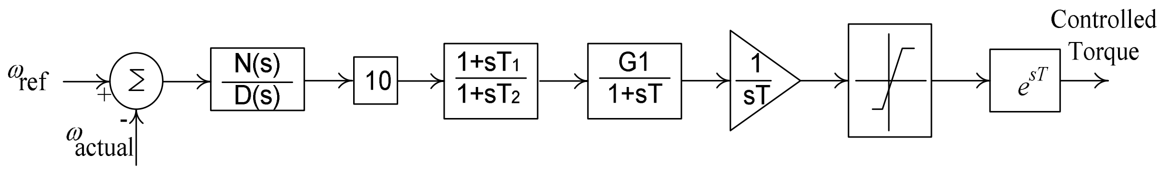


Figure 5- 6: Diesel engine and governor model

The electrical data of the generator is obtained from [5.24]. Generator rating is 28kVA, nominal voltage and current are 400V and 24.65A respectively, and the generator speed is 3000rpm. The machine impedances and time constants are listed in Table 22 in Appendix A [5.24].

B- Grid-excited 1-Phase Asynchronous Generator driven by Microwind Turbine

Single phase induction machine model

Microwind turbines are normally interfaced directly by asynchronous generators because such generators can run at different speeds, or interfaced by asynchronous generators and inverters. But the transient stability can be an issue when microwind turbines are interfaced to the grid directly by rotating machines. Microwind at residential level is connected to single-phase induction machines. Therefore, a small scale microwind turbine interfaced by a single-phase induction generator is modelled in this section.

The basic operation principles of single-phase induction machines are discussed in detail in [5.5], and are summarised as follows. Generally, for single-phase motor applications, the machine winding will produce no rotating magnetic field and hence no starting torque will be developed. So it is required to split this single winding (i.e. stator winding) into two with phase shift between their currents and hence rotating magnetic field will be produced. The two windings are displaced in space and time, and are connected in parallel to each other, and both are connected to the supply. One of the windings is the running winding and it is called main winding and the other is the starting winding which is called the auxiliary winding. The main purpose of the auxiliary winding in single-phase induction machines is to rotate the rotor at the start by making its current lead the current of the main winding as shown in Figure 5- 7.

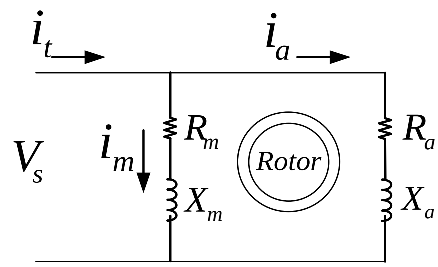


Figure 5- 7: Main and auxiliary windings connection diagram of a single-phase induction machine

V_s is a single phase ac source, and R_m and R_a are the main and auxiliary resistances. While X_m and X_a are the main and auxiliary reactances, and normally the main winding has a higher reactance with more turns, and lower resistance with comparison to the auxiliary.

The transient single-phase machine model is described in [5.25] and [5.26] and based on all the quantities of the basic machine equations to be transformed to d-q reference frame. All the electrical quantities and parameters of the machine are referred to the stator main and auxiliary windings axes. This model has been build in PSCAD/EMTDC and used in the transient stability analysis of a single-phase induction microgenerator connected to LV distribution network. The equations of d-q stator and rotor voltages components are given in (19) – (22), and the transient equivalent circuits are shown in Figure 5- 8 and Figure 5- 9.

d-q stator voltages components:

$$V_{qs} = R_{ms} i_{qs} + p\psi_{qs} \tag{19}$$

$$V_{ds} = -R_{as} i_{ds} - p\psi_{ds} \tag{20}$$

d-q rotor voltages components:

$$V_{qr} = R_{mr} i_{qr} + p\psi_{qr} - p\theta_r \psi_{dr} \tag{21}$$

$$V_{dr} = R_{ar} i_{dr} + p\psi_{dr} + p\theta_r \psi_{qr} \tag{22}$$

θ_r is defined as the angle by which the rotor winding axis leads the stator main winding axis (q-axis) with a constant rotor angular velocity ω_r. The subscripts *ar* and *mr* denote the auxiliary and main windings of the rotor, and *as* and *ms* denote the auxiliary and main windings of the stator.

$p\theta_r\psi_{dr}$ and $p\theta_r\psi_{qr}$ in the rotor voltage equations represent voltage created in the rotor windings which move at the slip speed $p\theta_r = S\omega_s$. For generator case, S and $p\theta_r$ are negative, so the rotor d-q voltages can be written as:

$$V_{dr} = R_{ar}.i_{dr} + \frac{d\psi_{dr}}{dt} + N\omega_r\psi_{qr} \tag{23}$$

$$V_{qr} = R_{mr}.i_{qr} + \frac{d\psi_{qr}}{dt} - \frac{\omega_r}{N}\psi_{dr} \tag{24}$$

Where N is the ratio of the number of the auxiliary windings turns to the number of the main windings turns.

V_{ds}, V_{dr} d-axis stator and rotor voltages (V)

V_{qs}, V_{qr} q-axis stator and rotor voltages (V)

R_{ms}, R_{as} main winding and auxiliary winding stator resistance (Ω)

R_{mr}, R_{ar} main winding and auxiliary winding rotor resistance (Ω)

ψ_{ds}, ψ_{dr} d-axis stator and rotor flux linkage components (H.A)

ψ_{qs}, ψ_{qr} q-axis stator and rotor flux linkage components (H.A)

ω_r electrical angular velocity and it is equal to mechanical speed multiply the number of pole pairs

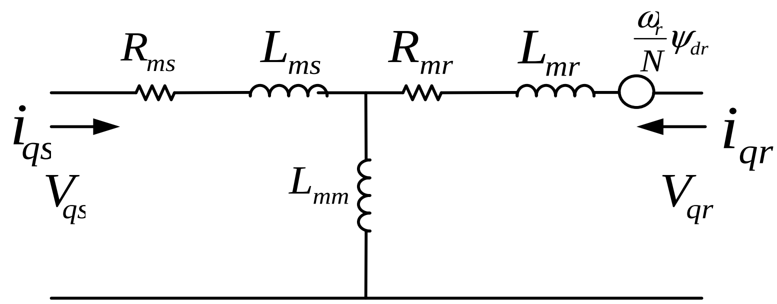


Figure 5- 8: q-axis (main windings)

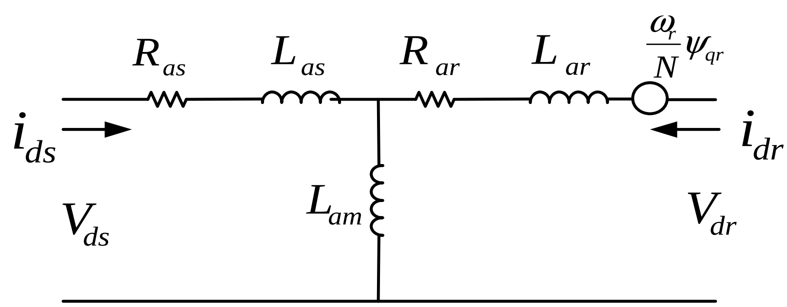


Figure 5- 9: d-axis (auxiliary windings)

The model takes into account the three important terms in asynchronous machine models as stated in [5.3]. The terms are; the drop term $R.i$, the transient term $\frac{d\psi}{dt}$, and the speed voltage term $N\omega_r\psi$.

Electrical power and torque:

The instantaneous power input to the stator is equal to $P_s = v_{ms} i_{ms} + v_{as} i_{as}$ and in the d-q axes is equal to $P_s = (v_{ds} i_{ds} + v_{qs} i_{qs})$ (25)

The instantaneous power input to the rotor is $P_r = (v_{dr} i_{dr} + v_{qr} i_{qr})$, and the power associated with the speed voltage term ($N\omega_r\psi$) is equal to

$$P_r = ((1/N)\psi_{qr} i_{dr} - N\psi_{dr} i_{qr})(p\theta_r) \quad (26)$$

The electromagnetic torque developed within the machine is obtained as the power associated with the speed voltages term ($N\omega_r\psi$) divided by the shaft speed in mechanical radian per second [5.3]. The rotor speed is equal to $-(p\theta_r)(2/Pole)$, and the torque is equal to $T_e = ((1/N)\psi_{qr} i_{dr} - (N)\psi_{dr} i_{qr})\dfrac{Pole}{2}$.

$$T_e = P.N(\psi_{qr}.i_{dr} - \psi_{dr}.i_{qr}) \tag{27}$$

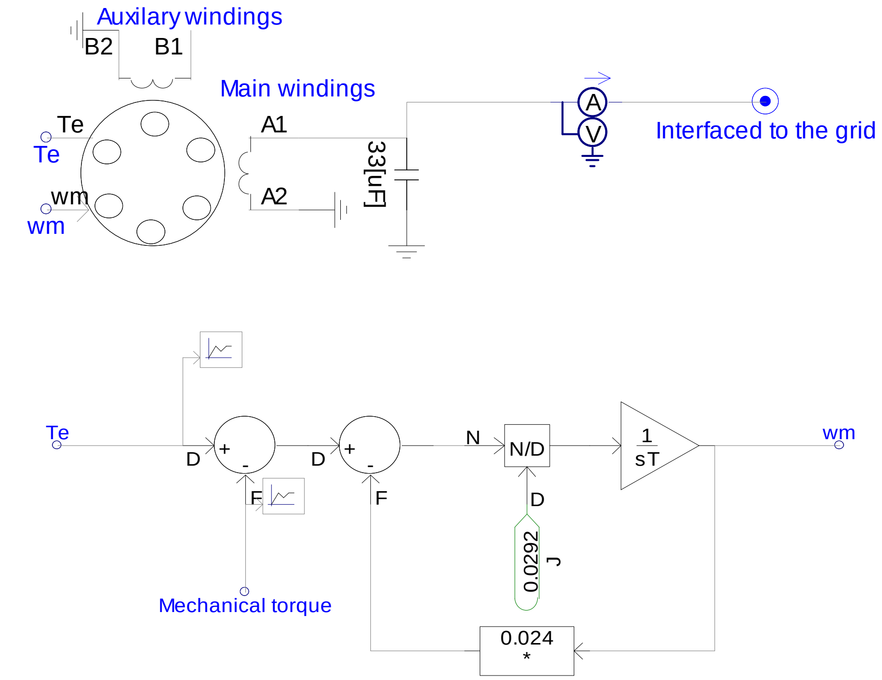
Microwind turbine model

The single-phase induction generator is assumed to be driven by a small size microwind turbine to deliver from (1-1.5kVA) output power based on the machine parameters and the mechanical speed. However, sometimes it is difficult to exactly identify the output power from a microgenerator wind turbine driven where the output power depends directly on a variable wind resource. Generally, the power produced by the wind generator depends on the average wind speed, the air density, and other factors. The electrical generated power can be calculated from the following formula [5.27]:

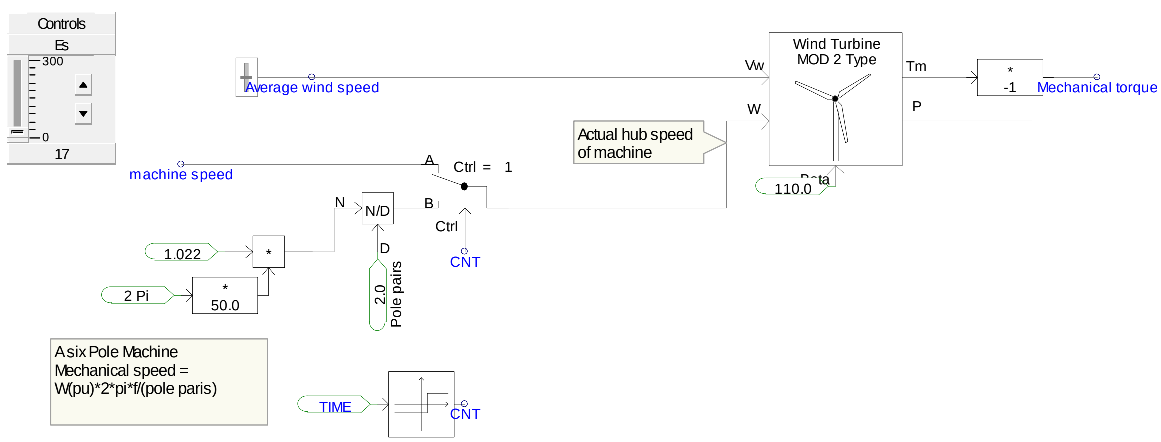
$$P = \frac{1}{2}\rho \times A \times V^3 \tag{28}$$

Where ρ is the air density, *A* is the area swept by the propellers, and *V* is the average wind speed.

The micro turbine model is developed in PSCAD, and it is assumed to be driven by a constant speed. Practical data regarding to the turbine dimensions and wind speed to provide power in range of few kilowatts is used for the model, and it is taken from the Swift Wind Energy System website [5.28]. From the power curve of the Swift device it has been identified that approximate average speed to provide from 1-1.5kVA power is around 16.5m/s. The other basic data used for the model is listed in Appendix C.



(a)



(b)

Figure 5- 10: (a) PSCAD single-phase induction machine model

(b) PSCAD wind turbine model

Since the machine is used in the studies as grid-connected, its excitation is made by the reactive power drawn from the grid. Any operation in isolation from the grid is not considered, so no excitation capacitances are used, and in the simulation only a capacitor for the machine power factor correction is used. All stator and rotor parameters are listed in Table 25 in Appendix C and obtained from [5.29][5.30], and [5.31].

5.5 Transient studies

The purpose of the transient studies conducted in this section is to investigate the transient performance of a range of LV connected microgeneration with different technologies and sizes in response to realistic network faults and thereby ascertain the range of conditions under which microgeneration might be expected to trip. The transient studies are divided into two parts; fault studies, and simultaneous disconnection and reconnection of large numbers of microgeneration studies.

5.5.1 Fault studies

The fault studies investigate in detail the impact of different fault locations, typical fault clearance times and generator/prime mover technologies on the ability of grid-connected microgenerators to maintain stability during and after clearing of both transient local and remote faults on the system. Any protection associated with the microgeneration has not been included in order to demonstrate their inherent capability and response.

In order to investigate the impact of different fault locations on the microgeneration transient performance, three fault scenarios cases as shown in Figure 5- 3 are considered in the studies. A transient local fault is assumed in case 1 to occur within the premises (i.e. residential and commercial) where the microgenerator is connected. In case 2 a transient fault is applied on the LV adjacent feeder, and in case 3 the fault is applied on a remote location on MV side. For each case the transient response and performance of the two types of microgeneration technologies (i.e. microgenerator interfaced by a three-phase synchronous machine and single-phase induction machine) is examined.

A- Three-Phase Synchronous Machine for microgeneration application (28kVA)

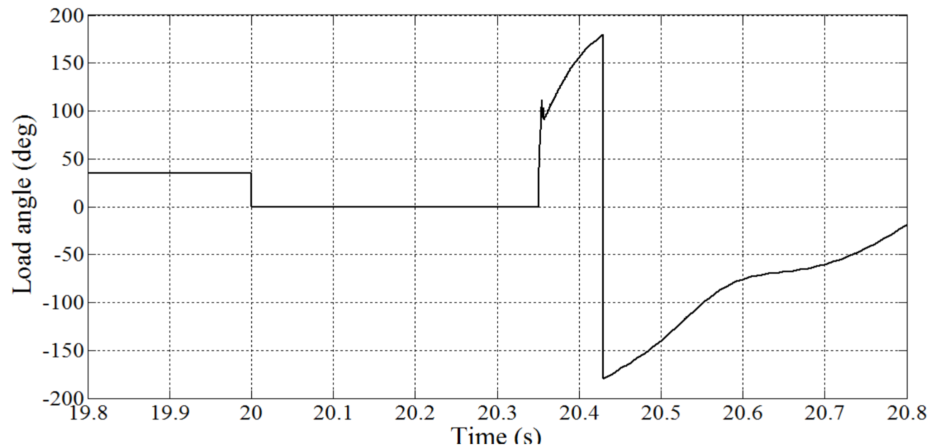
This type of technology is considered, because most of CHP microgeneration driven by reciprocating engines and connected at commercial and industrial level are interfaced by three-phase synchronous generators. Therefore, the following studies present the investigation of the transient stability of a small diesel as an CHP example powered three-phase synchronous generator connected to the LV distribution network described previously in Figure 5- 3. This will identify the resilience level of such technologies to ride through different transient disturbances on the system.

In this section the local and remote faults are considered to be three-phase to ground and the critical clearance time (CCT) is calculated during each case. The studies are performed for two values of combined inertia constant (H = 1s and 1.5s) and simulation results are shown for fault clearance times in excess of the CCT to illustrate the impact of generator pole slipping.

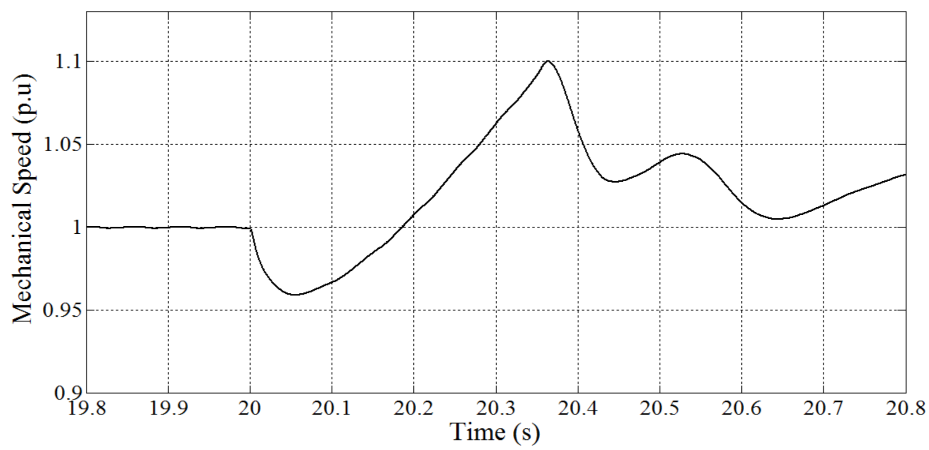
Case 1: Fault within LV Commercial Premises

The CCT for a three-phase fault applied within the same commercial premises as the generator was found by trial-and-error simulation studies to be 310ms and 336ms for the inertia constant values of 1s and 1.5s respectively. Figure 5- 11 illustrates the instability of the generator (H = 1s) by showing the machine angle responses for a fault duration larger than the CCT of the machine and applied at 20s. During the fault as illustrated in Figure 5- 11 the machine angle has fallen to zero, and the rotor has been accelerated up to 1.1pu due to the complete collapse of the machine terminal voltage as shown in Figure 5- 11c. When the fault is cleared after 350ms, the onset of instability can be observed from Figure 5- 11a where the rotor angle has increased rapidly to reach 180° within 80ms, and slipped at 1.1pu speed after the fault is cleared.

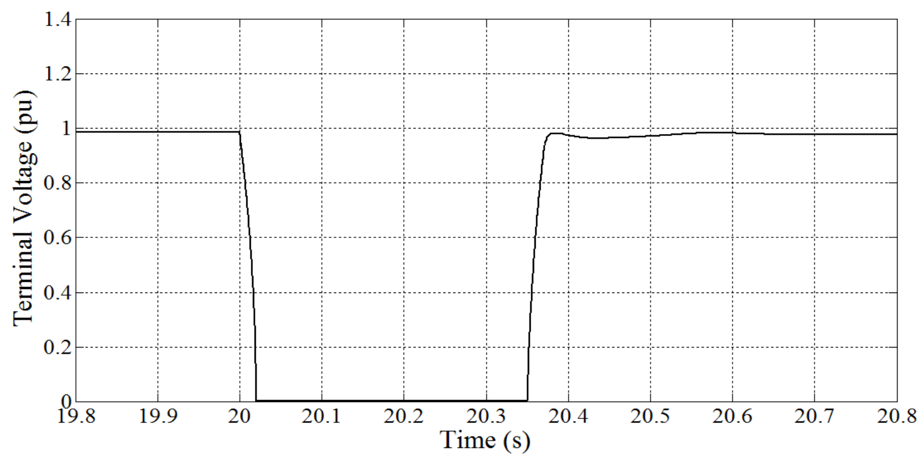
From the studies conducted in [5.6] it has been shown that in most of the cases for local fault the protection of distributed generation will operate around 100ms. So, faults within the commercial premises will be quickly cleared by the substantial fault current contribution from the mains supply and the low rating of the protection devices downstream. Thus wide instability arising from these events would be limited. It is expected that only a single machine may be tripped and such local fault will be cleared very quickly and may not impact the other machines connected nearby.



(a)



(b)

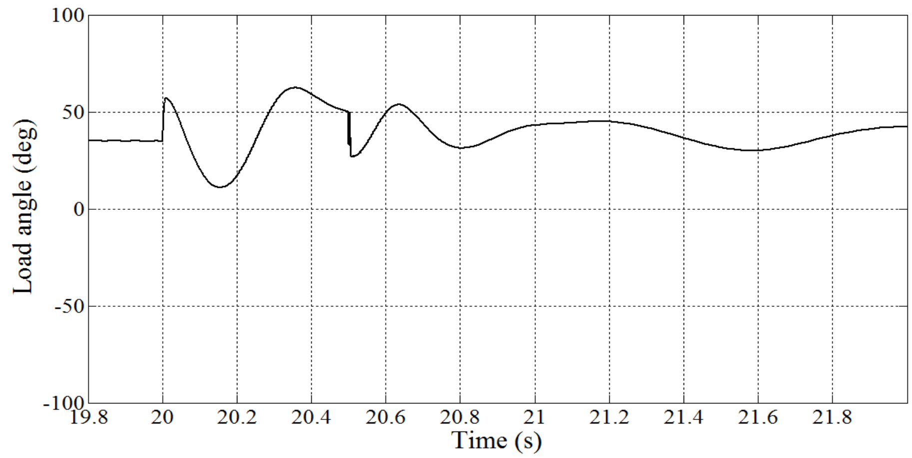


(C)

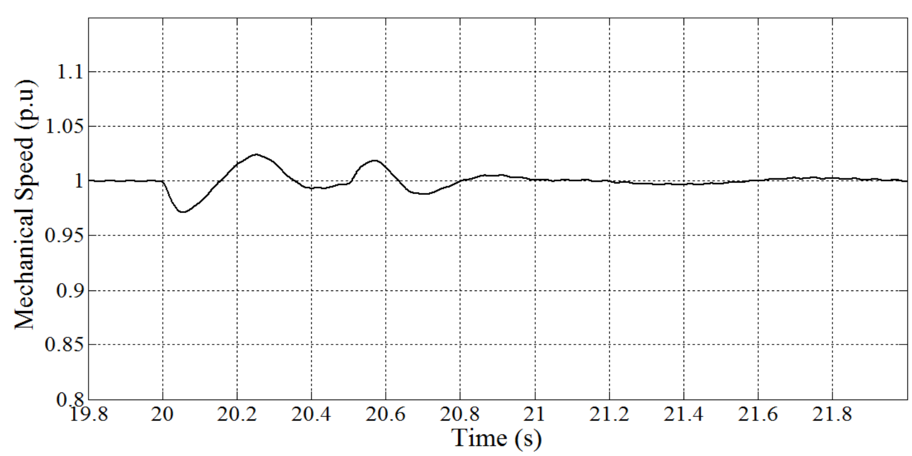
Figure 5- 11: The transient performance of 28kVA three-phase synch machine during local three-phase fault (a) machine angle, (b) shaft speed & (c) terminal voltage

Case 2: Fault on adjacent LV Circuit

In this case the fault is applied on the adjacent LV circuit as drawn in Figure 5- 3. The fault is assumed to be applied at the end of adjacent LV feeder of a typical distribution network. The aim of this case is to quantify the resilience of the machine when a fault is experienced on the local LV distribution network. The results of the machine transient response with H=1s to such fault scenario are sketched in Figure 5- 12. The fault is applied at 20 second and it lasts for 500msec as shown below on the figures. From a, b, and c figures below, it can be clearly observed that instability did not occur due to the relatively high retained voltage at the generator terminals.



(a)



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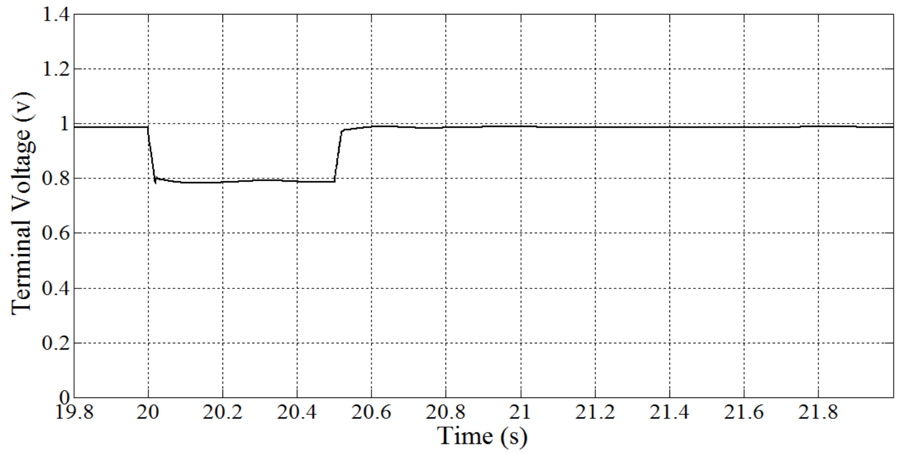


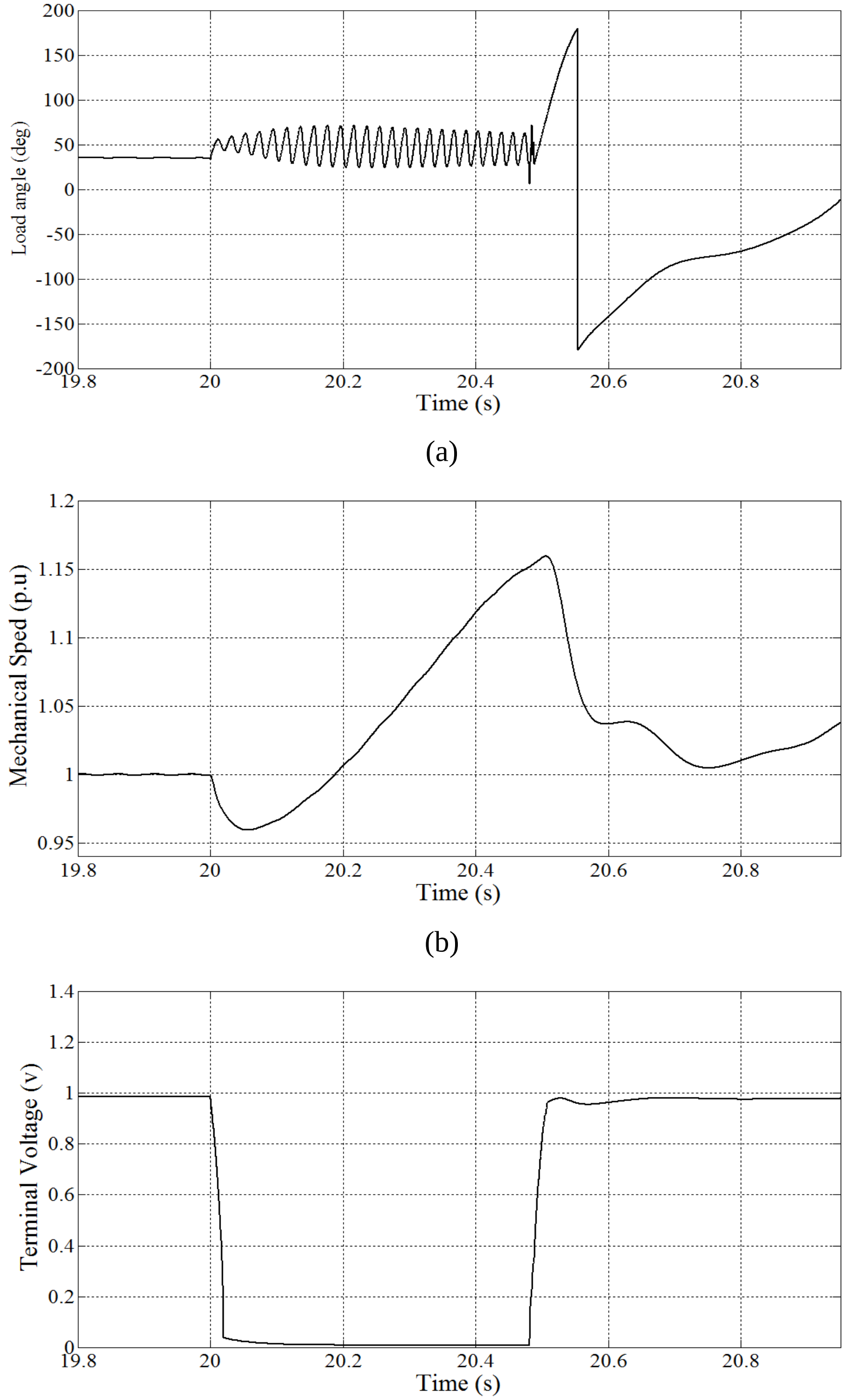
(C)

Figure 5- 12: The transient performance of 28kVA three-phase synch machine during an adjacent three-phase fault (a) machine angle, (b) shaft speed & (c) terminal voltage

Case 3: Electrically Remote faults on MV Network

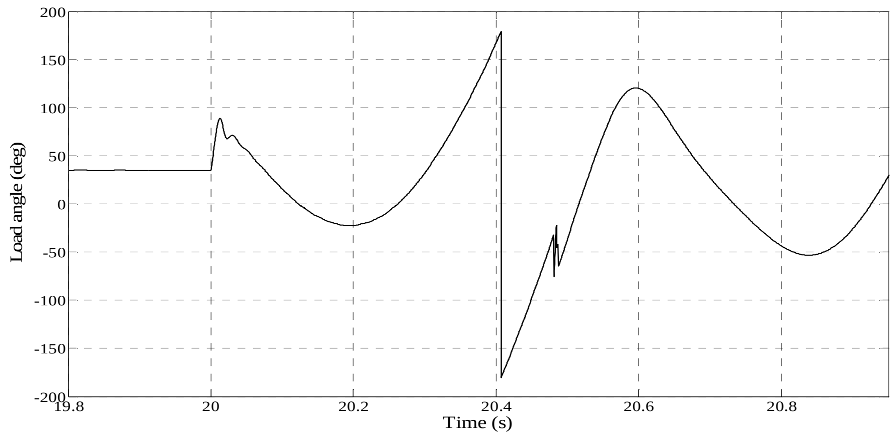
Two specific fault conditions are applied on the MV side of the secondary substation and the CCT of the machine is found for both cases with different inertia constants. The first fault condition is when a three-phase fault applied adjacent to the MV terminals of the secondary substation transformer. The second is when the same fault is applied at a remote location on MV circuit. These two fault scenarios are considered in order to address the fault ride through capabilities of the microgeneration due to remote faults where the protection (i.e. at MV level) could last few hundred milliseconds to clear the fault.

For the first fault condition, the CCTs are identified by the simulation studies as being 312ms and 340ms for the inertia constant values of 1s and 1.5s respectively. As for the second remote fault condition, the fault is assumed to be placed 500m far from the MV main bus along a length of cable as shown in Figure 5- 3. For the remote fault the CCTs of the generator are found be equal to 330ms and 353ms for H=1 and 1.5s respectively. Figure 5- 13 and Figure 5- 14 illustrate the transient instability response of the machine when the fault duration exceeds the machine CCT with the drop in terminal voltage again evident. When the fault is applied adjacent to the MV terminals of the substation at time=20s the voltage on the machine terminal falls to zero, and this has led the machine rotor to speed up during the fault as shown in Figure 5- 13b, and after the fault is cleared the machine angle increases rapidly until the machine reaches 180° and slipped at speed 1.16pu, and the stability of the machine is lost. During the second fault condition when the fault is applied at a remote location on MV circuit, the machine has experienced the same performance but the maximum rotor speed that has been reached by the machine was smaller due to the 20% retained voltage on the machine terminals.

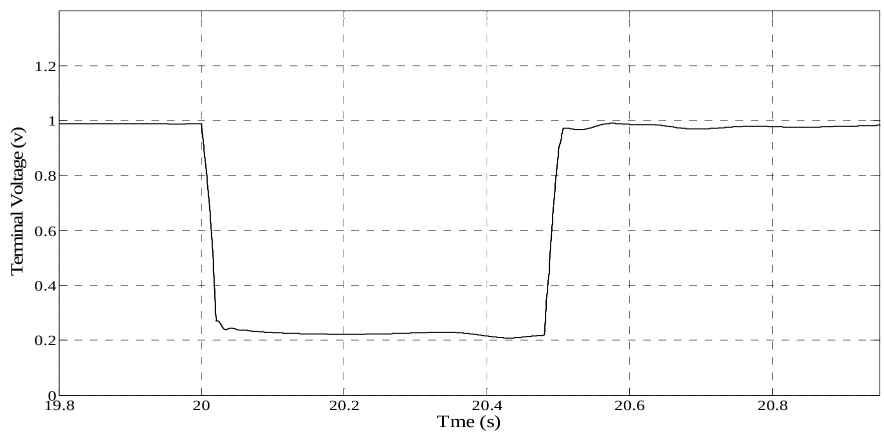


(C)

Figure 5- 13: The transient performance of 28kVA three-phase synch machine during MV transformer terminal fault - (a) machine angle, (b) shaft speed & (c) terminal voltage



(a)



(b)

Figure 5- 14: The transient performance of 28kVA three-phase synch machine during remote MV fault - (a) machine angle & (b) terminal voltage

B- Single-Phase Asynchronous Machine for microgeneration application

The following studies present the investigation of the transient performance of different size of small scale asynchronous generator. Two sizes of grid-exited asynchronous generator are used for the studies 1hp generator (746W) with power factor correction to provide 1kVA and 1.5kVA. These sizes are considered because they represent the typical size of small scale generators that could be connected at residential level, and also can be used to provide an understanding of how a grid-connected single-phase induction generator with different size can perform during fault conditions applied at different locations.

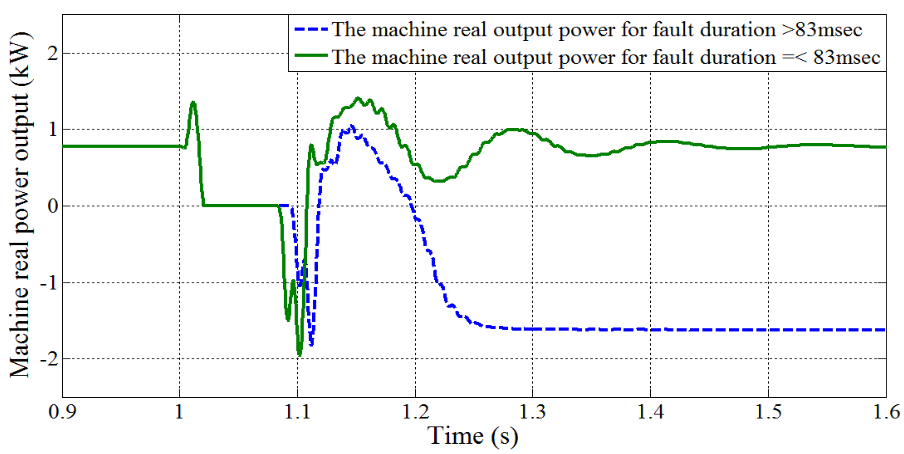
The same three cases regarding the fault locations applied for studies in section (I) are also applied in this section, and the fault type is considered to be a single-phase to earth at each location. The critical fault clearance times CCTs of the generators are found, and any nuisance tripping of the microgeneration that may occur due to different fault locations on the system is identified.

Case 1: Local fault within LV Residential Dwelling

In this case a solid single-phase fault is assumed to occur within the residential dwelling where the microgenerator is connected. The response of two different size microgenerators (1kVA & 1.5kVA) to the fault is examined, and the CCTs at each condition are found. The results of the studies are based on the comparison between the machine performance within the range of fault clearance less than the machine CCT and the machine performance after CCT is exceeded. The transient performance is examined in each case by assessing the machine output power, the machine speed, and the developed electromagnetic torque during and after clearing the fault.

Transient performance of 1kVA single-phase asynchronous generator

From the simulation studies, the 1kVA asynchronous generator output power during the fault has very quickly collapsed after the fault duration exceeds 83msec as shown in Figure 5- 15. So the machine can not ride through such fault if the fault lasts more than 83msec. This is evident by the machine developed electromagnetic torque shown in Figure 5- 16 where the torque recovers for the fault duration equal to 83msec, and it has collapsed to zero after exceeding this duration. This in turn will lead to release a relatively large kinetic energy gained during the fault within period larger than the CCT. This energy speeds up the machine rotor to uncontrollable speed and instability occurs. Figure 5- 17 illustrates the machine rotor performance in terms of the slip and speed when the fault duration is less than CCT and when it is large than the CCT of the machine. When the fault duration exceeds the machine CCT insufficient electrical torque is developed which does not have any impact on damping the machine speed, and hence instability is experienced. Over-speed protection would be required to operate to avoid damage to the machine and to avoid drawing a comparatively large amount of reactive power from the network. So for such small scale microgenerator with quite small inertia it will be very difficult to ride through large local disturbances such solid phase to earth short-circuit, and the trip of the machine is necessary.



(b)

Figure 5- 15: The transient performance of 1kVA single-phase induction generator during and after a local fault: the real output power during stable and unstable operation after the fault

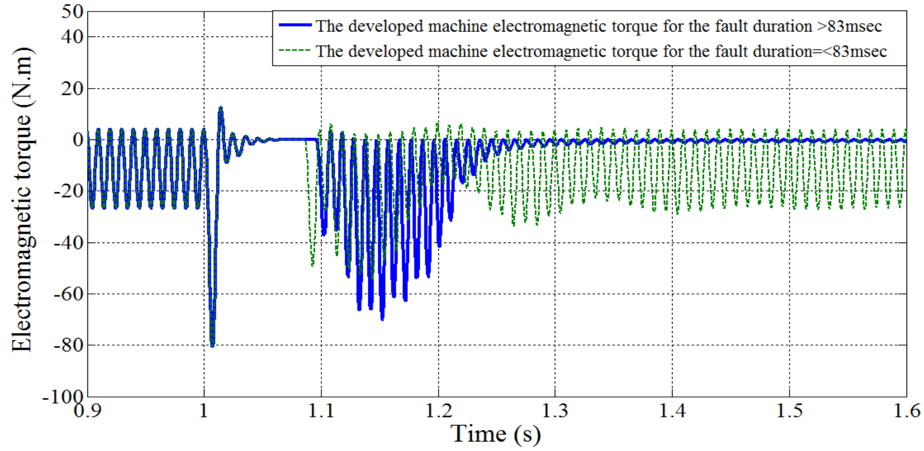


Figure 5- 16: The electromagnetic developed torque of 1kVA single-phase induction generator during stable and unstable operation

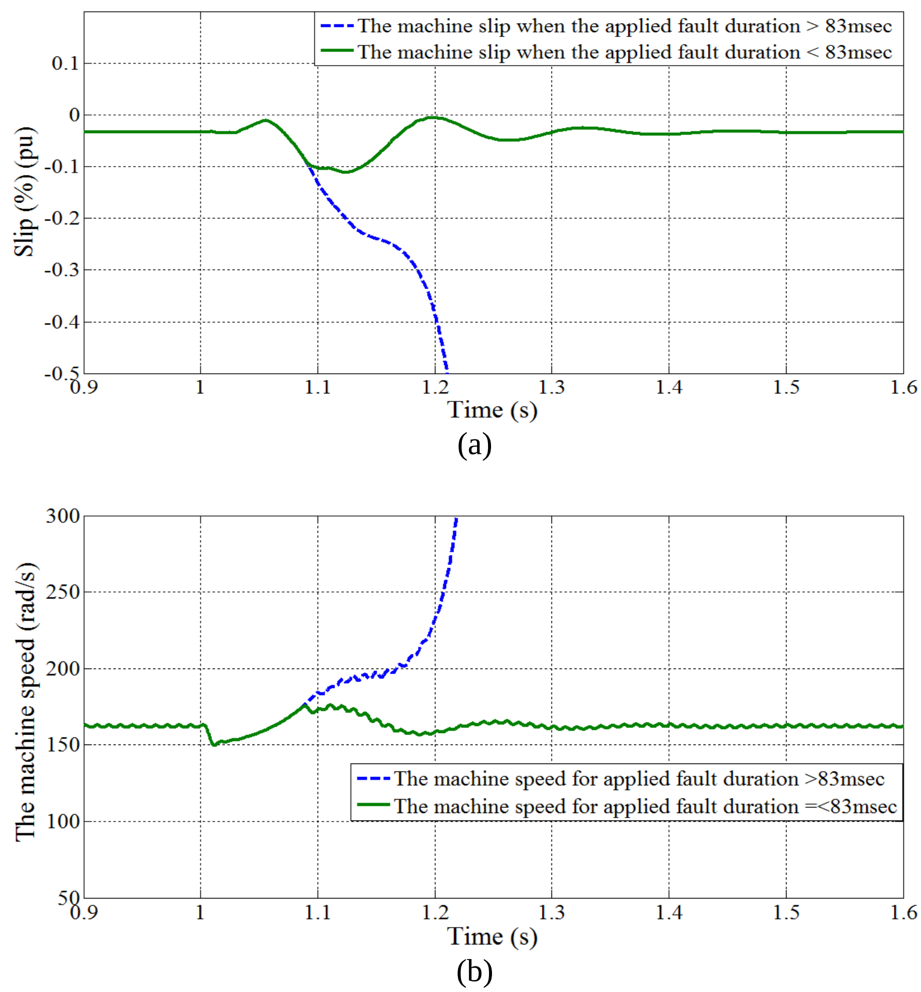


Figure 5- 17: 1kVA single-phase induction generator rotor performance: (a) the machine slip during stable and unstable operation & (b) the machine speed during stable and unstable operation

Transient performance of 1.5kVA single-phase asynchronous generator

The CCT of 1.5kVA generator during a local single-phase to earth fault has been found by the simulation studies to be equal to 93msec. The real and reactive output powers of the machine which reflect the machine performance before, during, and after the local fault are shown on Figure 5- 18. Also the comparison between the machine capability to ride through the fault and the machine incapability to do so is evidently explained by the performance of the developed electromagnetic torque shown on Figure 5- 19. The figure shows the collapse of the torque when the fault duration lasts more than 93msec. The impact of the developed torque during and after the fault on the machine rotor speed is shown on Figure 5- 20.

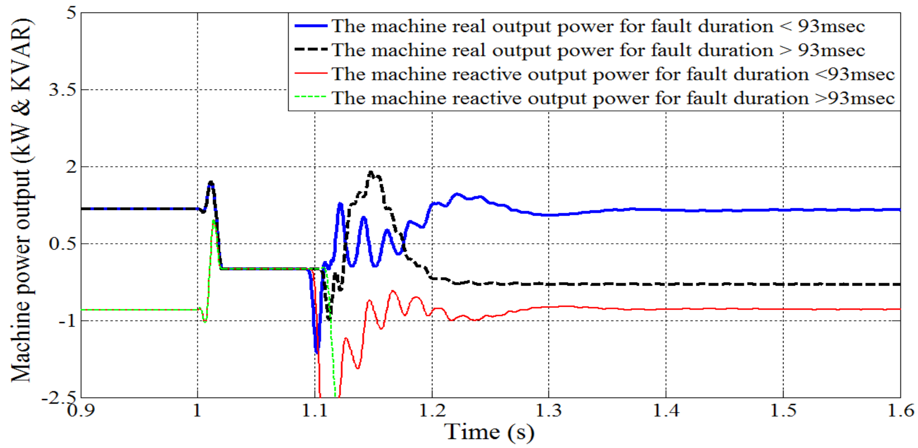


Figure 5- 18: The real and reactive output power of 1.5kVA single-phase induction generator during stable and unstable operation

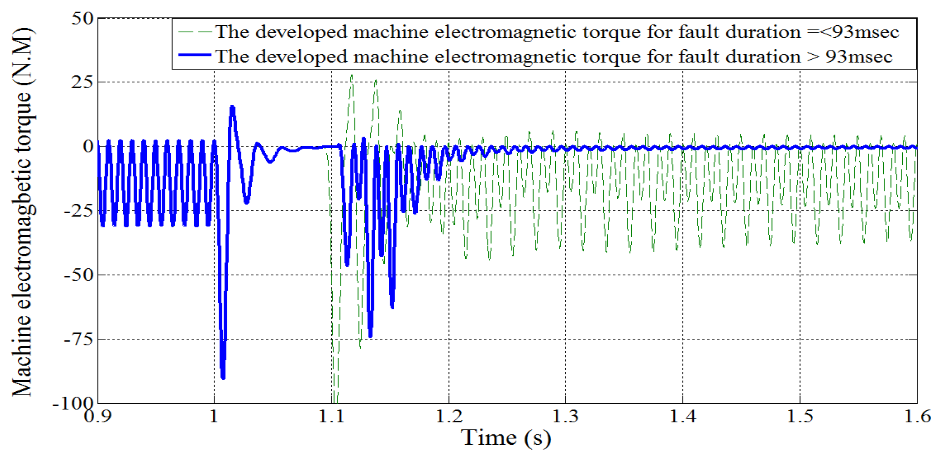


Figure 5- 19: The electromagnetic developed torque of 1.5kVA single-phase induction generator during stable and unstable operation

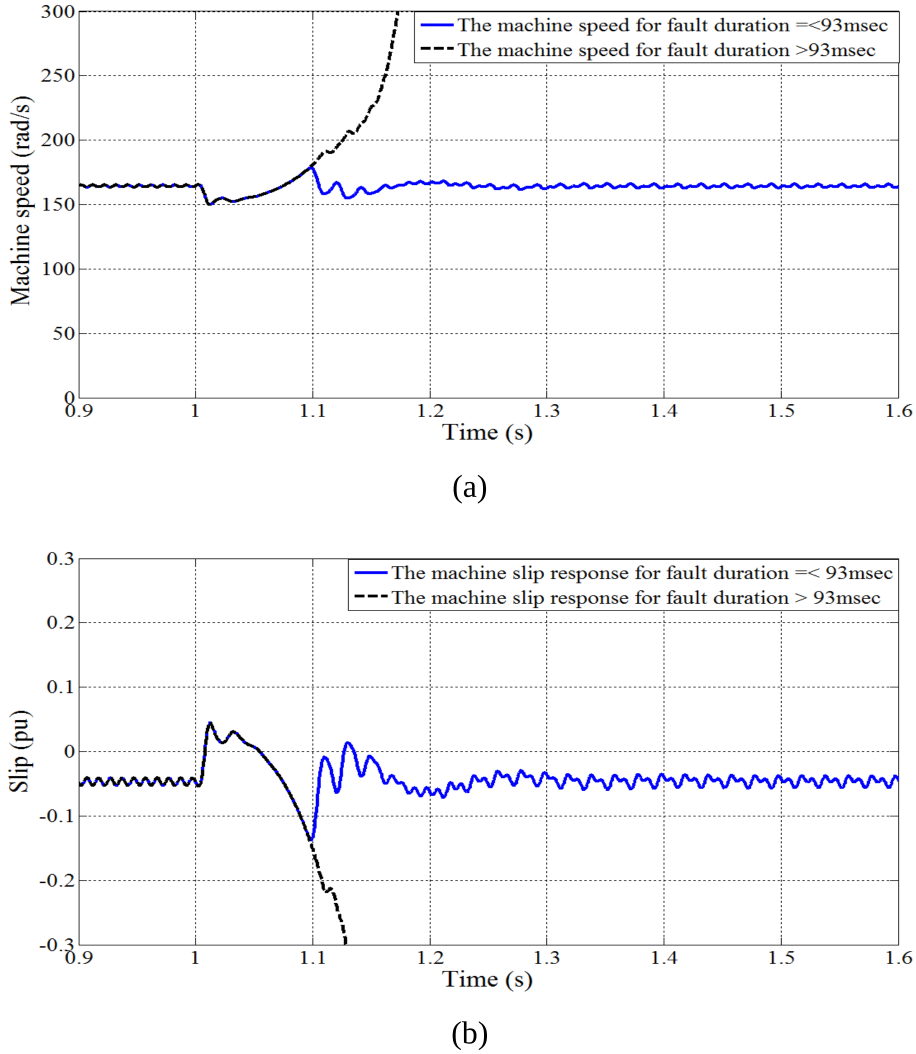


Figure 5- 20: 1.5kVA single-phase induction generator rotor performance: (a) the machine slip during stable and unstable operation & (b) the machine speed during stable and unstable operation

Case 2: Fault on adjacent LV Circuit

In this case a single-phase fault is applied on an adjacent LV circuit as sketched in Figure 5- 3. The fault at such location has impacted the microgenerator connected on the other LV feeder. The 1kVA machine terminal voltage drops up to 76% of the nominal voltage as shown in Figure 5- 21. The results of the simulation studies have found that is the 76% drop in the machine terminal voltage stays longer than 142msec the machine will experience instability performance, and it will not be capable of delivering power to the network after the fault is cleared. Therefore, the machine CCT is equal to 142msec for such type of fault. This is shown in Figure 5- 22. This is observed almost the same for 1.5kVA machine. The torque, slip, and the speed response during the adjacent fault are shown in Figure 5- 23 and Figure 5- 24 respectively. All variables undergo relatively small perturbations and return to their pre-fault values once the fault has been cleared before 142msec. However, this fault may not be seen as problematic if the local protection at the adjacent feeder is able to clear the fault within few milliseconds. In chapter four of the thesis a similar fault was cleared within 75msec. So faults occurs on LV side will be cleared very quickly because of the low operating rating of the protective devices at that level.

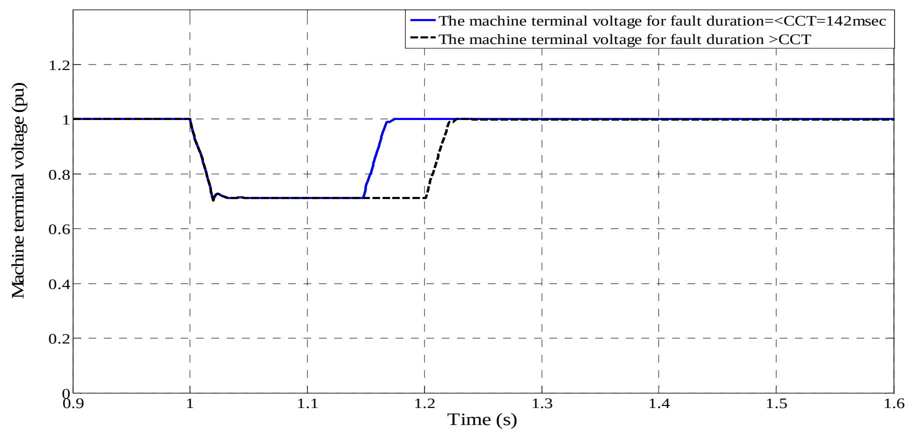


Figure 5- 21: The machine terminal voltage response during adjacent fault

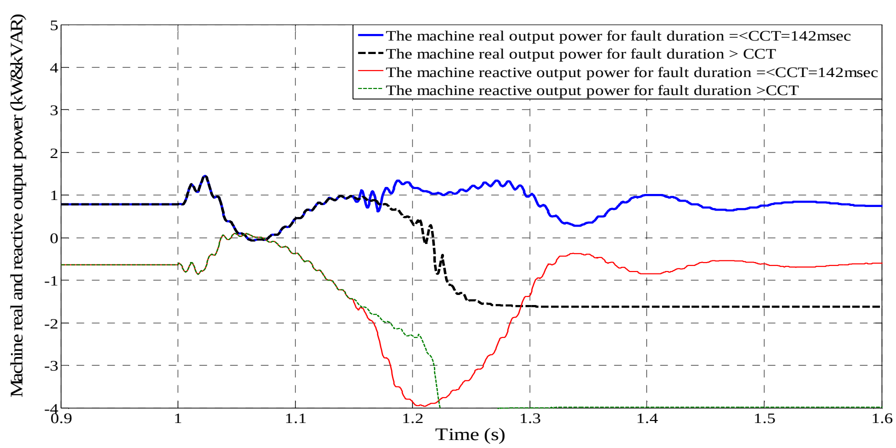


Figure 5- 22: The real and reactive output power of single-phase induction generator stable and unstable response to the adjacent fault

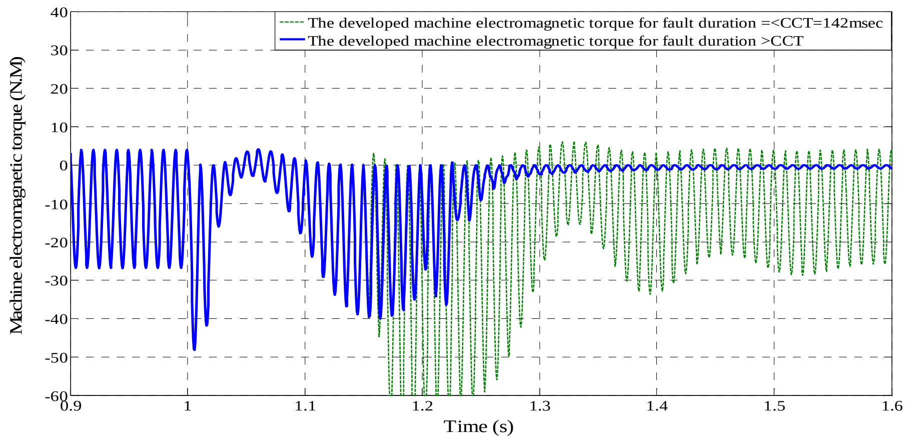
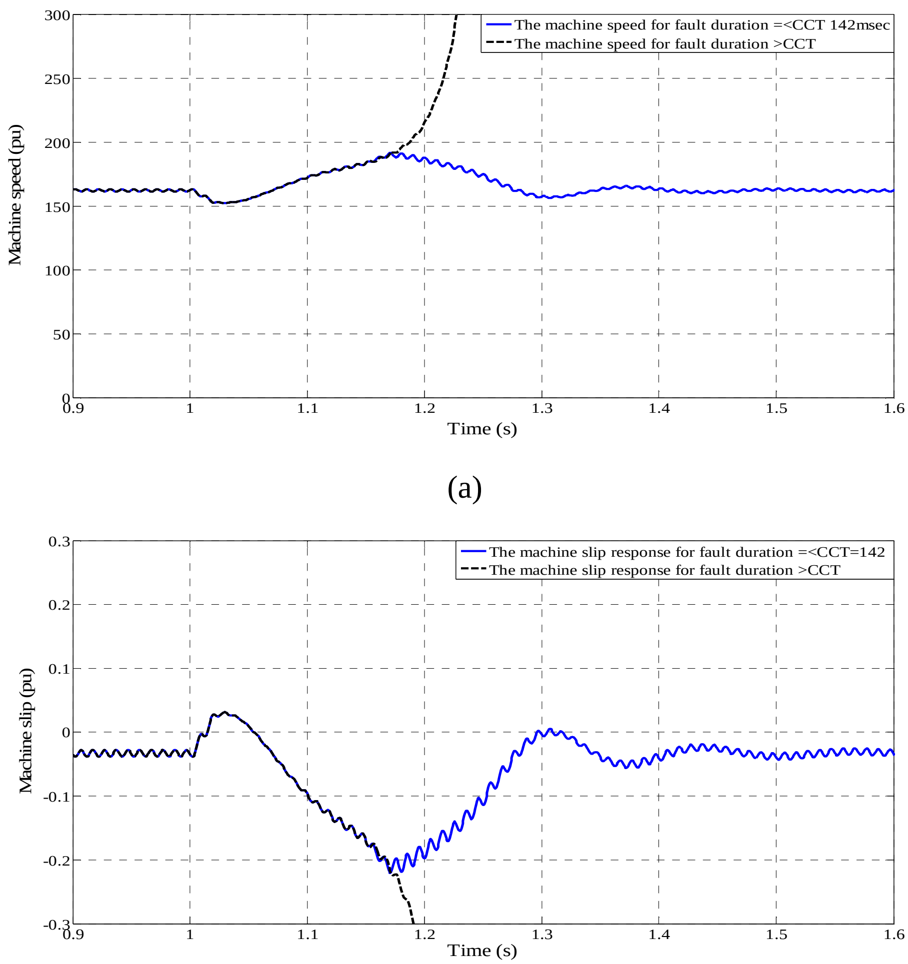


Figure 5- 23: The developed electromagnetic torque of single-phase induction generator stable and unstable response to the adjacent fault



(a)

(b)

Figure 5- 24: Single-phase induction generator rotor stable and unstable performance during adjacent fault: (a) the machine slip & (b) the machine rotor speed

Case 3: Electrically Remote Fault on MV Network

In this case the fault is applied at two locations on the MV side of the test network shown on Figure 5- 3. The first location is at the main 11kV bus, and the other is at remote location on MV circuit with length assumed to be 1500m. The length of the cable is assumed to be longer than the case study for three-phase microgenerator. This is because from the case 1 and 2 of this section the results show that small scale single-phase induction generator is very sensitive to fault conditions on the system, so if the further remote fault still has an impact on the generator performance then remedial solutions are vital. The transient response of the microgenerator with size 1kVA and 1.5kVA is investigated for both fault locations.

The fault is applied at MV bus

When the fault is applied at main 11kV bus, the voltage at LV falls to zero as shown on Figure 5- 25. The figure shows the voltage during the fault with two different durations. One is equal to the CCT of the microgenerator and the other is large than CCT, so the stable and unstable performance can be understood. The CCTs of 1kVA and 1.5kVA are found to be very close to each other and are equal to 78msec and 91msec respectively as shown below on the figures. The performance of each machine is determined by studying the response of the output power, developed torque, and slip and speed before, during, and after the fault and with two different durations as in Figure 5- 26, Figure 5-27, and Figure 5- 28.

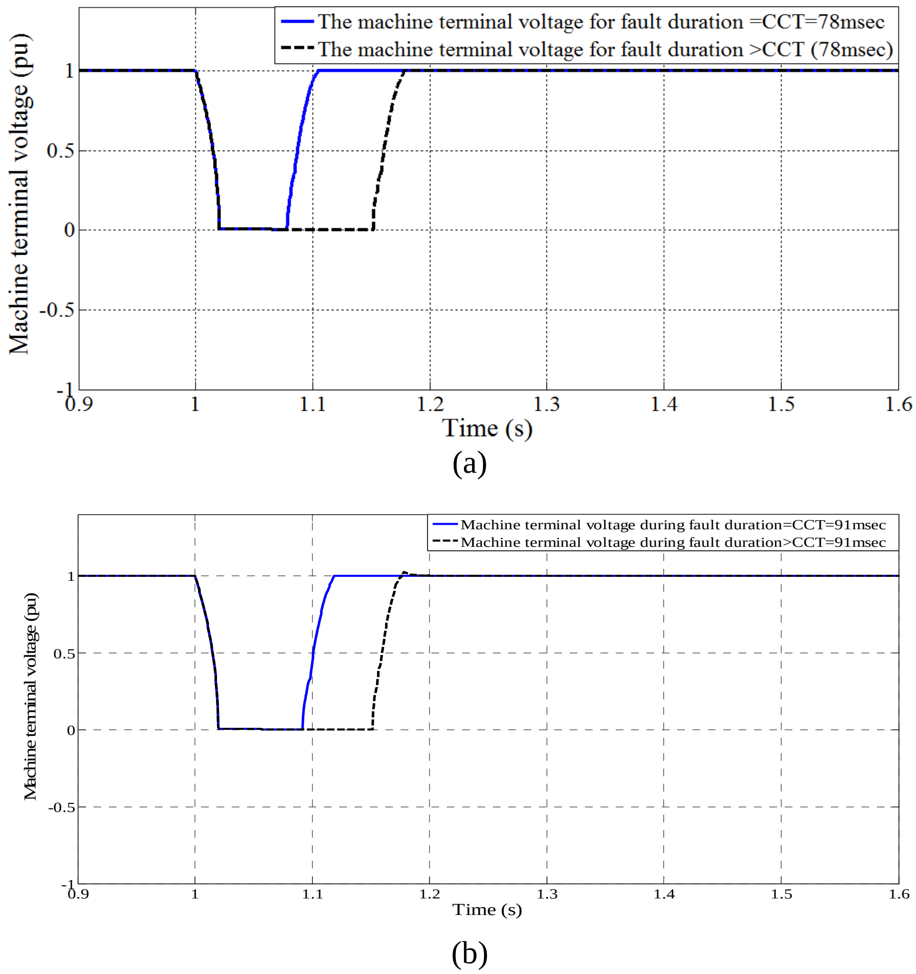
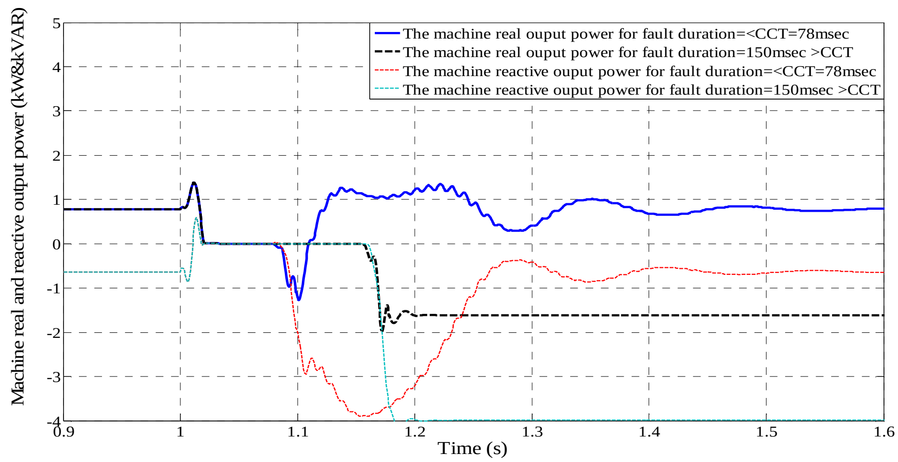


Figure 5- 25: The single-phase induction generator terminals voltage response to the fault at MV bus: (a) the terminal voltage of 1kVA machine & (b) the terminal voltage of 1.5kVA machine



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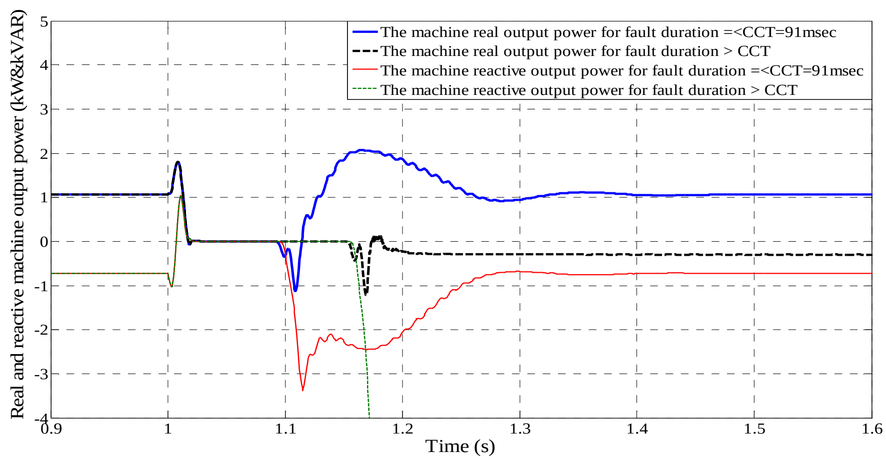

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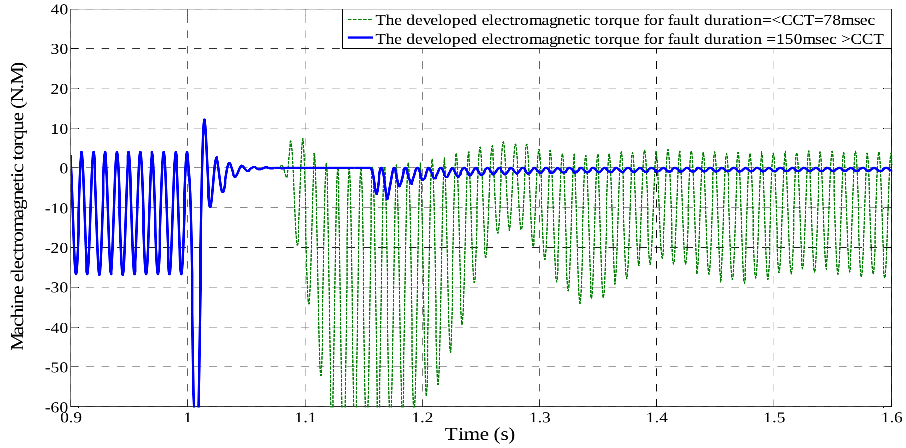
Figure 5- 26: The real and reactive output power of single-phase induction generator stable and unstable response to the fault at MV bus: (a) the output powers of 1kVA machine & (b) the output powers of 1.5kVA machine



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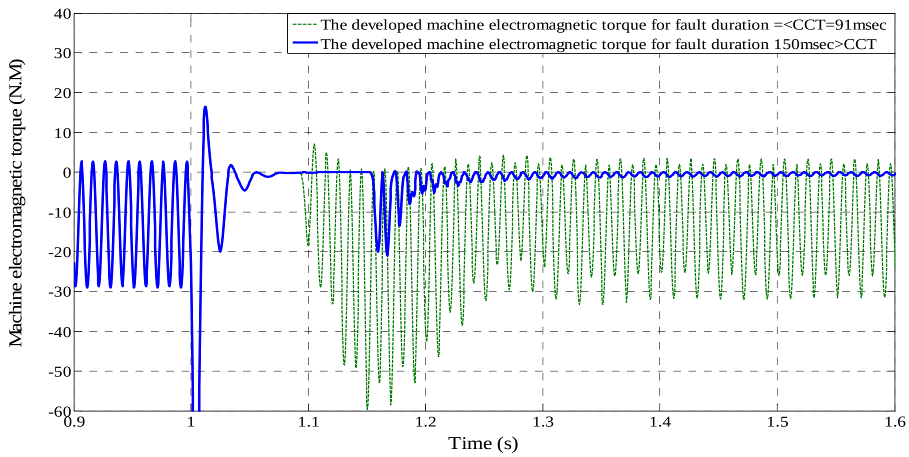
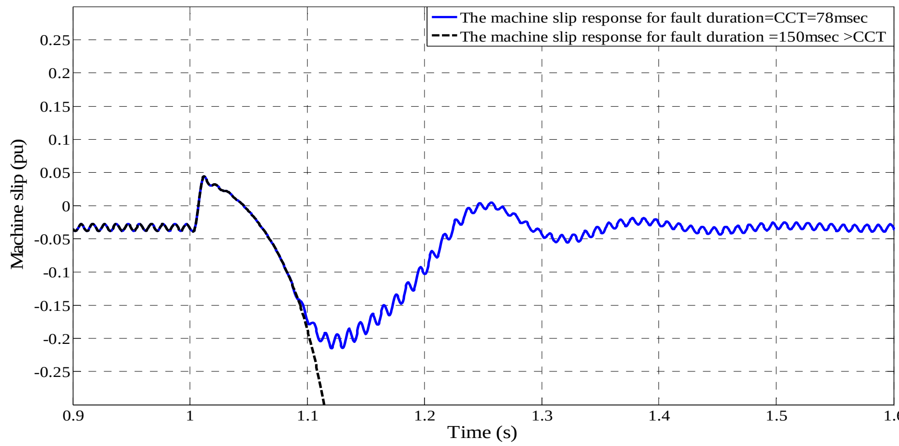


(b)

Figure 5- 27: The developed electromagnetic of single-phase induction generator stable and unstable response to the fault at MV bus: (a) the developed torque of 1kVA machine & (b) the developed torque of 1.5kVA machine



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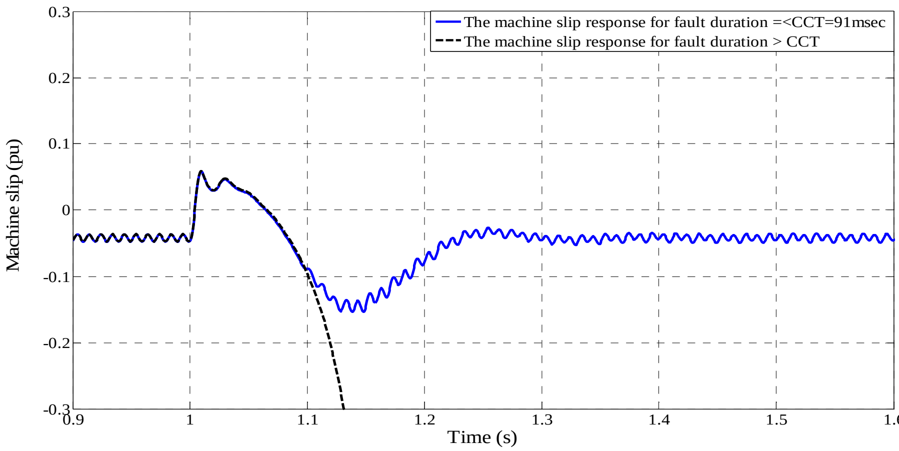


(b)

Figure 5- 28: The single-phase induction generator rotor stable and unstable performance during the fault at MV bus: (a) the 1kVA machine slip response & (b) the 1.5kVA machine slip response

The fault is applied at remote location on MV circuit

During this fault condition, there is a retained voltage at the terminal of the microgenerator. Figure 5- 29 below illustrates that the three-phase-to earth fault at 1500m far from the main MV bus has reduced the voltage on the machine terminal to 50% of the nominal value. This drop in the voltage is tested by the simulation on the transient performance of 1kVA which is more sensitive. The results have found that if such voltage dips lasts more than 96msec, the machine will definitely experience instability phenomena. The transient performance of the machine within the stability and instability margins is explained by the response of the machine output power, the developed torque, and the speed to the applied fault condition. The response is shown in Figure 5- 30, Figure 5- 31, and Figure 5- 32.

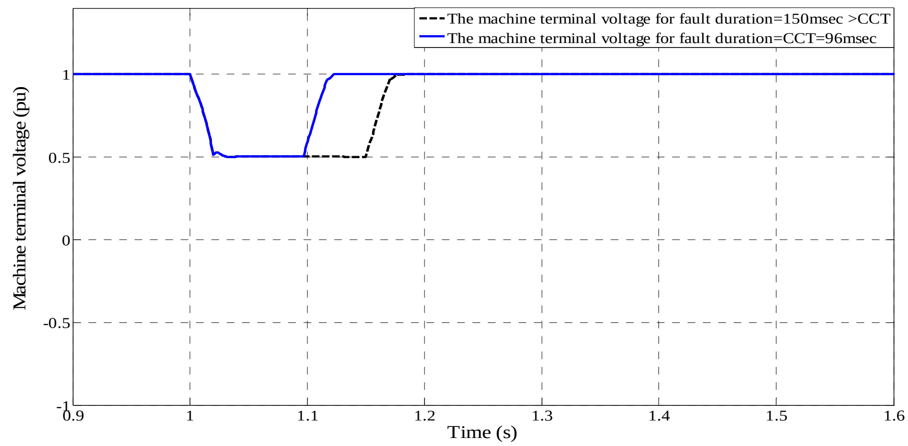


Figure 5- 29: The single-phase induction generator terminals voltage response to the fault applied at remote location the MV circuit

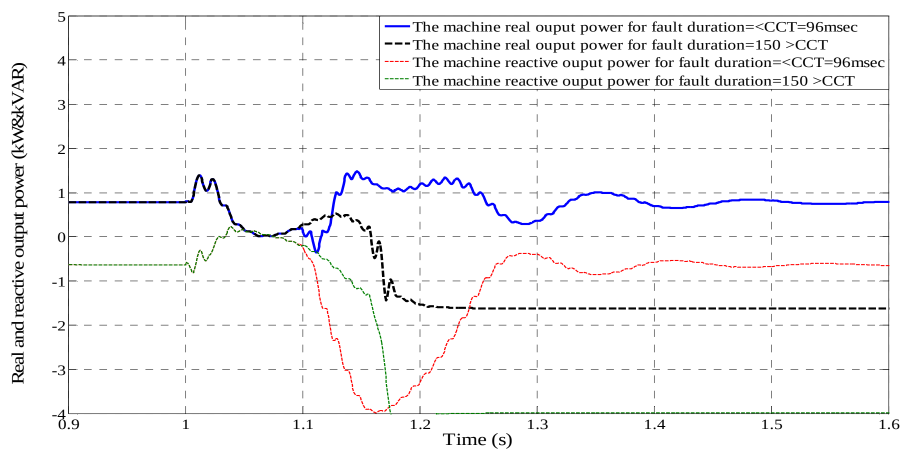


Figure 5- 30: The real and reactive output powers of 1kVA single-phase induction generator stable and stable performance during the fault applied at remote location on the MV circuit

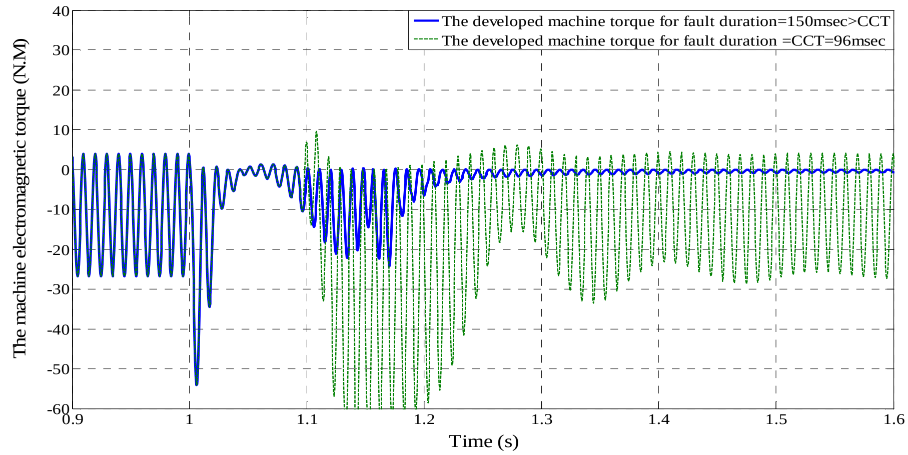
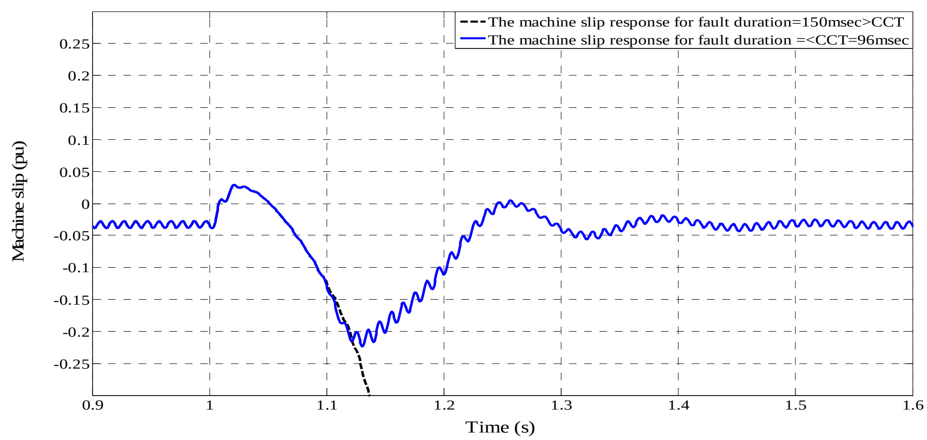


Figure 5- 31: The developed 1kVA single-phase machine torque response during the fault applied at remote location on MV circuit



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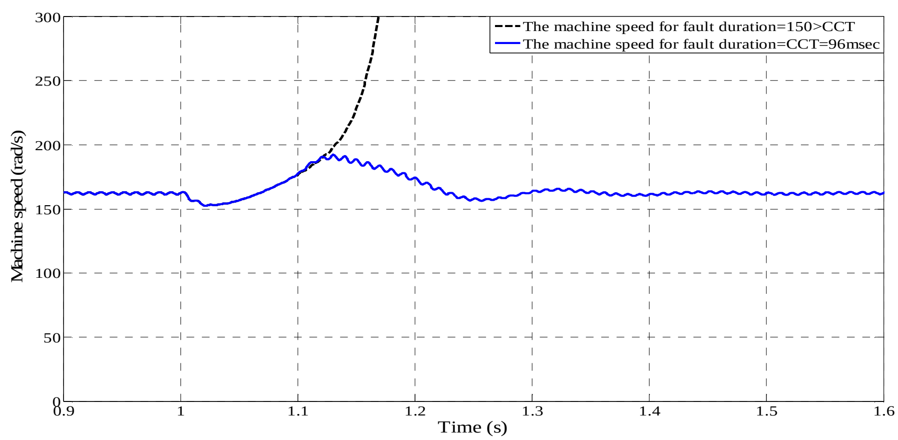


(b)

Figure 5- 32: The single-phase induction generator rotor stable and unstable performance during the fault at remote location on MV circuit: (a) the 1kVA machine slip response & (b) the 1kVA machine speed response

The impact of the remote fault considered in case 3 has also been examined on a high penetration of LV connected microgeneration interfaced by single-phase induction generators. The studies have been conducted when 90% of microgeneration penetration in respect to the local load (i.e. 162kVA across the feeder as considered in chapter three) is connected to LV feeder at residential level. The total numbers of microgenerators that have been modelled and used in the studies to represent 90% of the local load of the LV feeder are 97 microgenerators. When the remote faults in case 3 were applied to the network all the microgeneration penetration has become unstable when the fault lasted more than 80msec. This means the instability of microgeneration has been noticed 20% less than the typical protection time if 100msec is assumed as the typical protection operating times.

Therefore, remote fault scenarios applied in case 3 can be seen as most problematic scenario compared to other two local scenarios. The main difference between the two cases (i.e. local and remote faults) is that during local faults the impact on the microgeneration transient performance remains local due to the fast operation of the local protective devices, while during the remote fault scenario where the protection takes relatively longer time to clear the fault a wide area of LV connected microgeneration would be affected, and most of the microgenerators connected downstream to the fault would simultaneously trip. The simultaneous disconnection as well as reconnection of large amount of microgeneration may impact the distribution network performance, therefore, the impact of unnecessary disconnection and reconnection of microgeneration to an LV feeder is studied in the next section.

5.5.2 Simultaneous microgeneration disconnection and reconnection studies

The voltage profile and the voltage fluctuation during disturbances should remain within acceptable limits. The fluctuation limits are defined in Engineering Recommendation P28 not to exceed 3% of the nominal voltage. From the transient performances studies in section (5.5), the single-phase induction microgenerators are more likely to suffer from remote faults and experience unnecessary trip. The tripping of these devices simultaneously may impact the voltage profile and voltage fluctuation at low voltage networks. Therefore, the studies in this section examine the impact of tripping a large number of single-phase induction microgenerators within small area of distribution network at the same time due to transient instability. In addition, the simultaneous reconnection of a large penetration of single-phase induction microgeneration on voltage step changes at the point of the common coupling (PCC) is investigated.

The studies conducted the tripping and reconnection of the microgeneration penetration meeting 90% of the local load. All the microgenerators are connected in first case to one phase and the impact of tripping and reconnecting the microgenerators on the single phase voltage step and the voltage unbalance compared to other two phases is examined. The second case is when the microgenerators are equally distributed across all the three phases and the impact on the voltage step changes at PCC location is examined.

A- Studies of simultaneous disconnection of large amount of microgeneration impact on LV system

All the microgenerators are connected to phase C. Before the microgenerators are simultaneously disconnected from the feeder, the RMS voltage of all the three phases are measured during the simulation studies at the LV distribution board of the secondary substation in order to assess the impact of microgeneration on the voltage unbalance between the phases. Figure 5- 33 shows that phase C which accommodates the microgeneration has lower voltage, and this is because of the absorption of the reactive power from the grid by the induction machines. The difference between the average of all the three phase (239.0V) and individual phase C (238.2V) as shown in Figure 5- 33 is equal to 0.33% of the nominal voltage. This value is within the recommended limits for voltage unbalance in the UK which are defined in Engineering Recommendation P29 to not exceed the limit of 1.3% difference between the average of all three phase voltages and the individual phase voltage.

When all the microgenerators are disconnected simultaneously at 1.5s from phase C the voltage on phase C is jumped up to be almost equal to other RMS voltages of phase A and B as shown on Figure 5- 33. However, the voltage step is only 1.3% and it is still within the statutory limits which are defied in Engineering Recommendation P28 to not exceed 3% of the nominal voltage. When the microgenerators are connected equally across all three phases, so each feeder, the voltage unbalance between the phase is almost disappear, and the voltage steps still within the allowed limits and slightly lower than when all generators are connected to one phase. This is shown in Figure 5- 34.

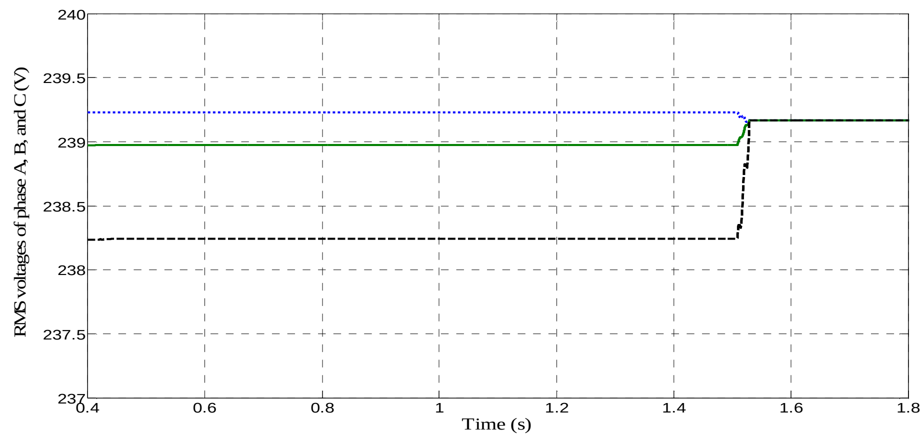


Figure 5- 33: The RMS voltage unbalance at the PCC between phase C and other two phases A and B

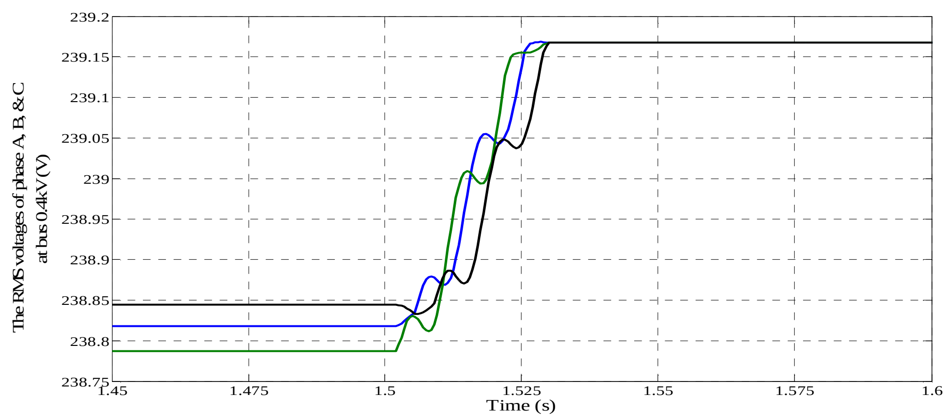
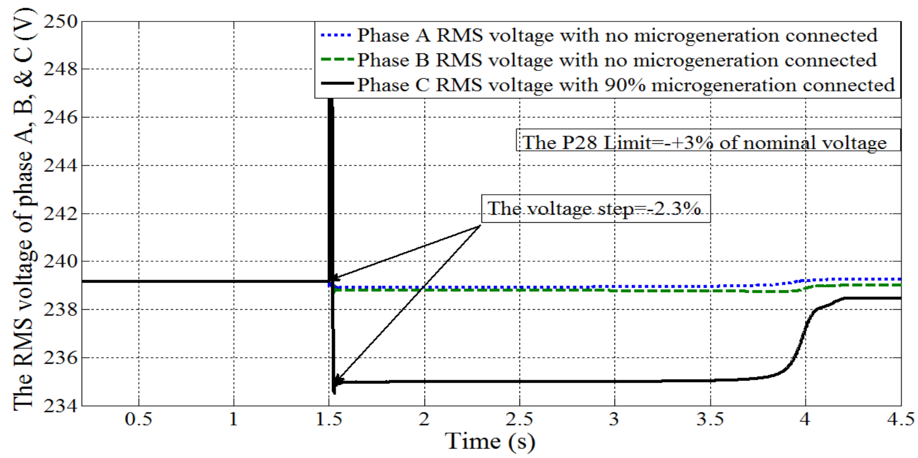


Figure 5- 34: The voltage step changes of the three phases at the PCC due to simultaneous disconnection of large amount of LC connected microgeneration

B- Studies of simultaneous reconnection of large amount of microgeneration impact on LV system

If large amount of microgeneration are unnecessary disconnected due to transient fault condition on the system, then the impact of bringing heavy level of microgeneration back to the grid would require studies in order to widen the understanding of the impact of transient instability of microgeneration that may have on the system performance. In G83 it has been recommended that following a protection initiated disconnection, the microgeneration is to remain disconnected from the DNOs network until the voltage and frequency at the supply terminals has remained within the nominal limits for at least 3 minutes. In this section, two scenarios of reconnections are considered. One is when all the microgenerators are reconnected together simultaneously, and the other is when the reconnection is spread over a period of time. The study investigates the step changes in supply voltage experienced due to the reconnection of 90% microgeneration interfaced to the network by single-phase induction generators at residential level. The microgenerators are reconnected in one case to the same phase, and in other case to all the three phases.

When a large number of induction generators are connected to the mains at LV side, the machines will draw large amount of reactive power at the instant of the connection, and after short time when the machines run at required slip the drawn reactive power is reduced to certain level. During this period induction machines could impact the voltage profile at LV level. This is evident by the obtained results in this section. When all the microgenerators are connected simultaneously at time 1.5s to the LV feeder as shown in Figure 5- 35, a voltage step has been observed. The step in voltage at the instant of the reconnection has reached -2.3% of the nominal voltage 240V as shown in Figure 5- 35a. The voltage magnitude is reduced to 234.5V for few seconds before the voltage returns back to its normal as in the Figure 5- 35 below. The change in the voltage steps is still within the allowed limit that is identified in Engineering Recommendation P28 not to be more than 3% of the nominal voltage. However, it is not negligible because the voltage step -2.3% is caused by microgeneration connected to only one feeder of the LV cell and meeting 90%. Another issue that may be caused by such voltage step is impacting traditional instantaneous overcurrent protection. Such an impact has not been considered in the thesis, and it could be investigated in future research. The simultaneous reconnection of the microgenerators has also impacted the sinusoidal waveform of the phase voltage as shown in Figure 5- 35b. Such impact may impair the quality of supply provided by the DNO to the other customers.



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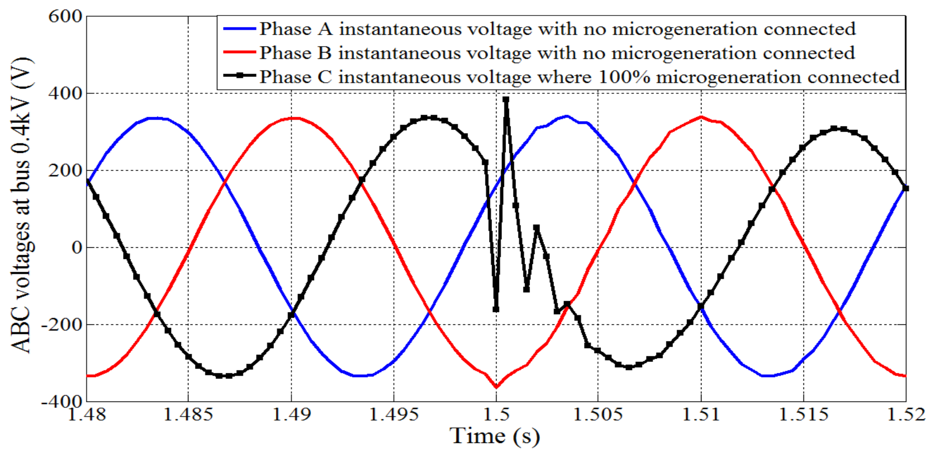
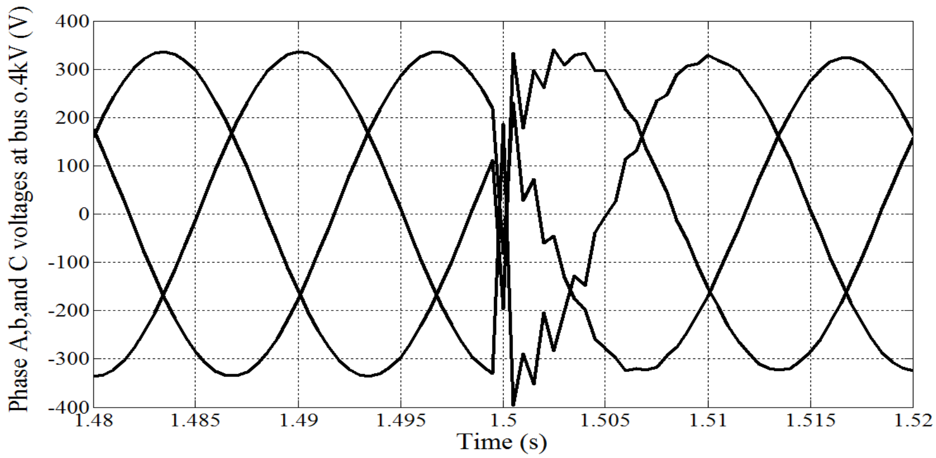


(b)

Figure 5- 35: The impact of simultaneous reconnection of large amount of microgeneration to one phase of the voltage performance at LV substation: (a) the impact on the RMS voltages & (b) the impact on the voltage waveforms

When all microgenerators are reconnected at the same moment to the three phase feeders together, the sinusoidal waveforms of all three phases are affected as shown below in Figure 5- 36. The results as in Figure 5- 36b have shown that the voltage step changes at PCC point can reach -1.13% of the nominal voltage. The microgeneration have taken 2.4s to reach their rating, and this has led the voltage to drop during this period due the reactive power drawn by the induction machine during starting.



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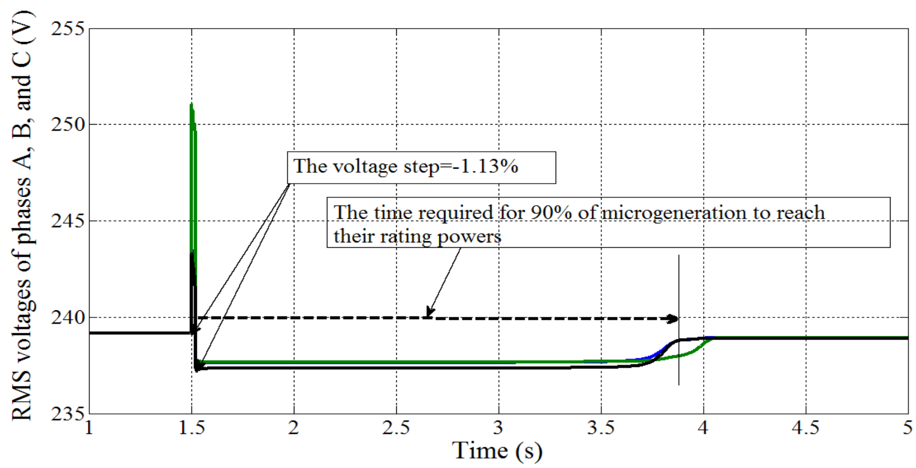
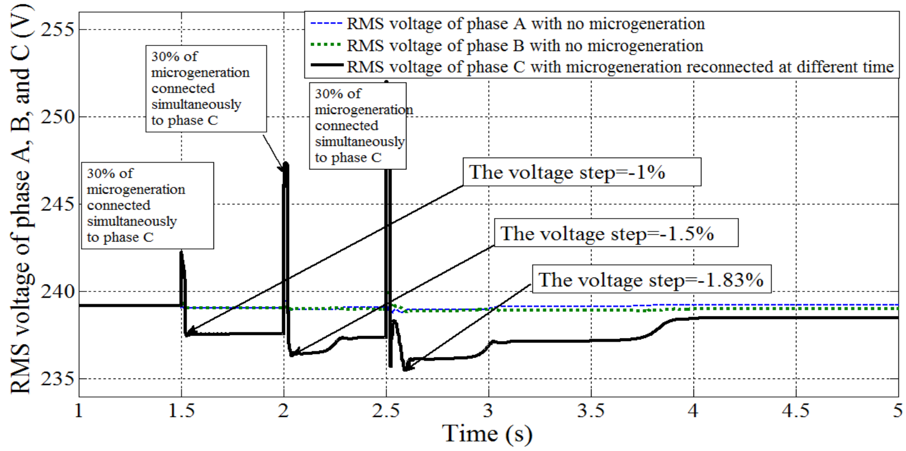


(b)

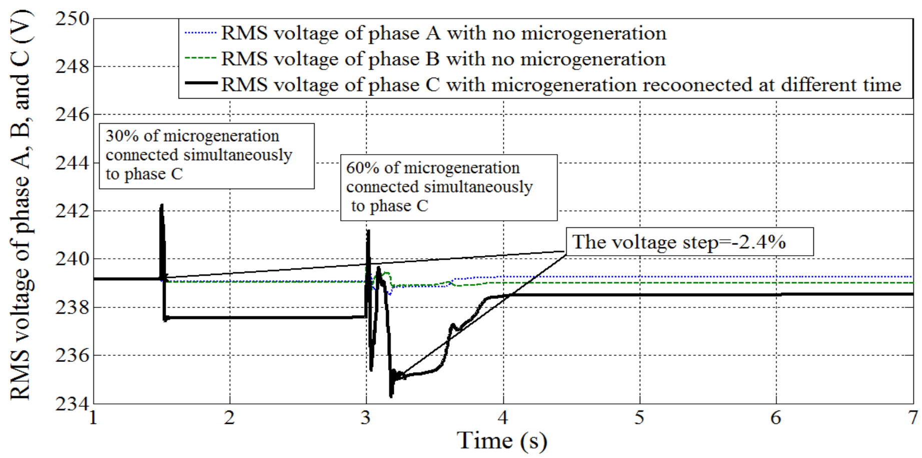
Figure 5- 36: The impact of simultaneous reconnection of large amount of microgeneration across all three phases on the voltage performance at PCC: (a) the impact on the voltage waveform & (b) the impact on the RMS voltage

The effect of the spread of reconnection time on the voltage of the LV bus at the secondary substation has also been demonstrated. In the simulation studies 30% of the total microgeneration are reconnected simultaneously at time 1.5s, and after 0.5s another 30% are together connected to the system, and after another 0.5s extra 30% are connected simultaneously. During this spread of reconnection the voltage steps down to -1%, -1.5%, and -1.8% respectively as shown in Figure 5- 37a. This means the time of reconnecting large numbers of microgenerators is very important. For example, when all the penetration of local microgeneration is connected at the same time the voltage has dropped to -2.3%, and when the same amount of microgeneration is divided into three groups and connected during spread of reconnection time, the impact has been found to be less, and the largest voltage steps has been found to be 1.8%. This is as result of connecting the second and the third penetration during the starting of the microgeneration of the first penetration. During the starting of microgeneration interfaced by induction machines, a large reactive power will be drawn until the machines reach steady state operation mode. So when other microgenerators are connected during this period the voltage step will be larger. For example, when 60% of total microgeneration are reconnected during the starting of already connected 30% of microgeneration as shown in Figure 5- 37b, the voltage step has reached -2.4% which is almost similar to the voltage step experienced when all the 90% of microgeneration are connected simultaneously. So, not only the level of the microgeneration penetration reconnection can impair the local voltage profile but also the spread time of reconnections.

To prove this, the same amount of microgeneration shown in Figure 5- 37a have been reconnected within larger interval between the three reconnections as shown in Figure 5-38. The results have shown that when the second and third microgeneration penetration are connected to the network at time equal to 3s and 6s respectively, the voltage steps have been found to be very much insignificant (-0.6%) compared to the previous as in Figure 5- 37. This means if a large penetration of microgeneration is disconnected due to unstable performance and then being reconnected again within very short period of time (i.e. during the starting period) the voltage steps may become an issue. If this is not considered then degradation in the quality of the supply may result.



(a) The impact of the spread of reconnection time of microgeneration with very small intervals on the RMS voltage of the LV bus at the secondary substation



(b) The impact simultaneous reconnection of 60% of microgeneration on the RMS voltage of the LV bus at the secondary substation

Figure 5- 37: The impact of reconnection of large amount of microgeneration with different penetration at different time

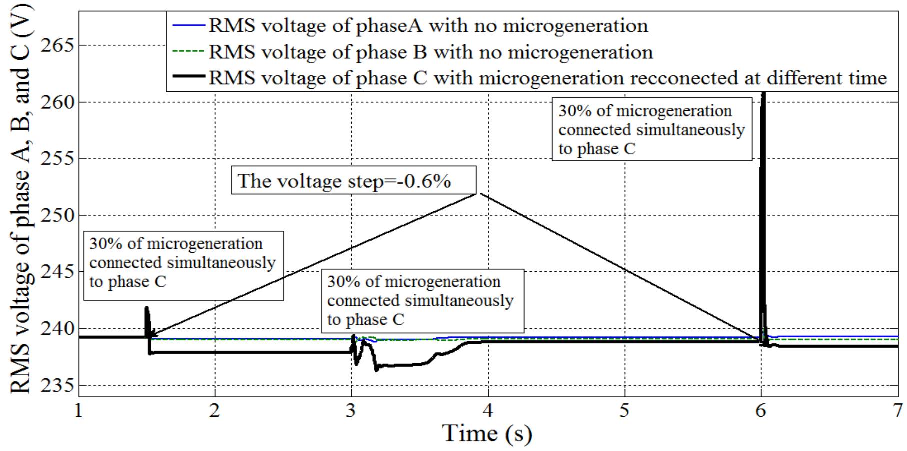


Figure 5- 38: The impact of the spread of reconnection time of microgeneration with large intervals on the RMS voltage of the LV bus at the secondary substation

5.6 Chapter summary

The studies of this chapter have investigated the transient performance of a range of LV connected small scale microgeneration technologies in response to realistic network faults applied at different locations. Two types of technologies have been considered: a small scale CHP based on diesel engine driving a three-phase synchronous machine connected within commercial premises; and a small microwind turbine interfaced directly within residential dwellings by a single-phase induction generator. The studies have provided an understanding of how LV connected microgeneration within a Highly Distributed Power Systems (HDPS) will respond to different faulted conditions on the system. The studies have specified the conditions under which circumstances that microgeneration will be unnecessarily tripped by unstable performance due to system transient disturbances and when they can survive the disturbances. The finding of the studies are summarised as follows:

- The transient stability phenomenon of LV connected microgeneration is a significant issue due to the nature of the microgeneration with very small inertia and limited controllability. In addition, the performance of the protection of traditional distribution systems is not sufficient enough for supporting the fault ride through capabilities of microgeneration with small scales and connected at LV distribution level.

- The transient stability of microgeneration is detrimentally affected by MV remote faults on urban network more than local faults. Local faults can be cleared very fast due to the low operating time of downstream protection, and their impact will be limited to very limited number of microgeneration. While MV remote faults on urban networks at two different locations at main MV bus and at 1.5km far from the MV bus have led to large voltage dips on the LV system which in turn have resulted in widespread instability of all the microgeneration connected downstream. In addition, the operating time of upstream protection at MV of urban network could last few hundreds milliseconds, this may not support the local generation transient stability. Based on the chapter literature review which is based on utility experience the typical operating time was chosen to be 100msec.

- The response of 28kVA three-phase microgenerator interfaced by synchronous generator at commercial level to the MV remote faults has shown that the machine will experience unstable operation if the fault lasts more than 330ms. Unstable operation of such machine still can be avoided, because based on typical protection time the fault will be cleared before 330ms.

- The MV remote fault impact has been studied on the transient performance of LV connected microgeneration interfaced by single-phase induction generators and meeting 90% of the local average load. It has been observed that all these microgeneration will go unstable following the remote fault in 20% less time than the typical protection operating time.

- The impact of simultaneous nuisance tripping of microgeneration meeting 90% of the local load on the local network performance has been demonstrated. Simultaneous disconnection and reconnection of this amount of local generation has impaired the network voltage at the main bus of the secondary substation and caused local power quality issue by forcing voltage unbalance and voltage steps to be close to the allowed limits identified in Engineering Recommendation P28 and

P29. When all the amount of microgeneration was reconnected simultaneously the voltage step has reached -2.3% which is just 0.7% under the normal limits -3%.

- The effect of the spread of reconnection time on the voltage of the LV bus at the secondary substation has also been demonstrated. The results of the studies have found that the intervals of reconnecting large numbers of microgenerators are very important. When the total amount of microgeneration is divided into three groups and reconnected during spread of reconnection time, the impact on the local voltage profile has been found to be less compared to simultaneous reconnection. This is true when the intervals between the reconnections are larger than the starting time of the already connected microgeneration. However, when a high penetration of microgeneration is reconnected during the starting of other already connected microgeneration interfaced by induction machines where a large reactive power will be drawn, the voltage steps will be larger. Therefore, if a large penetration of microgeneration is disconnected due to unstable performance and then being reconnected again within very short period of time (i.e. during the starting period) the voltage steps may become an issue, and degradation in the quality of the supply may emerge. To avoid such operation, microgeneration with a high penetration should be reconnected within suitable intervals.

To sum up, a nuisance tripping of microgeneration as consequence of microgeneration instability due to remote MV faults on an urban network example has been experienced. This in turn would impose numbers of issues including the result in impaired local power quality due to voltage fluctuation. A source of interference between the local network performance and connected microgeneration under fault conditions as consequences of transient instability of the LV connected microgeneration has been observed. Therefore, a remedial measure by which the impact of remote faults at MV level on the microgeneration transient performance is reduced is vital in future power systems. The work in chapter six exclusively proposes the using of Resistive-type Superconducting Fault Current Limiters (RSFCLs) as remedial measures to improve significantly the fault ride through capabilities of a large penetration of LV connected microgeneration to remote MV faults.

5.7 Chapter References

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Chapter Six: Analysis of Transient Performance Enhancement of LV Connected Microgeneration by Using Resistive-Type Superconducting Fault Current Limiters

6.1 Introduction

The studies in the previous chapters three, four, and five have found numbers of problems that can emerge within local distribution networks incorporated with a high penetration of LV connected microgeneration under transient fault conditions. It was found that adding heavy amount of generation at low voltage networks could result in the prospective short circuit current exceeding the rating of the switchgear connected to the network. This may cause damage to the installed equipment. Also it was found that remote faults on the MV distribution circuits would lead to undesirable and widespread tripping of all downstream connected small scale single-phase microgeneration. The results have shown that from technical perspective, disconnection or reconnection of considerable amount of microgeneration due to transient instability would impair the performance of the local distribution network by causing voltage unbalance and voltage steps to exceed the nominal limits, and this would impact the supply quality of most of the connected customers.

On the strength of the results obtained from the previous three chapters where the fault level can be an issue in urban networks due to microgeneration connection, and also the finding that MV remote faults' impact on the LV connected microgeneration is more severe than the local faults, and the high sensitivity of the microgeneration units weakening the stiffness of the host network performance, this chapter proposes a network solution that can manage these emerging problems. The proposed solution is based on using resistive-type superconducting fault current limiters (RSFCLs) by which the transient stability of a large number of LV connected microgeneration is significantly improved, and at the same time the impact of the units on the network performance such as the contribution to the fault level is managed.

The RSFCL is used because of its significant advantages compared to other measures which are discussed in detail in section (6.2). The section investigates the advantages of the usage of the transient characteristics of RSFCL as a remedial measure to improve the transient performance of large numbers of LV connected microgenerators. The main operation principles of RSFCL are discussed in section (6.3). Section (6.4) investigates practical locations of RSFCL in the distribution networks, and section (6.5) introduces a new analytical method that can used to determine the minimum resistive element of RSFCL that is required to ensure the stability of large numbers of single-phase induction microgenerators during remote faults. The effectiveness of the method is validated in section 6.6) by using detailed transient stability studies by using a digital simulation program PSCAD and detailed microgeneration transient stability.

6.2 Supporting transient performance of LV distribution networks incorporating a high penetration of microgeneration

Since improving the fault ride through capabilities of LV connected small scale microgeneration can play a significant role in supporting the performance of local distribution systems, enhancing the microgeneration fault ride through becomes highly desirable. In terms of improving the transient performance a number of solutions have been proposed and developed by different researchers. Some research such as in [6.1] and [6.2] have explained that any measures reducing the rotor acceleration or regulating the generator terminal voltage during the fault will improve the machine transient response. However, most of the measures that have been developed to enhance the transient performance of rotating machines as documented in numbers of articles are suitable for large distributed generators.

6.2.1 Examples of measures for transient performance improvement

Some examples of the developed measures for transient stability improvement of distribution networks integrated with distributed generation interfaced by rotating machines are outlined as following:

- The stability of an induction generator which is widely used to interface wind turbines into the grid can be improved by using braking resistors connected to the machine rotor windings such a scheme operates based on comparing the received signals to predetermined threshold values (e.g. machine speed and terminal voltage) [6.1][6.2].

- The transient stability of distributed generation interfaced by induction machines can be also improved by the employment of an electronically controlled external resistance connected to the machine rotor windings. This can reduce acceleration of the rotor during transient faults. The induction machines stability could also be improved by controlling and supporting the voltage applied to the rotor through a static converter [6.3].

- The use of novel fast clearance protection schemes to protect distributed generation could improve transient stability and also improve power quality by reducing voltage sag duration [6.4].

- Coordination of voltage sags at the machine terminals and the overcurrent protection of distributed generator in order to disconnect the machine in favour of other sensitive equipments can ride through voltage dips caused by faults [6.5].

- It has been proposed that the fault ride through capabilities could be improved by the adjustment of the generator under-voltage protection according to CCT-voltage dip curves. Using the curves would improve the machine transient stability performance during larger voltage dips [6.6].

- There are some other measures to improve the transient performance of rotating machines such as excitation, stabilizers, and governor controls which are used for relatively large synchronous machines [6.6][6.7].

- System reconfiguration can be used sometimes for transient stability improvement. For example such a scheme incorporating post fault switching could allow separation of two parallel lines that would increase the impedance of the network, and hence the voltage dips on the nearby machines would be less and the stress on the machine would be reduced.

From the above examples it can be very clearly seen that most of the measures if not all provide device level solutions. The techniques could be applicable to large machines where they have limited number on the system and their sizes allow some level of controllability. But it may become unrealistic to apply such solutions to each individual device of millions of microgenerators with few kilowatts ratings. Results in chapter five have evidently shown that small scale microgeneration particularly those interfaced by single-phase induction generators will reach their speed limits very fast. So applying corrective solutions to each individual device may not be financially viable and technically inefficient where the distribution networks cover normally very wide areas of the power systems. Also making a radical change in the existing protection of distribution systems to allow large amounts of distributed generation to ride through faults may require a wide area of system changes, and this could be a costly solution [6.5]. Another disadvantage of applying some of the above traditional methods for improving the system transient performance is consequently reducing the reliability level and at the same time increasing the losses. This has been shown in the case of the system reconfiguration method.

Therefore, the nature of microgeneration as sensitive units with poor transient performance, the high density of the units distributed over the LV networks, and the source of the biggest problem recognised here is as stemming from remote faults, necessitates a solution that considers all these factors. When a large penetration of microgeneration is installed within LV distribution networks, network based solutions are preferable to individual device based solutions. This is because the network based solutions will improve the performance of a wider area of distribution networks, and hence support the performance of a higher penetration of local generation.

6.2.2 Using SFCL for improving the transient performance of active distribution networks

The thesis in this chapter proposes the usage of Superconducting Fault Current Limiter (SFCL) as remedial measure that would provide useful contribution to both the network performance and the microgeneration units in terms of transient performance. This is, mitigating the problems associated with the microgeneration transient stability issue, while also managing the fault level contribution made by microgeneration. This would help avoid the costly solutions such as upgrading equipment or reconfiguring distribution networks. The SFCL has numbers of useful characteristics that can support the system performance during fault conditions. These characteristics are discussed as follows:

- From technical perspective SFCLs can react within milliseconds, and this is necessary for an improved transient response.

- The SFCLs provide almost zero impedance during normal operation, and its impedance is developed as a limitation element during fault conditions based on the amount of the fault current. So the SFCL is a self-operated device that is controlled by the condition of the currents passing through it.

- SFCLs are feasible to be installed in urban and suburban distribution systems between the substation busbar and medium-voltage (MV) feeders [6.8]. For distribution level SFCL application, the heat management is less of a problem than SFCL application for transmission systems. Thus the SFCL is more practical to be first put in action in distribution systems [6.9].

- SFCL is a fast and an effective measure which forces the fault currents to be reduced providing additional headroom against switchgear ratings, and providing improved sag performance to consumers connected to unfaulted feeders. SFCL would help to avoid the replacement of the overdutied circuit breakers as well as the need for network reconfiguration (i.e. avoid split buses) which may reduce the reliability level and increase the losses [6.10].

- The application of the SFCL would not only decrease the stresses on devices but also offer a higher interconnection to secure the network, and it can be very effective means to enhance the power quality in terms of managing the voltage drops [6.9][6.10][6.11]. Offering a higher system interconnectivity and better power quality could be a real need for future power grids which would have extreme complexity.

- Another significant advantage of SFCLs application is the automatic recovery property which allows continuous operation of the limiter on the power system and removes the need for service calls following each fault limiting operation [6.12].

The SFCLs can be either inductive or resistive types, however, resistive types (RSFCL) have an added advantage of currently being more available for commercialization [6.13]. In addition to the lower cost compared with other SFCLs, RSFCL is the most attractive from the simplicity and the size (i.e. more compact) point of view [6.8]. This could be an important point when the limiter is equipped in urban networks where space plant can be an issue. Also resistive types not only restrain the fault currents but also consume electrical energy during the fault, suppressing the excessive kinetic energy of fault-contributing generators [6.13]. The RSFCL increases the decay speed of the fault current by reducing the time constant of the decay component of the fault currents, and it can also make the system less inductive [6.14]. Therefore, RSFCL type is considered to support the microgeneration ride through capabilities.

6.3 The principles of RSFCL supporting microgeneration fault ride through

The RSFCL limiter is a device that ideally should not impact the system by its presence in the case of normal operation. The basic principles for all types of RSFCL in terms of limiting the system fault current are relatively straightforward. During normal conditions the superconducting material of the RSFCL presents zero resistance. When the fault appears a high current flows and a high non-linear resistance is inherently developed within the path of the fault current to cause current limiting which minimises the fault current to the required level. Reduction in the fault current is directly resulting in reduction in the voltage dips on the nearby areas to the fault location. This will lead to improving the retained voltage on the terminals of microgeneration connected to the system, and hence reducing the acceleration force applied on the affected machine rotor and improving the transient performance of the machine.

The value of the RSFCL non-linear resistance is a function of different parameters, such as the current flows through the limiter (i.e. normal and fault current), the fault duration, and the superconducting materials which include the permissible temperature of the superconductor and the volume and the size of the superconductor [6.15]. Therefore, the limiter's resistance curve changes as a function of time, and the change is based on the change in the current magnitude and the temperature of the superconductor. So how much resistance the limiter can provide during the fault and how fast this resistance can be increased during the fault will dictate how significant the RSFCL to improve the microgeneration connected close to the faulted area. The RSFCL can provide a rapid action to limit the fault current within first peak, but on the other hand it can not recover rapidly from limiting state to superconducting state. It needs some time depends on the cooling down of the superconductor. The resistance profile of the limiter during the fault can be identified by the following equation [6.15].

$$R_{fcl} = \frac{V_s}{I_f} = \frac{V_s}{th.w.\sqrt{\frac{C_p.\Delta T}{\rho.\Delta t}}} \tag{29}$$

Where R_{fcl} is the FCL resistance

V_s is the system RMS voltage

ΔT is the maximum permissible temperature rise

Δt is the fault duration

ρ, th, and w are the resistivity, thickness and width of the superconductor

C_p is the effective specific heat of the superconductor

RSFCL requirements

These are some of RSFCL ideal requirements when the limiter is used to support the transient performance of distribution systems [6.16]

- The limiter should not impact the protection coordination strategy.
- The limiter needs to react within the first peak of the fault current.
- The limiter should exhibit low impedance and low energy losses in normal operation.
- The limiter should provide a smooth and gradual change of impedance from the normal to fault mode and vice-versa.
- The limiter should contain fail-safe operation.

6.4 Practical locations of RSFCL in the distribution networks

The location of SFCL in distribution networks in order to manage the fault level issues and support the system stability is a significant issue to be addressed [6.17]. This is because, not all the locations of SFCL will enhance the transient stability of the distribution system, and particularly the stability of connected microgeneration. This can be explained further by the following examples which describe different SFCL locations, outline the impact of these locations on the stability performance and other side benefits, and identify the disadvantages and issues associated with these locations.

A- Generation connection

In this case the SFCL can be added in series with a particular connected generator if the infeed from the generator is expected to introduce a fault level problem as shown below in Figure 6- 1. According to [6.17] such SFCL application is normally applied in industrial, distributed generation, and transmission level. From stability perspective, if the generator is a synchronous machine, then the impedance between the generator and the fault would be higher compared to not using SFCL, and this may increase the CCT of the generator. However, SFCL at this location will have a limited impact on the transient stability improvement of the generator. This is because the limiter is not located between the fault and the grid, and this will make the voltage of the main bust to drop to zero during the fault and hence impacting the machine performance.

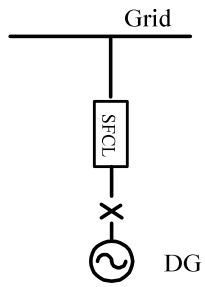


Figure 6- 1: SFCL is in series with grid-connected distributed generator

Adding SFCL to the location shown in Figure 6- 1 is still useful from fault level perspective to avoid the replacement of the system equipments, but adding SFCL to improve the stability of each of the local generators will require large numbers of SFCLs, and this may not be seen as effective cost solutions.

B- Incoming MV feeders location

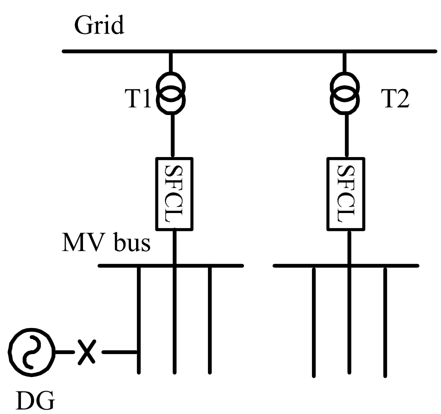


Figure 6- 2: SFCL in series with the substation transformer

The SFCL can also be installed at the substation between the transformer and the main MV bus as shown in Figure 6- 2. Any fault on MV side will be current limited by the SFCL, so the transformer and the bus are protected from a high fault level. In terms of transient stability, there is no general improvement to the generator transient performance for faults on either the MV side or HV side. The limiter could only improve the transient stability of the connected generator if a fault occurs on the MV side of the transformer T2. So the limiter has limited scope or useful impact from the transient stability perspective. The main advantage of this configuration is using a single limiter to protect downstream feeders to the transformers, and this can save cost. However, the limiter can not reduce the fault contribution caused by the distributed generator shown in Figure 6- 2.

C- Bus coupling connection

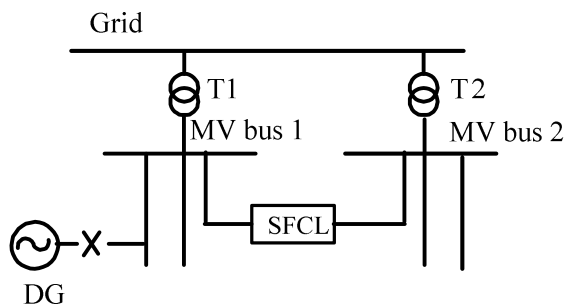


Figure 6- 3: SFCL bus coupling connection

Another possible application of SFCL is to be installed at the bus-tie location. This would increase the reliability of the system by avoiding the need to split buses in addition to limiting the fault contribution from the grid to faults at MV side [6.10]. The impact of the limiter on the fault level reduction would be less effective compared to the example in B. The grid fault contribution to MV fault would be limited by splitting the two transformers and hence the contribution to the fault would be dictated by the value of the transformer impedance. In terms of transient stability performance of the DG, for any faults on MV side of transformer T1 there will be no impact at all on the DG transient stability improvement. This is because the limiter is not in the position that would mitigate the voltage drop on bus 1 as shown in Figure 6- 3. For a fault at bus 2, the retained voltage on the grid side is determined by the transformer T2 impedance, and the SFCL will not provide a significant impact on improvement of the generator transient stability.

D- Outgoing MV Feeders location

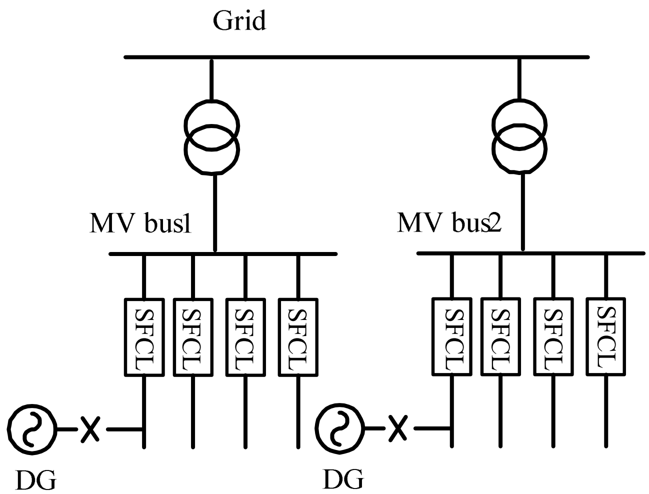


Figure 6- 4: SFCL connected at the beginning of MV feeders

When an SFCL is located at the beginning of each MV feeders as depicted in Figure 6-4, a significant improvement in fault level control and the transient performance of generation connected downstream to MV bus is obtained. The positive impact of the application would cover a wide area of disturbance. For example any fault on MV feeders would see its fault current controlled and the voltage dips on the main MV buses mitigated. This will help local microgeneration to ride through remote faults on the wider system. The only drawback of the application compared to the application in B (i.e. does not support microgeneration transient stability) is the cost, where more limiters are needed.

Location	Fault contribution management (fault on MV side)	Local generation transient stability improvement
in series with distributed generator	Only fault contribution from downstream is limited	Limited impact and a single device solution
in series with the substation transformer	Only fault contribution from upstream is limited	Limited impact
at bus coupling connection	The fault contribution from upstream and downstream is limited	Limited impact
at the beginning of MV feeders	The fault contribution from upstream and downstream is limited	Significant impact, and wide area solution

Table 16**:** Different RSFCL locations added to MV distribution networks

The results from chapter five have shown that remote faults on MV networks can cause widespread tripping of all the LV connected microgeneration interfaced by single-phase induction generators. Also chapter three results have concluded that heavy penetration of microgeneration would increase the fault level at distribution networks to its limit for urban distribution network examples. Based on the comparison in Table 16 above, the most suitable location of SFCLs to mitigate these two significant problems is adding the limiters at the beginning of each MV feeders. Therefore, resistive-type SFCLs to be located at beginning of MV feeders are used in this thesis to improve the resilience level of an urban distribution network overlyed with multiple cells incorporating a high penetration of microgeneration as shown in Figure 6- 5.

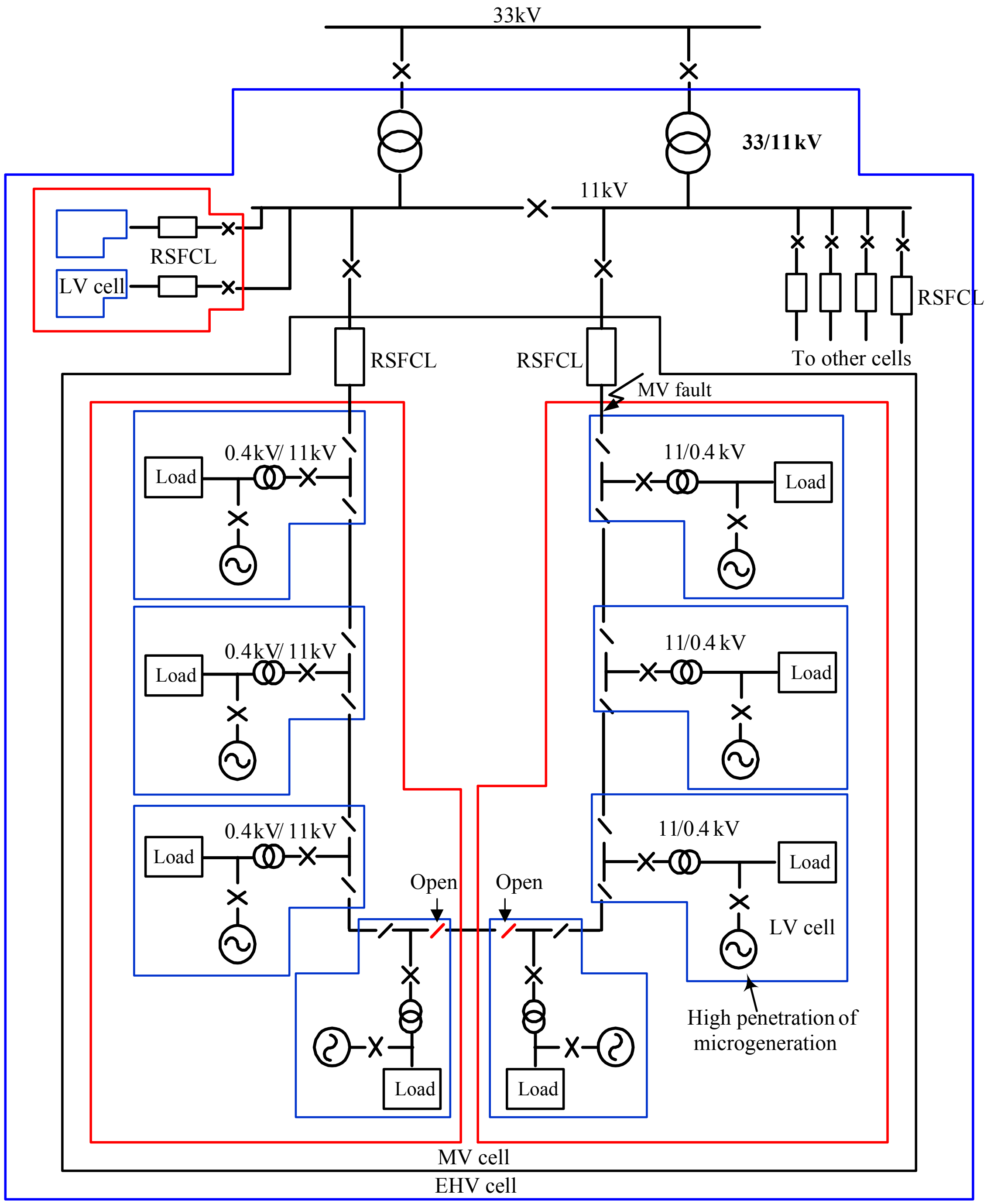


Figure 6- 5: An active urban distribution network with added RSFCLs and based on multiple cells

6.5 Theoretical analysis of microgeneration transient stability enhancement using RSFCL

The results in chapter five have shown that MV remote faults on distribution networks can lead to a widespread of disconnection of the LV connected microgeneration interfaced to the grid by single-phase induction generators due to the sensitivity of such small size machines to the voltage dips caused by remote faults. Therefore, this section proves how RSFCL can be used to improve the transient stability of such technologies by introducing a new mathematical approach that can be used to determine the minimum value of the resistive element of RSFCL device that needs to be reached by the limiter during the fault.

In this section the RSFCL is located between the MV buses and each of the MV outer feeders as shown above in Figure 6- 5. A test system as presented in Figure 6- 6 is used to analyse the effectiveness of RSFCL as a remedial measure to improve the transient performance of a single-phase LV-connected microgenerator unit. A three phase fault is assumed to occur on the feeder adjacent to where the microgenerator is connected as shown in Figure 6- 6 and the response of the connected unit to such a remote disturbance assessed with and without the RSFCL.

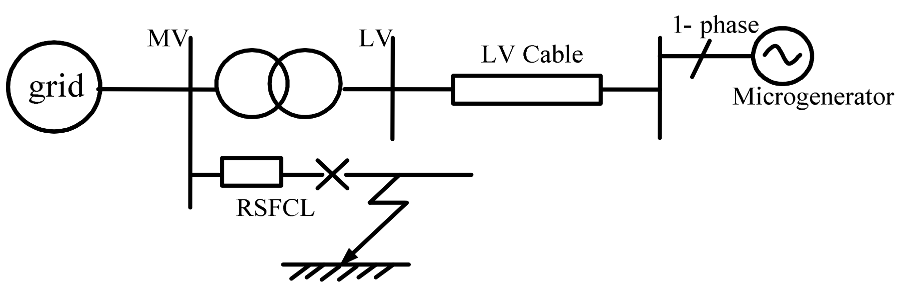


Figure 6- 6: Simplified diagram of a distribution power system with one LV-connected microgenerator

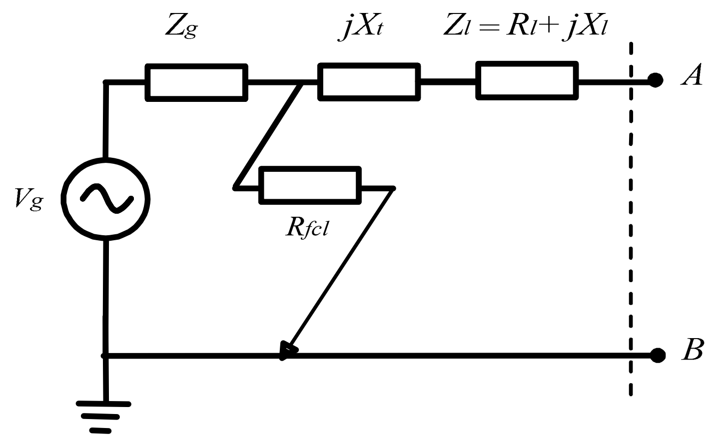


Figure 6- 7: The equivalent circuit of the faulted network with inclusion of RSFCL

The equivalent circuit of the faulted network is drawn as in Figure 6- 7 above. The Thevenin's equivalent circuit of the faulted network as viewed looking from the microgenerator terminals (i.e. points A-B) is calculated. The Thevenin voltage as viewed from the microgenerator terminals is:

$$\overline{V_{th}} = V_g \frac{R_{fcl}}{(R_{fcl}+R_g) + j(X_g)} = V_{th} e^{j\theta_{th}} \tag{30}$$

$$\left|\overline{V_{th}}\right| = V_{th} = V_g \frac{R_{fcl}}{\sqrt{(R_{fcl}+R_g)^2 + (X_g)^2}} \tag{31}$$

Where V_g is the grid voltage, and V_{th} is the retained voltage at the microgeneration terminals with the system faulted. R_g and X_g are the resistance and the reactance of the grid source. R_{fcl} is the developed resistance of the fault current limiter during the fault, and $\theta_{th} = \tan^{-1}(X_g / (R_{fcl}+R_g))$. The Thevenin impedance as viewed from the microgenerator terminals is:

$$Z_{th} = Z_L + Z_t + R_{fcl} \,//\, Z_g = R_{th} + jX_{th} \tag{32}$$

Where Z_L is the impedance of the LV cable and it is equal to $R_L + jX_L$, and Z_t is the impedance of the transformer and it is equal to the reactance jX_t.

$$Z_{th} = \frac{R_{fcl}(R_g + jX_g)}{(R_{fcl} + R_g) + jX_g} + R_L + j(X_t + X_L) \quad (33)$$

$$Z_{th} = \frac{R_{fcl}R_g + R_L(R_{fcl}+R_g) - X_g(X_t+X_L) + j(R_{fcl}X_g + R_LX_g + (R_{fcl}+R_g)(X_t+X_L))}{(R_{fcl}+R_g)+jX_g} \quad (34)$$

If the numerator and the denominator of the above equation (34) is multiplied by $(R_{fcl} + R_g) - jX_g$, then R_{th} and X_{th} can be found. The resulted denominator will be equal to $(R_{fcl} + R_g)^2 + X_g^2$, and the real part of the numerator is equal to $(R_g + R_L)R_{fcl}^2 + (R_g^2 + 2R_gR_L + X_g^2)R_{fcl} + R_L(R_g^2 + X_g^2)$ while the imaginary part of the numerator is equal to $(X_g + (X_t + X_L))R_{fcl}^2 + 2R_g(X_t + X_L)R_{fcl} + (R_g^2 + X_g^2)(X_t + X_L)$.

If $A_1 = (R_g + R_L)$ (35)

$$B_1 = (R_g^2 + 2R_gR_L + X_g^2) \quad (36)$$

$$C_1 = R_L(R_g^2 + X_g^2) \quad (37)$$

$$A_2 = (X_g + (X_t + X_L)) \quad (38)$$

$$B_2 = 2R_g(X_t + X_L) \quad (39)$$

$$C_2 = (R_g^2 + X_g^2)(X_t + X_L) \quad (40)$$

Then the Z_{th} can be written as in the following equation (41).

$$Z_{th} = \frac{A_1R_{fcl}^2 + B_1R_{fcl} + C_1}{(R_{fcl} + R_g)^2 + (X_g)^2} + j\frac{A_2R_{fcl}^2 + B_2R_{fcl} + C_2}{(R_{fcl} + R_g)^2 + (X_g)^2} = R_{th} + jX_{th} \quad (41)$$

It can be seen that the R_{th} and X_{th} are functions of the resistance of the fault current limiter, and *A1, B1, C1, A2, B2,* and *C2* are constants which consist of the parameters of the system. The faulted network in the diagram shown in Figure 6- 7 can be reduced to its Thevenin's equivalent circuit as drawn below in Figure 6- 8.

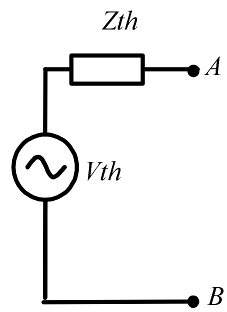


Figure 6- 8: The Thevenin equivalent circuit of the faulted network shown in Figure 6-7

To represent the impact of the fault current limiter on the machine performance during fault conditions, the Thevenin equivalent circuit of the faulted network with the inclusion of the RSFCL as shown in Figure 6- 7 can now be connected at points A and B to the equivalent circuit of the single-phase induction generator as shown in Figure 6- 9.

The equivalent circuit used to represent the microgenerator is assumed to be a steady state single-phase machine model. This model is widely used with acceptable accuracy to determine the critical speed that can be reached by the machine rotor during the fault according to the results of the studies conducted in [6.18], [6.19], and [6.20]. In addition, the steady state single-phase machine model provides simplification in the derivative of the approach without significantly impacting the accuracy of the approach. This is the main reason why this model of the machine is used instead of a complete transient single-phase induction generator model which can make the derivative of the approach extremely complicated.

The steady state model of an induction machine as introduced in [6.21] is given in detail in Appendix D. The Figure 6- 9 shows the connection of the Thevenin's equivalent circuit of faulted network and the induction microgenerator.

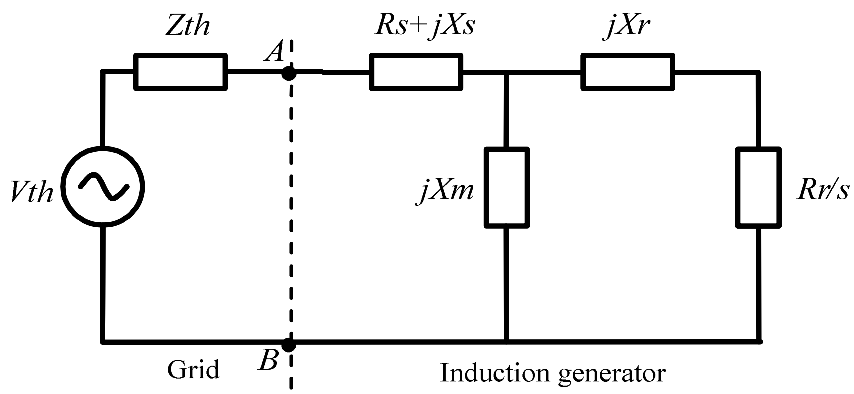


Figure 6- 9: Thevenin's equivalent of faulted network with microgeneration interfaced by an induction machine

The dynamic performance of an induction machine as discussed in chapter five can be obtained with acceptable results by using the mathematical relationship between the developed electrical torque and the machine speed [6.20]. Figure 6- 10 shows the relationship between the torque and the slip of such a machine. Such characteristics have been used in [6.20] as an analytical method for identifying the stability margin of an induction machine.

In this chapter, the same characteristics are used to derive an analytical approach to identify the minimum value of the resistance ($R_{fcl\min}$) that the RSFCL should have to ensure the transient stability of a high penetration of LV connected microgeneration interfaced by induction generators. The influence of RSFCL on the transient performance of an induction generator is investigated by comparing three different operating conditions of the system; pre-fault, during fault, and post-fault conditions. The investigation is conducted as follows.

A- Pre-fault condition

Before the fault occurs the limiter presents R_{fcl} equal to zero, and the connected induction generator operates on curve A as shown in Figure 6- 10. Curve A represents the characteristics of the developed electrical machine torque T_e and the machine slip S when the mechanical torque T_m is assumed to be constant. The electrical torque is changed by changing the machine speed, and it crosses the mechanical torque when $T_e = T_m$ at two points. The first crossing point is when the generator operates at the steady state slip S_0, and the second crossing point is when the machine reaches its maximum slip (i.e. critical slip) S_{cr} as shown in Figure 6- 10. S_{cr} has been identified in many research efforts as a dynamic stability limit of induction generators, and based on its value, the critical fault clearance time of induction generators is calculated as in [6.20] and[6.22].

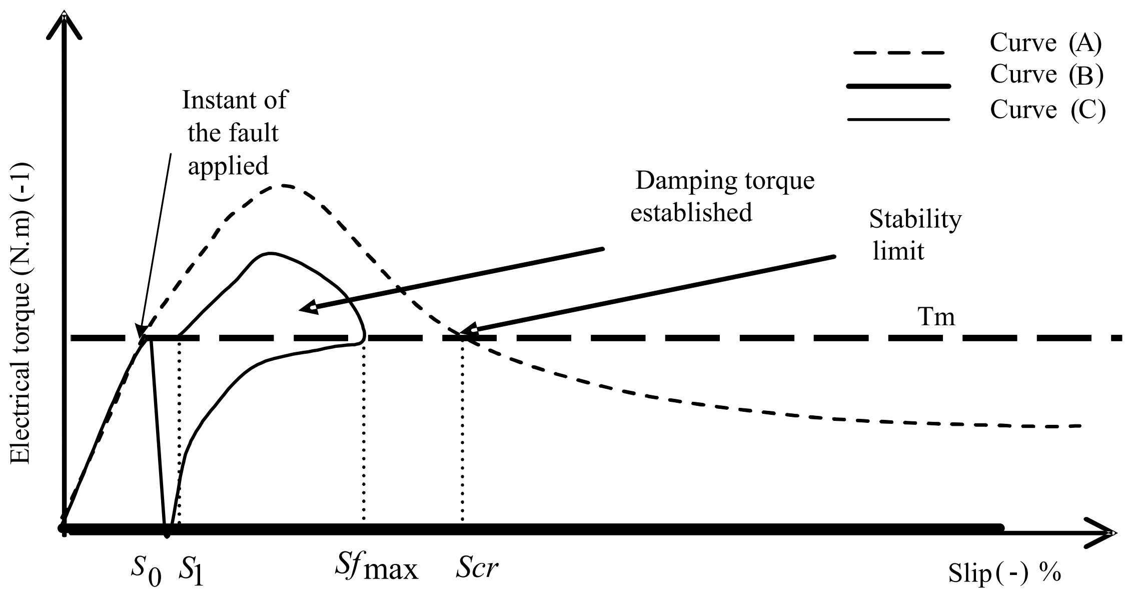


Figure 6- 10: The impact of RSFCL on the stability margin of induction generator

B- During the fault condition

In the event of the fault and when there is no RSFCL, a sudden reduction in the machine electrical torque is experienced due to the drop in the machine terminal voltage as shown on curve B in Figure 6- 10, and as a consequence the machine rotor will rapidly speed up. If the slip exceeds S_{cr} then the machine will not return to stable operation after the clearance of the fault.

In the case with the RSFCL deployed, its resistance element R_{fcl} will start increasing from zero to its maximum value during the fault. The electrical torque T_e from the generator will fall to zero at the instant of the fault and then it will be re-developed due to the increase in R_{fcl}. In order to ensure the transient stability and prevent the machine from reaching its stability limit, the value of R_{fcl} must be large enough to help the machine electrical torque to be developed until it exceeds the mechanical torque T_m and a damping torque is established. Therefore, the minimum value of R_{fcl} for applying a damping torque during the fault is defined at $T_e = T_m$. The value of this resistance needs to be reached by the limiter within a time before the CCT, and as soon as this value is reached the stability of the induction machine can be maintained even if the fault lasts more than the CCT. Also at this point the machine slip will reach its maximum value $S_{f\max}$ as shown on curve C in Figure 6- 10. This slip will be then decreased when $T_e \geq T_m$. When R_{fcl} reaches its maximum during the fault the machine will operate stably and the slip will be reduced to a new value S_1 as shown in Figure 6- 10. This value is much smaller than S_{cr}. As a result, the action of applying a damping torque during the fault period will hold the machine speed to be within the stability limit (i.e. $S_0 < slip < S_{cr}$). This will ensure the transient stability of the generator regardless of the fault clearance time, because whenever the fault is cleared the rotor speed is always less than its stability limit, and after the fault the speed will be controlled by the post-fault damping torque.

The required minimum value of R_{fcl} to maintain the transient stability of the machine is defined to be $R_{fcl\min}$ and it can be determined as follows.

When $T_e = T_m$ during the fault, R_{fcl} is equal to $R_{fcl\min}$ and the slip is equal to $S_{f\max}$. This will correspond to R_r / S of the machine steady state equivalent circuit shown in Figure 6- 9 being at its smallest value and the converted electrical power in (38) being at its largest value.

$$P_{max} = I_r^2 \frac{R_r}{S_{max}} = \omega T_e = \omega T_m \tag{42}$$

Where I_r is the magnitude of the rotor current, and ω is the machine speed.

The machine magnetization reactance X_m is normally significantly larger than the rotor reactance X_r, and this can be noticed from real data of different machines as reported in [6.23] and [6.24]. Therefore, for simplification purpose, the X_m shown in Figure 6- 9 is assumed to be infinite, so the circuit can be simplified and reduced as shown below in Figure 6- 11.

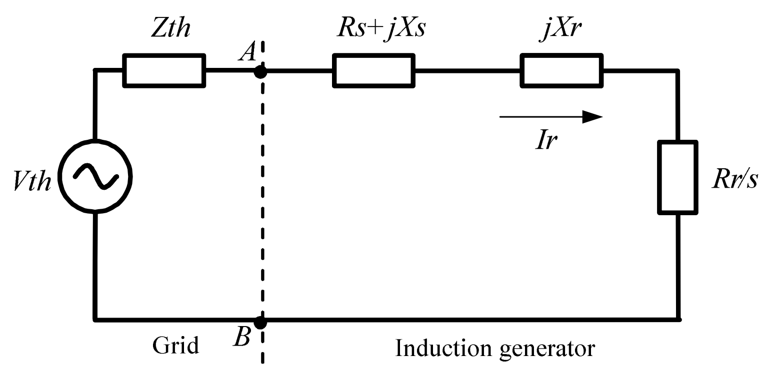


Figure 6- 11: Simplified circuit diagram of an induction machine connected to the grid

By using the maximum power transfer theorem [6.25], the maximum power that can be delivered will occur when the load reactance is made as close to the Thevenin reactance as possible and the load resistance is set to the following value:

$$\frac{R_r}{S\,max} = \sqrt{(R_{th} + R_s)^2 + (X_{th} + X_{load})^2}$$

From Figure 6- 11, the $X_{load} = X_r + X_s$. Thus the maximum power is delivered when

$$\frac{R_r}{S\,max} = \sqrt{(R_{th\,min} + R_s)^2 + (X_{th\,min} + X_r + X_s)^2} \tag{43}$$

Where $R_{th\,min}$, and $X_{th\,min}$ are the real, and imaginary parts of Thevenin's impedance respectively when $R_{fcl} = R_{fcl\,min}$.

The rotor current I_r will be at its maximum when the machine slip reaches its largest value. I_r can be easily calculated as following:

$$|I_r| = \frac{V_{th\min}}{\sqrt{(R_s + \frac{R_r}{S_{\max}} + R_{th\min})^2 + (X_s + X_r + X_{th\min})^2}} \quad (44)$$

By substituting the Value of I_r from (44) in (42), the following equation is obtained:

$$T_e = T_m = \frac{R_r}{S_{\max}\omega} \cdot \frac{V_{th\min}^2}{(R_s + \frac{R_r}{S_{\max}} + R_{th\min})^2 + (X_s + X_r + X_{th\min})^2} \quad (45)$$

$$[(\frac{R_r}{S_{\max}} + (R_s + R_{th\min}))^2 + ((X_s + X_r) + X_{th\min})^2] = \frac{R_r}{S_{\max}} \frac{V_{th\min}^2}{\omega T_m}$$

$$(\frac{R_r}{S_{\max}})^2 + 2\frac{R_r}{S_{\max}}(R_s + R_{th\min}) + (R_s + R_{th\min})^2 + [X_{th\min} + (X_s + X_r)]^2 = \frac{R_r}{S_{\max}} \frac{V_{th\min}^2}{\omega T_m}$$

$$(\frac{R_r}{S_{\max}})^2 + (R_s + R_{th\min})^2 + [X_{th\min} + (X_s + X_r)]^2 = \frac{R_r}{S_{\max}} \frac{V_{th\min}^2}{\omega T_m} - 2\frac{R_r}{S_{\max}}(R_s + R_{th\min}) \quad (46)$$

By substituting the value of $\frac{R_r}{S_{\max}}$ from (43) in the equation (46), the following equation is resulted.

$$2(R_{th\min} + R_s)^2 + 2(X_{th\min} + X_s + X_r)^2 = \sqrt{(R_{th\min} + R_s)^2 + (X_{th\min} + X_s + X_r)^2}\,[\frac{V_{th\min}^2}{\omega T_m} - 2(R_s + R_{th\min})] \quad (47)$$

Taking the square of the two sides of the equation (47)

$$[(R_{th\min} + R_s)^2 + (X_{th\min} + X_s + X_r)^2]^2 = (R_{th\min} + R_s)^2 + (X_{th\min} + X_s + X_r)^2[\frac{V_{th\min}^2}{2\omega T_m} - (R_s + R_{th\min})]^2$$

$$\begin{aligned}(R_{th\min} + R_s)^4 &+ 2(R_{th\min} + R_s)^2(X_{th\min} + X_s + X_r)^2 + (X_{th\min} + X_s + X_r)^4 = \\ &(\frac{V_{th\min}^2}{2\omega T_m})^2(R_{th\min} + R_s)^2 - \frac{V_{th\min}^2}{\omega T_m}(R_s + R_{th\min})^3 + (R_s + R_{th\min})^4 + \\ &\quad (X_{th\min} + X_s + X_r)^2[(\frac{V_{th\min}^2}{2\omega T_m})^2 - \frac{V_{th\min}^2}{\omega T_m}(R_s + R_{th\min}) + (R_s + R_{th\min})^2]\end{aligned}$$

$$(X_{th\min}+X_s+X_r)^2[(R_{th\min}+R_s)^2+(X_{th\min}+X_s+X_r)^2]-\frac{V_{th\min}^2}{\omega T_m}[\frac{V_{th\min}^2}{2\omega T_m}-(R_s+R_{th\min})][(X_{th\min}+X_s+X_r)^2+(R_{th\min}+R_s)^2]=0$$

$$[(R_{th\min}+R_s)^2+(X_{th\min}+X_s+X_r)^2][(X_{th\min}+X_s+X_r)^2-\frac{V_{th\min}^2}{\omega T_m}[\frac{V_{th\min}^2}{2\omega T_m}-(R_s+R_{th\min})]=0 \quad (48)$$

From equation (48) it can be seen that $(R_{th\min}+R_s)^2+(X_{th\min}+X_s+X_r)^2=0$ or

$$[(X_{th\min}+X_s+X_r)^2-\frac{V_{th\min}^2}{\omega T_m}[\frac{V_{th\min}^2}{2\omega T_m}-(R_s+R_{th\min})]=0 \quad (49)$$

By substituting the values of $V_{th\min}$ from (27) and $R_{th\min}$ and $X_{th\min}$ from (41) in (49) the following equation is resulted.

$$(\frac{A_2R_{fcl}^2+B_2R_{fcl}+C_2}{(R_{fcl}+R_g)^2+(X_g)^2})^2+2\frac{A_2R_{fcl}^2+B_2R_{fcl}+C_2}{(R_{fcl}+R_g)^2+(X_g)^2}(X_s+X_r)+(X_s+X_r)^2-$$
$$V_g^4\frac{R_{fcl\min}^4}{(2\omega T_m)^2[(R_{fcl}+R_g)^2+(X_g)^2]^2}+V_g^2\frac{R_{fcl\min}^2}{\omega T_m[(R_{fcl}+R_g)^2+(X_g)^2]}R_s+ \quad (50)$$
$$V_g^2\frac{R_{fcl\min}^2}{\omega T_m[(R_{fcl}+R_g)^2+(X_g)^2]}\frac{A_1R_{fcl}^2+B_1R_{fcl}+C_1}{(R_{fcl}+R_g)^2+(X_g)^2}=0$$

From (50) the following fourth order equation (51) (i.e. function of R_{fclmin}) is obtained. The details of the derivative steps are given in Appendix (F).

$$\boxed{F(R_{fcl\min})=D_1R_{fcl\min}^4+D_2R_{fcl\min}^3+D_3R_{fcl\min}^2+D_4R_{fcl\min}+D_5=0} \quad (51)$$

Where the coefficients *D1*, *D2*, *D3*, *D4*, and *D5* are constants, and can be calculated from the following formulae.

$$D_1=A_2^2+2A_2(X_s+X_r)+(X_s+X_r)^2-V_g^4\frac{1}{(2\omega T_m)^2}+\frac{V_g^2}{\omega T_m}R_s+A_1\frac{V_g^2}{\omega T_m} \quad (52)$$

$$D_2=2A_2B_2+4A_2(X_s+X_r)R_g+2B_2(X_s+X_r)+4R_g(X_s+X_r)^2+2\frac{V_g^2}{\omega T_m}R_sR_g+B_1\frac{V_g^2}{\omega T_m} \quad (53)$$

$$D_3 = (2C_2A_2 + B_2^2) + 2A_2(X_s + X_r)(R_g^2 + (X_g)^2) + 4B_2(X_s + X_r)R_g + 2C_2(X_s + X_r) + 2(R_g^2 + X_g^2)(X_s + X_r)^2 + 4R_g^2(X_s + X_r)^2 + \frac{V_g^2}{\omega T_m}R_sR_g^2 + \frac{V_g^2}{\omega T_m}R_s(X_g)^2 + C_1\frac{V_g^2}{\omega T_m} \qquad (54)$$

$$D_4 = 2B_2C_2 + 2R_g^2B_2(X_s + X_r) + 4C_2(X_s + X_r)R_g + 2B_2(X_s + X_r)(X_g)^2 + 4R_g(R_g^2 + X_g^2)(X_s + X_r)^2 \qquad (55)$$

$$D_5 = C_2^2 + 2C_2(X_s + X_r)R_g^2 + 2C_2(X_s + X_r)(X_g)^2 + (X_s + X_r)^2(R_g^2 + X_g^2)^2 \qquad (56)$$

A1, B1, C1, A2, B2, and *C2* are constants which consist of the parameters of the system, and their formulae are given above in equations from (35) to (40).

The numerical solution of the equation (51) to find $R_{fcl\min}$ can be obtained by two ways. One is by applying Newton's method (an iterative process) [6.26] as in (57) until the desired accuracy is obtained for the resultant function of $R_{fcl\min}$ (i.e. F($R_{fcl\min}$)=0). This has been conducted by using MATLAB to solve the equation.

$$(R_{fcl\min})_{n+1} = (R_{fcl\min})_n - \frac{F(R_{fcl\min})_n}{F'(R_{fcl\min})_n} \qquad (57)$$

For *n=0, 1, 2, 3, …….*

The second is by calculating directly the roots of the equation. These roots can be easily found by using MATLAB for example, and from the obtained roots, the most suitable values of $R_{fcl\min}$ can be chosen. The obtained $R_{fcl\min}$ from the solution of equation (51) will be the minimum value of the resistance element of the SFCL that will ensure the transient stability of LV connected induction microgeneration.

C- Post fault condition

During the fault the machine is held within a stable region $T_e \geq T_m$ due to the applied damping torque as result of the RSFCL performance during the fault. So, whenever the fault is cleared the rotor speed will be forced to slow down and return to its new steady state operating mode as shown on curve C in Figure 6- 10.

The $R_{fcl\min}$ identified in equation (51) is an important criterion to ensure that the LV connected induction microgenerator will converge to its equilibrium regardless the fault duration. This is because when the fault is cleared the machine post fault state will be within the transient stability region. So the RSFCL would have a critical value of resistance that should be reached to ensure that the limiter can be used for improving the transient stability of the downstream microgeneration or its performance would be limited only to limiting the perspective fault current.

6.6 RSFCL application for distribution systems transient stability enhancement

The main aim of studies is to investigate the effectiveness of using RSFCL as remedial measures by which the transient stability of a large penetration of LV connected microgeneration is significantly improved, and at the same time the increase in the fault level is curtailed. For a passive distribution network when an RSFCL is used to limit the fault current contribution from the grid, the limiter is designed based on the fault current that will pass through the limiter. The amount of the fault current is directly impacted by the X/R ratio of the grid source. However, for an active distribution network the mathematical approach as given in equation (51) shows that when the RSFCL is used to improve the transient stability of a small scale grid-connected induction microgenerator, the parameters of the machine as well as the parameters of the network (i.e. X/R ratio and short circuit capacity) will impact the minimum required value of the resistive element of the RSFCL. So if the same limiter is added to different distribution networks with different source impedances to improve the transient performance of same induction microgenerators, the impact on the machines transient stability will be different. In order to investigate these issues and the significance of the RSFCL transient performance on the transient stability improvement of distribution systems as well as validating the developed approach (51), the test network 2 and induction microgenerator transient models that were developed previously in chapter five are used in the studies of this chapter.

The RSFCLs are located as shown on the test network 2 diagram as in Figure 6- 12, and the studies are divided into three main sections: examining the RSFCL performance during the fault, evaluating the impact of RSFCL on the transient performance of LV connected microgeneration, and lastly investigating the significance of $R_{fcl\,\min}$ value on the transient stability of LV connected microgeneration. In addition, the impact of distribution systems with different X/R ratio and different machines with different parameters on the $R_{fcl\,\min}$ value is also investigated. The last section of the studies is also used for validating the mathematical approach developed by formula (51) for identifying the value of $R_{fcl\,\min}$.

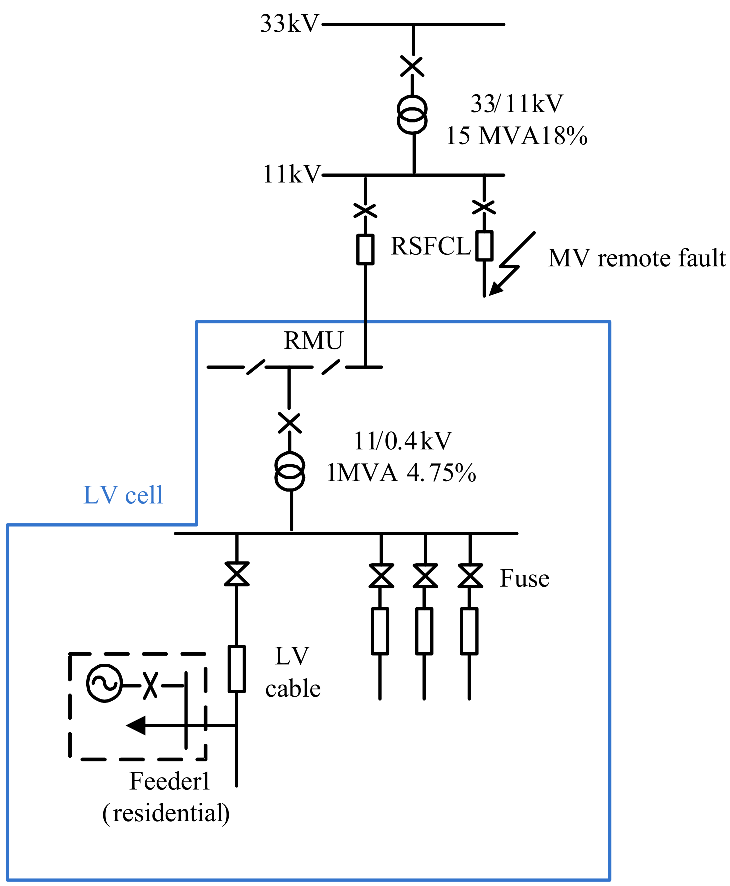


Figure 6- 12: Test network 2 incorporated with RSFCL

6.7 RSFCL Model

The limiter is modelled to change its state at the instant of the fault (i.e. when the current exceeds the appropriate threshold) to limit the first peak of the fault current (peak make). The threshold value of the fault current to initiate the RSFCL is chosen to be larger than twice the full load current which is normally considered as the minimum required current for relays to operate. In [6.27] which investigates the dependence of critical current density on the Joule heat for a RSFCL, the critical current is identified based on the critical temperature of the limiter to be equal to 2.35 times the load current. Also in [6.28] and [6.29] it has been stated that the superconductor of RSFCL would be designed to have critical current from 2 to 3 times the full load current. Therefore, within the model of RSFCL developed in this section, the critical current of the RSFCL is chosen to be 3 times the full load current.

RSFCL in each phase is modelled by using a variable nonlinear resistance connected in series with an ammeter as shown in Figure 6- 13, and located as in Figure 6- 12. When the fault current exceeds the activation value, the resistance R will be changed nonlinearly as a function of time as shown in Figure 6- 14. The resistance versus time curve is based on the model that has been developed in [6.30] to represent the transient characteristics of RSFCL as a function of fault duration time, fault current, and temperature. The resistive element of the limiter within the model reaches its maximum values within 20msec. The model of the resistive element of the limiter in [6.30] is derived by scaling the resistive characteristic produced by experimental work reported in [6.31] in defining the nonlinearity of RSFCL. The nonlinear RSFCL model is used because a linear model is not sufficient to represents the RSFCL transient characteristics [6.30]. Because the faulted feeder will be disconnected by the main breaker as shown in Figure 6- 12, the recovery time of the limiter connected to the faulted feeder will have no impact on the system. Also since the limiters are added to MV feeder, and the chapter three studies have proven that the contribution from LV microgeneration to a fault at MV side will be very limited due to the presence of MV/LV transformers, and hence the reverse current provided by downstream microgeneration will not be strong enough to activate the limiters of the health feeders. This means there will be also no impact of the recovery of time the limiter of the healthy feeders because they will not be activated. Therefore the impact of the recovery time of RSFCL is ignored in the studies of this chapter.

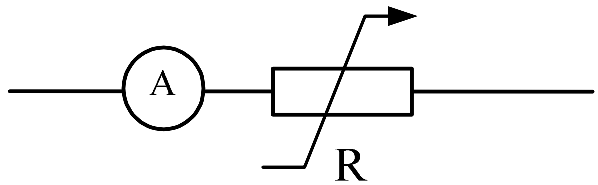


Figure 6- 13: Resistive-type superconducting fault current limiter model

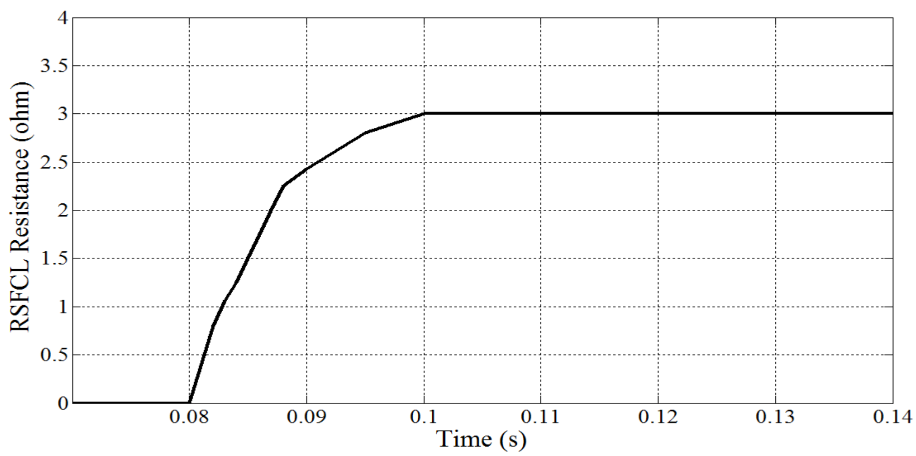


Figure 6- 14: The Resistive SFCL characteristics during the fault [6.30].

6.8 Transient studies

A three-phase to ground fault is assumed to be applied on the feeder at MV side as shown in Figure 6- 12. The fault is applied at time t=3.08ms with fault duration equal to 1s and voltage angle=0 to obtain the maximum asymmetrical current within the first half cycle. The fault duration of 1s is chosen to exceed the microgeneration fault critical clearance times that were found in chapter five (79msec). The simulation studies allow the quantification of the response of the RSFCL transient model on the applied fault, and the resulting influence on the transient stability of the LV connected microgenerator.

6.8.1 RSFCL Response during fault on MV circuit

Figure 6- 15 shows two results of the fault current with and without adding RSFCL at the beginning of the MV faulted feeder of the distribution network shown in Figure 6-

12. Without adding RSFCL, the peak value of the transient fault current (peak make) has reached 22kA peak within first cycle. With RSFCL insertion, the results have shown no pre-fault effect, and when the protected circuit is faulted, the limiter is initiated when the fault current reaches 848.5A (peak). The first peak of the fault current is reduced by the limiter to 15kA, and when the values of the resistive element is developed according to the resistance time curve shown in Figure 6- 14, the dc component of the fault current has been rapidly removed by the limiter, and the fault current is reduced further to be 4.09kA. The limiter has provided a reduction factor ($I_{fault} / I_{\lim ited}$) equal to 1.4 on the peak make, and reduction factor equal to 3.09 on the peak break.

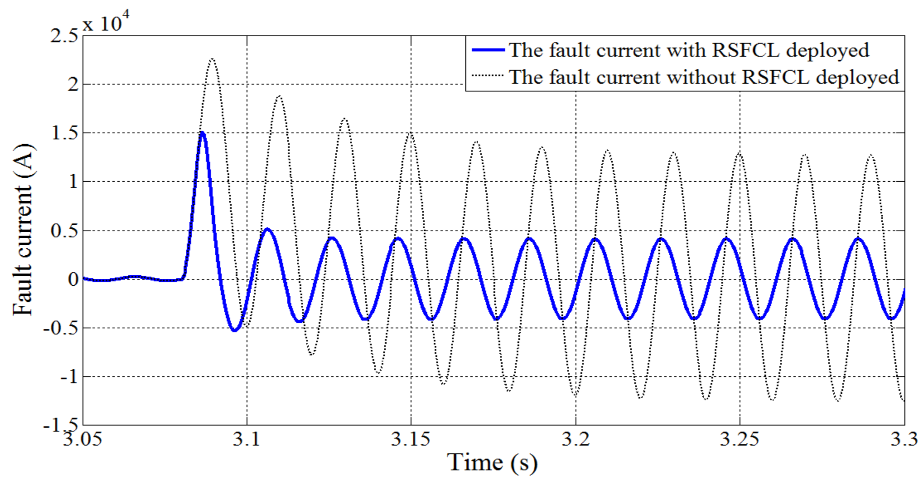


Figure 6- 15: Fault currents with and without the inclusion of RSFCL

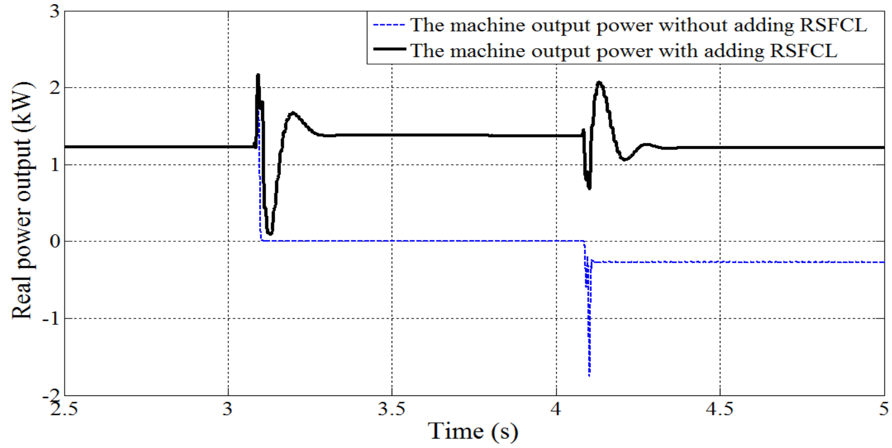
The results above have shown how significant the usage of the RSFCL in limiting the perspective fault current. This would lead to numbers of advantages. For example, the reduction in the fault level even if the fault current has not exceeded the short circuit limit would reduce the stress of the heat on the protected system component, and this in turn could make the component lasts longer. Another advantage is, by using RSFCL to reduce the fault current, lower rating equipment with smaller size can be installed in small spaces. Such applications can be very important in urban areas where no many spaces are available and the cost of the land is normally very expensive. From the technical perspective, reduction in the fault current is actually resulting in reduction in the voltage dips on the nearby areas to the fault location. This can be seen as a significant measure to improve the power quality.

6.8.2 Impact of RSFCL on LV-Connected Microgeneration Transient Stability

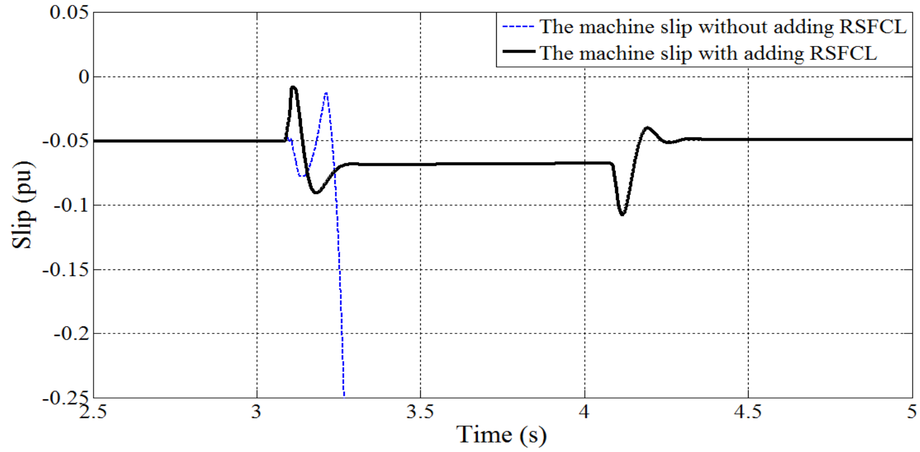
The following presents the investigation of the impact of using RSFCL on the fault ride through capabilities of LV-connected microgeneration with different sizes. The investigation is initially achieved by studying the influence of the transient characteristics of RSFCL based on the resistance time curve shown in Figure 6- 14 on the transient response of the output power and the machine slip of 1.5kVA single-phase induction generator. The same data for the machine which was used in chapter five and available in appendix C is used within the study.

Figure 6- 16 below illustrates the transient response of grid-excited 1.5kVA single-phase induction generator connected at residential level to remote MV fault as shown on the test network 2 depicted in Figure 6- 12. The response is tested with and without adding RSFCL to the network. When there no RSFCL is deployed, the machine output power falls to zero during the fault, due to the 100% drop in the machine terminal voltage. This has led to a high acceleration of the machine rotor during the fault period as explained in Figure 6- 16b. When the fault is cleared the machine has lost its transient stability and its output power has collapsed as shown in Figure 6- 16a.

When the RSFCL is added to MV feeders and with the same fault condition, the results in Figure 6- 16 have shown a very significant improvement in the fault ride through capabilities of the downstream connected microgenerator. This is because the RSFCL during the fault period has reduced the drop in the downstream voltage, and hence the machine has experienced a retained voltage on its terminals. This retained voltage has made the machine to be capable of still providing output power, and its rotor has not been accelerated to uncontrollable level as shown in Figure 6- 16. Because the retained voltage is less than 1pu, the machine speed during the fault has been increased (i.e. within stability limits) slightly higher than the normal speed as sketched in Figure 6- 16b. This increase caused the output power during the fault to be higher than the rated power until the fault is cleared. When the fault is cleared after 1s, the microgenerator has maintained its transient stability, and the machine has returned to its normal stable operation as shown in Figure 6- 16 below.



(a)



(b)

Figure 6- 16: The transient performance of grid-excited 1.5kVA 1-phase induction generator with and without using RSFCL

The results in above subsections have shown that adding RSFCL to MV feeders will remarkably limit the fault level at MV side and at the same time significantly improve the transient stability of downstream connected microgeneration during remote faults. However, the transient stability of the microgenerator has been improved because the resistance of the RSFCL has reached its maximum value 3Ω within 20msec. This value of the resistance is larger than the required $R_{fcl\min}$ to ensure the stability of the microgenerator, and also the resistance of the limiter has exceeded the $R_{fcl\min}$ before the CCT of the machine which is equal to 79msec. Therefore, it is important to identify the critical value that the resistance time curve of the RSFCL should reach before the critical clearance time of the downstream microgenerator in order to ensure the capability of the microgenerator to overcome transient remote faults. This can emphasise the importance of the analytical approach described in equation (51) within this chapter to determine $R_{fcl\min}$.

6.8.3 The significance of *Rfclmin* value on the transient stability of LV connected microgeneration

RSFCL can not always improve the transient stability of connected microgeneration, even if it is sufficient for limiting the fault current. So the transient studies in this section is to quantify the significance of determining the $R_{fcl\min}$ within the resistance time curve of RSFCL on the transient performance of LV-connected microgeneration. Four single-phase induction microgenerators 1.5kVA, 1kVA (1hp), 700W, and 1.1kW are used within the studies to evaluate the impact of $R_{fcl\min}$ on their transient stability. Different size of microgeneration with different transient parameters have been used in order to quantified the impact of different machine parameters on the value of $R_{fcl\min}$.The transient parameters of the microgenerators are obtained from [6.32], [6.33], [6.34], and [6.35]. The parameters from these sources have been evaluated by different simulation and experimental tests such as applying DC voltage to the main and auxiliary windings of single-phase induction machines to identify the windings resistances, and stand-still test, synchronous speed test, and steady state test to identify the windings and magnetizing reactance of the machines. All the machine parameters are listed in Appendix E.

The $R_{fcl\min}$ of RSFCL for transient stability of each machine to be maintained is determined within the simulation studies by trial-and-error, and listed below in Table 17. Then the values of $R_{fcl\min}$ are set as endpoints that the resistance time curves of RSFCL should reach before the CCT. Based on determined $R_{fcl\min}$, the real resistance time curve shown in Figure 6- 14 is scaled to provide new resistance time curves with endpoints equal to $R_{fcl\,\min}$ that ensure the stability of each of the four microgenerators as depicted in Figure 6- 17. $R_{fcl\,\min}$ can be reached within 20msec similar to the curve in Figure 6-14.

Microgeneration size	1.5kVA	1kVA	700W	1.1kW
$R_{fcl\,\min}$ (ohm)	1.19	1.31	1.218	1.485

Table 17: The required value of $R_{fcl\,\min}$ of RSFCL for transient stability of each machine to be maintained

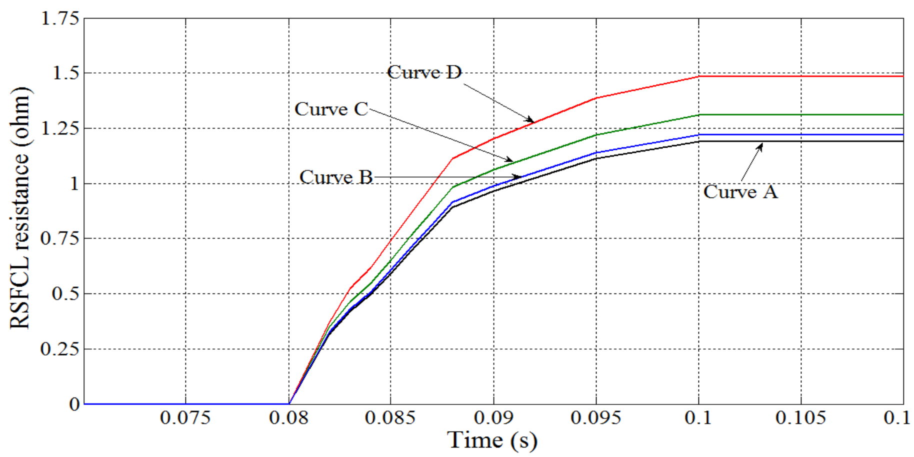


Figure 6- 17: Different Resistance time curves of RSFCL during fault condition

The curves sketched in the above figure are used to evaluate the impact of different RSFCL with different resistance time curves characteristics on the transient stability of small scale induction microgenerators. During the simulation studies, the curve A with smallest resistance profile as shown in Figure 6- 17 has been found to be sufficient to maintain the transient stability of the microgenerator 1.5kVA when $R_{fcl\,\min}$ reached 1.19Ω within 20msec which is smaller than the machine CCT which is equal to 79msec. The results below represent three different areas of investigation. One is when there is no RSFCL added to the system, the other is when the RSFCL is added and its resistance profile (i.e. curve A) reaches the required $R_{fcl\,\min}$ before the CCT of the microgenerator, and the third is when the maximum value of the RSFCL resistance time curve does not reach the value of $R_{fcl\,\min}$ as identified in Table 17 before the machine CCT.

In the first case as shown below in Figure 6- 18, the voltage at the terminals of the microgenerator is dropped to zero when there is no RSFCL applied. This has led the machine to experience unstable performance since the applied fault duration is larger than the CCT of the machine (i.e. 1s fault duration and the CCT was found 79msec). Figure 6- 19 shows such performance.

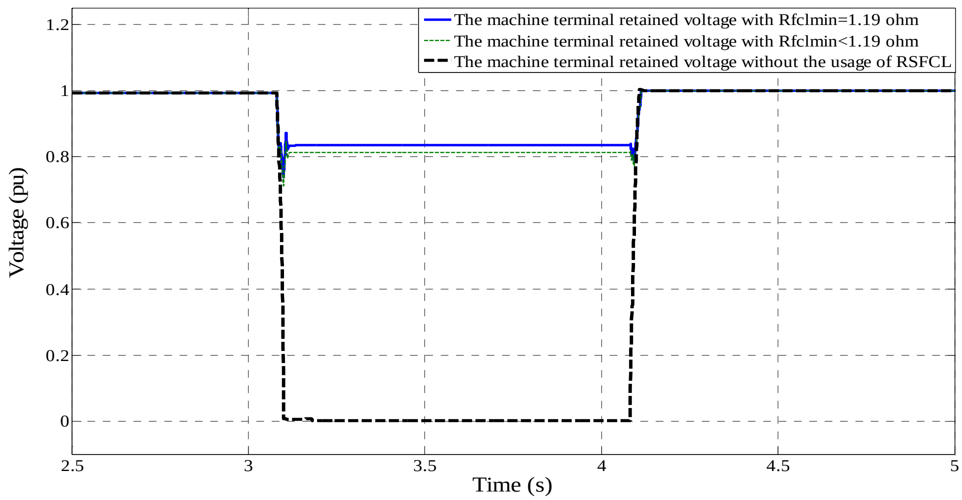
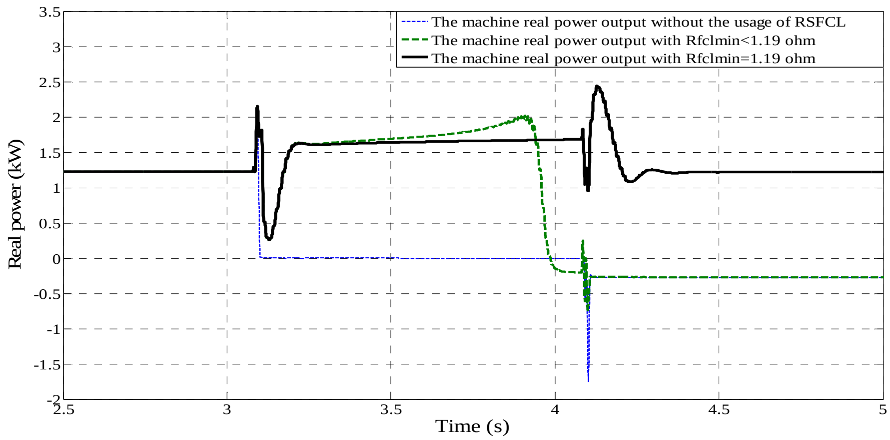
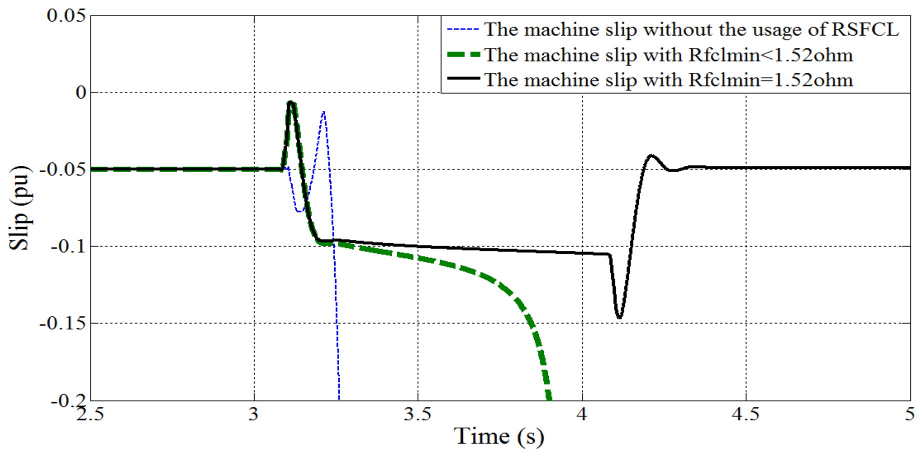


Figure 6- 18: The terminal voltages of grid-excited 1.5kVA 1-phase induction generator impacted by remote fault on MV circuit

When RSFCL is added and the maximum value of its resistance time curve to be reached within 20ms has been set to be equal to $R_{fcl\min}$, the microgenerator has been held at its critical speed after 20msec of the fault occurrence until the fault is cleared after 1s. Within this period (i.e. 20msec to 1s) the retained voltage has been dropped to its critical value which was found to be 83% of the nominal voltage. Therefore, if an RSFCL with resistance profile has values less than the profile shown on curve A in Figure 6- 17, the machine will exceed its critical speed and the transient stability of the machine will be lost. This phenomena has been considered in the simulation studies by adding a RSFCL with resistance profile that has maximum resistance less than $R_{fcl\min}$, and the results as shown in Figure 6- 19 have proven that a limiter with such transient characteristics is not a sufficient to maintain the transient stability of 1.5kVA single phase induction microgenerator. However, the limiter is still sufficient for limiting the fault current down to 25% of the perspective fault current.



(a)

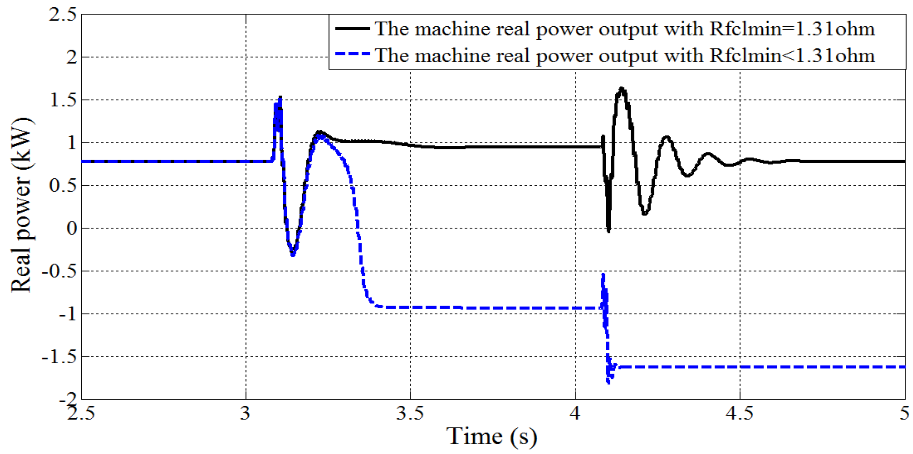


(b)

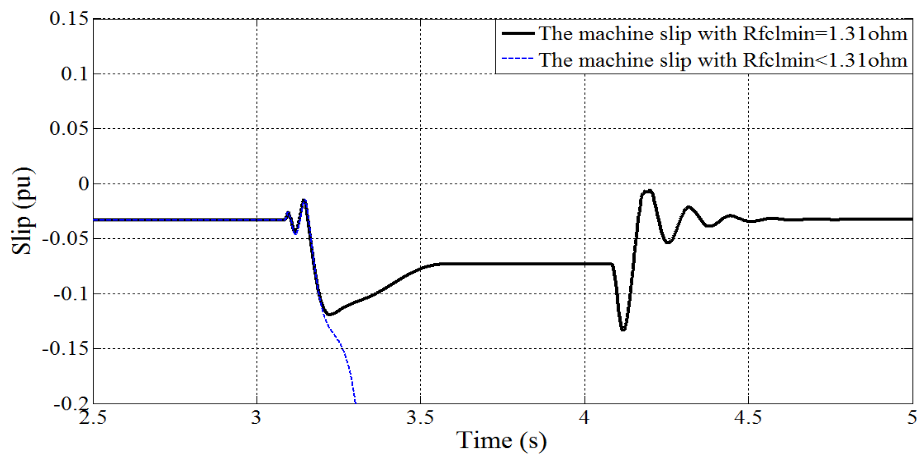
Figure 6- 19: The transient performance of grid-excited 1.5kVA 1-phase induction generator with and without using RSFCL

The results shown below in Figure 6- 20, Figure 6- 21, and Figure 6- 22 prove that based on the parameters of LV connected microgeneration machines, the RSFCL transient characteristics can be designed to ensure that the resistance of the limiter versus in time during the fault includes the $R_{fcl\min}$ that is required for stability improvement. For example during the studies, the RSFCL with curve A characteristics as shown in Figure 6- 17 was found sufficient to maintain the stability of the 1.5kVA and it is not sufficient for maintaining the stability of the other three machines as shown in figures (6-20 to 6-

22). This has been found because of the influence of the differences in the machines stator and rotor parameters on the $R_{fcl\,\min}$ of the limiter.

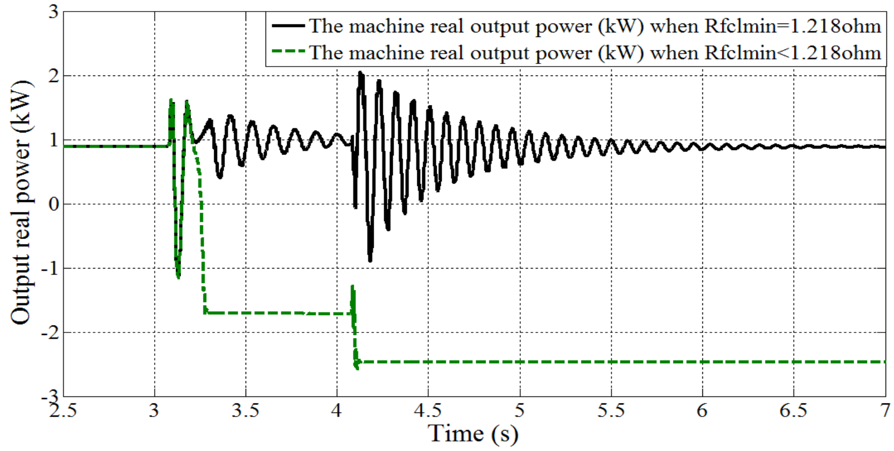


(a)

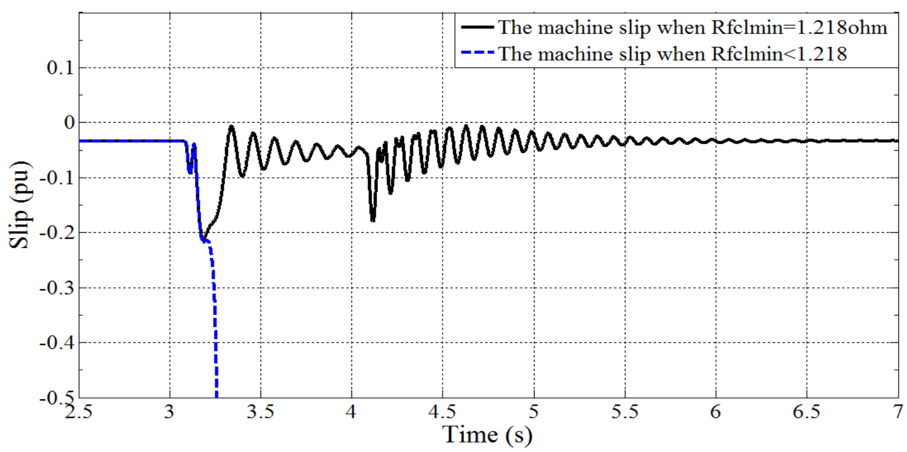


(b)

Figure 6- 20: The transient performance of grid-excited 1kVA 1-phase induction generator with and without using RSFCL: (a) the real power output, & (b) the slip of the machine

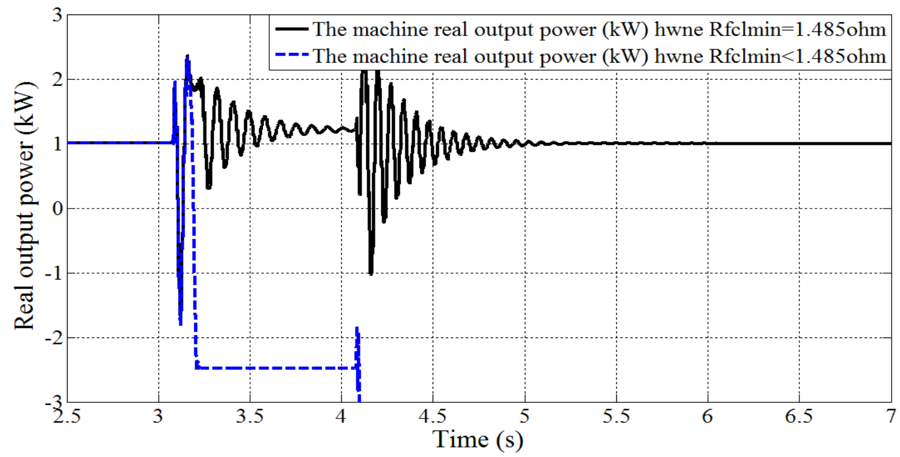


(a)

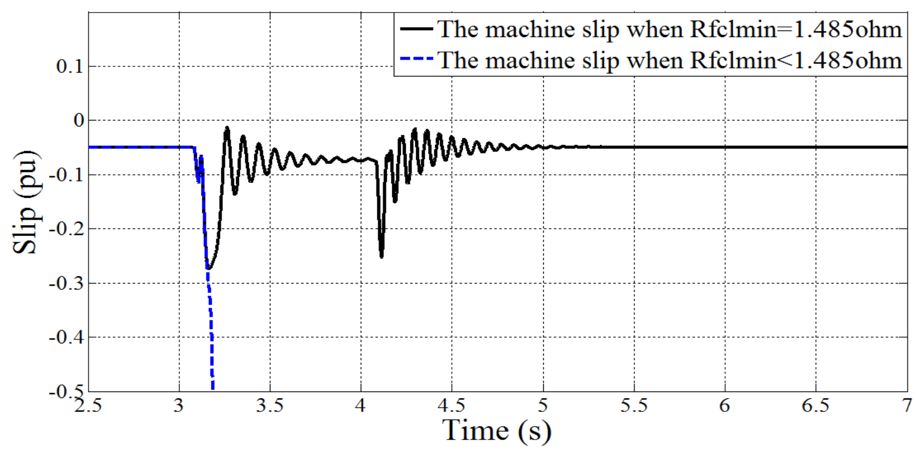


(b)

Figure 6- 21: The transient performance of grid-excited 700W 1-phase induction generator with and without using RSFCL:



(a)



(b)

Figure 6- 22: The transient performance of grid-excited 1.1kW 1-phase induction generator with and without using RSFCL

The results of this section bring very interesting findings to identify at which conditions the RSFCL can provide two useful functions, managing the increase in the fault level and at the same time providing an enhancement of transient stability of downstream connected microgeneration, and at which condition the limiter performs only its main function (i.e. limiting the fault current). So if RSFCLs are applied for the future power system as remedial measures to improve the transient system performance, its design should consider the transient stability improvement and fault limiting functions.

6.8.4 Evaluation of the proposed analytical method to calculate $R_{fcl\min}$

Identifying $R_{fcl\min}$ by using simulation programmes by systematically change parameters it consumes time, and requires detailed transient models and informative studies. Therefore, the analytical approach described by equation (51) can be used as a useful approach to identify the required value of $R_{fcl\min}$ based on the characteristics of the host system and the connected microgeneration. This section of studies contains two phases. One is the investigation of the impact of different distribution systems with different characteristics on the $R_{fcl\min}$ of RSFCL that can ensure the transient stability of downstream microgeneration. This can be useful to identify which RSFCL can be added to the host system to enhance the transient stability of the microgenerators connected to the system. The second phase is the investigation of the impact of different single-phase induction microgenerators with different parameters on the $R_{fcl\min}$ of RSFCL in order to identify which parameters have most impact on the $R_{fcl\min}$ value, and hence limiter design.

A- Impact of different host systems with different characteristics on $R_{fcl\min}$

Figure 6- 23 is used to explain the concept of this section. It is assumed that identical two microgenerators are connected to different distribution systems with different parameters as shown as grid 1 and 2 in the figure below, and the transient stability of the machines connected to each system is required to be improved by RSFCL. In this case adding identical RSFCLs to each system may not give the same performance. Because the $R_{fcl\min}$ to maintain the stability of the microgenerator can be influenced by the system parameters (i.e. X and R of the system).

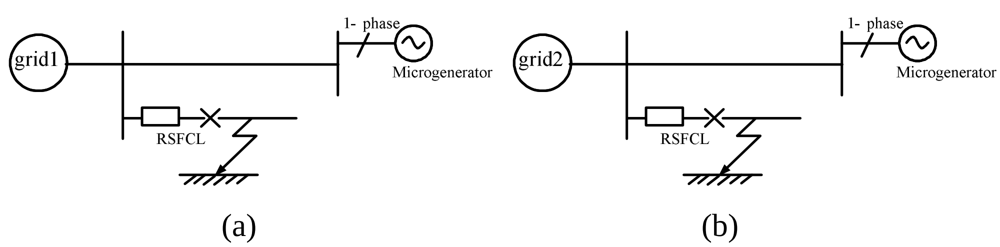


Figure 6- 23: RSFCL added to two systems with different characteristics

To quantify the impact of different systems with different characteristics on the value of $R_{fcl\,\min}$, 1kVA machines with the same parameters listed in appendix E are assumed to be connected to 11 distribution networks based on actual data with different grid parameters based on different X/R ratios at 11kV substations. The X/R ratios of the tested systems are taken from 11 actual different distribution networks operated by ScottishPower [6.36] and their data are listed in Table 18. All the parameters of the machines, LV cable, and MV/LV transformer are kept constant and only the resistance and the reactance of the used system sources R_g and X_g respectively are different for each system based on actual different perspective fault level at 11kV of each system.

X/R	14.99	14.81	19.13	15.07	12.64	9.41	6.48	5.48	7.15	3.86	2.56
Fault level (MVA)	449.8	213.4	198.7	159.6	158.8	157.2	152.4	143.2	121.9	115	114
Rg(Ω)	0.018	0.038	0.035	0.052	0.06	0.0813	0.121	0.15	0.137	0.294	0.38
Xg(Ω)	0.268	0.566	0.608	0.78	0.759	0.7655	0.785	0.831	0.982	1.01	0.98
Zg(Ω)	0.269	0.567	0.609	0.758	0.762	0.7698	0.794	0.845	0.992	1.052	1.06
$R_{fcl\min}$ (Ω)	1.65	3.497	3.51	4.804	4.94	5.21	6.945	8.107	8.216	13.92	17.4

Table 18: Actual values of different source impedances of different 11kV substation and the calculated values of the $R_{fcl\,\min}$

The R_g and X_g of each of the systems are calculated from the actual X/R ratios and the actual fault levels at the 11kV substations of the chosen networks as tabulated in Distribution Long Term Development Statement for ScottishPower Distribution [6.36]. Based on R_g and X_g values, the $R_{fcl\,\min}$ is calculated in each case from the approach given in equation (51) and the values are listed above in Table 18. The value of $R_{fcl\,\min}$ represents the required value of the resistance of the RSFCL that needs to be reached before the critical clearance time of the microgenerator (i.e. CCT from chapter five= 79msec). The results in Figure 6- 24 below show that MV distribution networks with higher source impedances will require an RSFCL with a higher resistive time curve in order to maintain the transient stability of 1kVA microgenerator connected at LV side. For example, the substation with lowest source impedances (0.269Ω) requires RSFCL limiter with $R_{fcl\min} < 2\Omega$, while the substation with the largest source impedance as shown in Figure 6- 24 (1.06Ω) requires a limiter with $R_{fcl\min} > 17\Omega$.

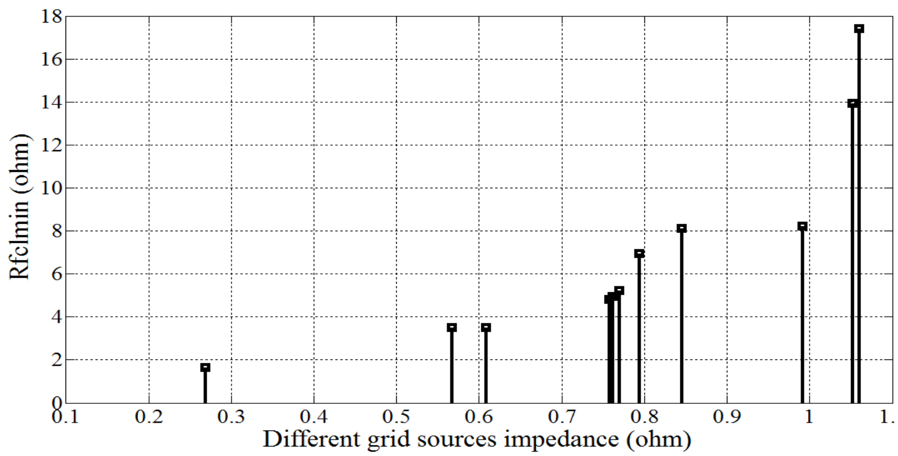


Figure 6- 24: The impact of different source impedances of different distribution networks on the value of $R_{fcl\min}$

For those 11kV substations have source impedances higher than 0.8Ω and require RSFCL with $R_{fcl\min}$ higher than 8Ω, the limiter may have a side effect on the performance of the systems. For example, if $R_{fcl\min}$ is compared to the maximum value of the actual RSFCL resistance profile (3Ω) identified above in Figure 6- 14, the $R_{fcl\min}$ can be considered relatively high. Large $R_{fcl\min}$ may lead to increase the recovery time of the limiter where higher resistance to be reached by the limiter needs higher temperature which makes the limiter requires longer time to dissipate the heat. Also inserting a higher resistance during the fault duration will increase the reduction in the fault current and this may delay the operating times of overcurrent relays of the MV feeders. Therefore, identifying $R_{fcl\min}$ can give an indication at which condition and for which network RSFCL can be suitable for improving the transient stability and managing the increase in the fault level. For an RSFCL to be designed to support the transient performance of distribution networks, it may recommend the evaluation of a combination of the RSFCL impact on fault level, transient stability performance, and protection performance of the networks. This evaluation has not been considered in the thesis, and it will be considered in the future work.

B- Impact of microgeneration with different parameters on $R_{fcl\min}$

In this phase, only the microgenerator parameters are hypothetically changed, and their influence on the $R_{fcl\min}$ is examined. From formula (51) and from the simplified network shown early in the chapter in Figure 6- 11, it can be seen that the three machine parameters Xs, Xr, and Rs may impact the value of $R_{fcl\min}$. The $R_{fcl\min}$ is calculated from the equation (51) in one case when the (Xs+Xr) is constant and Rs is changed, and in the second case when Rs is constant and (Xs+Xr) is changed, and the results are tabulated below in Table 19 and 20.

(Xs+Xr)=2Ω

Rs (Ω)	0	0.5	1	1.5	2	2.5	3	3.5	4
$R_{fcl\min}$ (Ω)	0.605	0.375	0.2904	0.2299	0.1936	0.1815	0.1573	0.1452	0.133

Table 19: The impact of the change in the stator resistance on the value of $R_{fcl\min}$

Rs=0Ω

Xs+Xr (Ω)	0	1	1.5	2	2.2	2.25	2.3	2.4	2.45	2.5	2.55	2.56	2.57
$R_{fcl\min}$ (Ω)	0.007	0.229	0.363	0.605	0.834	0.92	1.041	1.428	1.815	2.613	5.832	8.312	15.66

Table 20: The impact of the change in the stator reactance on the value of $R_{fcl\min}$

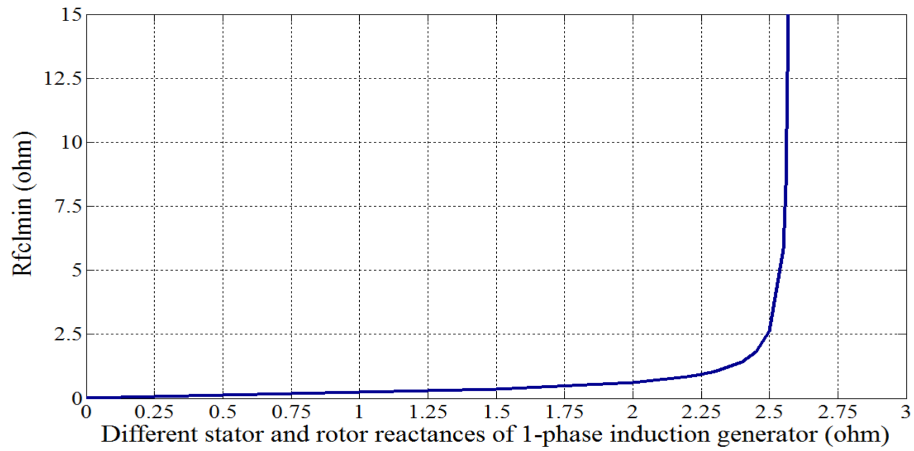


Figure 6- 25: The impact of the changes in the parameters Xs & Xr on the $R_{fcl\min}$

The results above as in table 17 and 18 and shown in Figure 6- 25 can clearly illustrate that the change in the stator and rotor parameters of single-phase induction microgenerators would lead to a significant change in the required value of $R_{fcl\min}$. It can be seen that higher reactances would require higher $R_{fcl\min}$, and the relationship between the $R_{fcl\min}$ and Xs and Xr is nonlinear. After Xs+Xr reaches 2.5Ω, any a slight increase in the reactances would lead $R_{fcl\min}$ to be very large, and unrealistic $R_{fcl\min}$ values compared to the actual RSFCL resistance profile as depicted in Figure 6- 14 has been experienced when Xs+Xr is equal to 2.57Ω. While the increase in the value of the machine stator resistance has led to gradual decrease in $R_{fcl\min}$ as in Table 19.

The results from Figure 6- 24 and Figure 6- 25 can explain that the $R_{fcl\min}$ of RSFCL limiter would be significantly impacted by the grid impedances and the machine characteristics.

6.8.5 Validation of the mathematical approach (32) to identify $R_{fcl\min}$

To validate the approach developed in section 6.5 and described by equation (51), the same four machines with practical data as explained in section 6.8.3 are used within the repeated simulation studies to identify the values of $R_{fcl\min}$, and these values are compared to the $R_{fcl\min}$ calculated from (51). Table 21 contains all the values of $R_{fcl\min}$ obtained by the mathematical equations by using steady state machine parameters, and contains the values of $R_{fcl\min}$ obtained from transient studies of the four machines.

Rating	1.5kVA	1hp	700W	1.1Kw
$R_{fcl\min}$ (Ω) from the simulation studies	1.19	1.31	1.22	1.485
$R_{fcl\min}$ (Ω) calculated from the approach (51)	1.561	1.65	1.621	1.76
Error %	23	20	24	15.6

Table 21: The minimum required values of $R_{fcl\min}$ to maintain the stability of LV connected 1-phase induction microgenerators

It is clear from the results in Table 21 that the values of $R_{fcl\min}$ across the two methods the repeated transient stability studies and the analytical approach are similar but the difference is not negligible. The source of the difference is mainly because of the following reasons. In the mathematical approach a steady state equivalent circuit model is used to represent the machine, and also the values of the magnetizing reactances are neglected during the derivation of the approach for reasons of simplicity. While for the transient simulation studies a detailed transient model of the machine and a typical distribution network is used for determining the value of $R_{fcl\min}$.

The simulation results have proven that the developed mathematical method has acceptable feasibility for identifying the minimum required resistance that needs to be reached by the limiter in order to maintain the transient stability of LV connected microgeneration. The error between $R_{fcl\min}$ calculated from the mathematical method and $R_{fcl\min}$ obtained from the simulation is in such a direction that stability is not impaired. This can be explained from Table 21 where the calculated $R_{fcl\min}$ is higher than the obtained $R_{fcl\min}$ from the studies for all four microgenerators, and this means if the calculated $R_{fcl\min}$ is used instead of $R_{fcl\min}$ obtained from the simulation, the transient stability of tested microgenerators still can be improved. Therefore, the resulted error here is, however, not a significant deterrent to the validity of the analytical approach.

The obtained results from the approach are still considered acceptable, and the advantages of the analytical method outstrip the observed disadvantages. These are summarised below:

- The proposed analytical approach is based on equation solution and not trial-and-error simulation studies. Therefore, it is no longer dependent on digital transient simulation programs and detailed microgeneration transient models. Solution speed is therefore significantly improved compared to consuming time in modelling and running and repeating simulation studies several times, and hence reducing the time required for each investigation.

- For the analytical approach only steady state machine data is required, while a full set of transient data is needed for the alternative simulation based method. Since the obtained results from the approach in relative to simulation results are acceptable, this gives another advantage of using the approach in terms of simplification of data requirements.

- Another advantage that makes the analytical approach preferable as a simple guide to identify $R_{fcl\min}$ is, only limited parameters are required. The approach can also give an indication about the suitable RSFCL for different distribution systems based on the system parameters.

The main limitation of the approach is; for example if the RSFCL is design based on a certain size of machine, and the customer has changed his generator with different characteristics, then the already calculated $R_{fcl\min}$ may not provide the same transient stability performance for the new machine. Therefore, when $R_{fcl\min}$ is determined it should consider the smallest typical size of machines that are expected to be connected at domestic level.

6.9 Balancing the benefits of using RSFCLs and the added cost

The studies in chapters three and five have shown that there are two sources of the problem when the system incorporated with heavy level of microgeneration and operates under fault conditions. One is the contribution of microgeneration to the prospective fault current which can lead to fault level issues in urban network examples. The other is the impact of the network performance during fault conditions on the transient stability of LV connected microgeneration units, where unnecessary disconnection of large penetration of such units was experienced in the studies. In G83 under the network design consideration section, it has been stated that in the event that the connection of new small scale embedded generation causes or is expected to cause operational difficulties for the DNO, the DNO in co-operation with the Installer/Manufacturer shall agree how the best to alleviate these difficulties [6.37]. So, problems caused by adding new microgeneration would greatly make it imperative that the existing distribution systems require some reinforcement so that the uptake of microgeneration can be motivated. Therefore, using RSFCL as a remedial measure to mitigate the problems associated with connecting a large amount of microgeneration will benefit both, the system operator and the microgenerator owner by providing the following benefits:

- Curtailing the increased fault level. This can have technical and economic benefits by reducing the stress on the system and protecting the system. In addition, enabling the use of equipments with lower short circuit rating and smaller size, so save in the cost of the equipment and in the cost of the space can be made. Additional cost saving can be achieved by elimination or reduction of the replacement of system equipments.

- Improving the power quality by limiting the expansion of the disturbances and mitigating the voltage dips on the system.

- Supporting the stability of the system by improving the fault ride through capabilities of a large penetration of microgeneration distributed across the low voltage systems. This will maximise the benefits of microgeneration by avoiding their unnecessary trip, so the impact of their tripping on the system can be avoided, the hours of totally depending on electricity from the grid will be reduced (i.e. more money could be saved), and the trust in such technologies could be increased. In addition, keeping renewable and low carbon microgeneration to be connected as long as possible will potentially contribute to the saving in primary energy and tackling climate change.

- Improving the system reliability by avoiding the split systems.

However, the benefits provided by the RSFCL should be balanced in practice with the cost of installing the limiters. According to the US Department of Energy (DOE), utilities pay hundreds of millions of dollars each year to maintain and add new circuit breakers to their systems to protect their grids [6.38]. The DOE believes that investing in smart technology such as FCL can save billions of dollars on transmission and distribution equipments [6.38]. In addition, fault level managed by FCL could save up to 30% of the capital investment compared to other measures [6.30]. Also, when the limiter is installed in an urban distribution network, the high cost of space for installing higher rating equipment can be reduced. So the utilities would benefit from installing SFCL. Some companies have already started installing SFCLs into medium voltage (11kV) substations in order to optimize the performance and the safety of the local power network [6.39]. This can justify the usage of RSFCL as a remedial to enhance the transient performance of distribution networks incorporating a large amount of local generation. Also taking account during the limiter design of the values of $R_{fcl\min}$ that is required for stability enhancement to be included in the limiter resistance time characteristics will increase the benefits of the limiter, and hence the cost may be justified. So since the benefits are shared between the utilities and the owner of local generation the question is who will pay for this new added component?

Under the general arrangement section of Engineering Recommendation G59/1 (i.e. recommendation for the connection of the embedded generation to the public electricity system) has clearly reported that if it is necessary for a DNO to provide extra electrical plant, or for any other works to be carried out to enable the installation of embedded generation, the DNO may require payments in respect of any expenditure incurred in carrying out this work [6.40]. So if there is fault level issue caused by adding local generation, the DNOs may see the problem comes from the customers who own generators. On the other hand, if numbers of customers' generators are disconnected due to remote faults on the system, the customers would say why my generator is disconnected due to someone else fault? So this question would be open, and could be investigated in further research on how to share the cost based on the level of the gained benefits.

6.10 Chapter summary

On the strength of the results of this chapter, the MV distribution networks can be equipped with resistive- type superconducting fault current limiters (RSFCLs) to help the increased fault level to be controlled and at the same time help microgeneration cope with external transient disturbances on remote locations of the host network. In addition to limiting fault currents, the results of the studies have proven that RSFCL can significantly improve the transient stability of LV-connected microgeneration. In order to achieve that the investigation of the chapter has found that the most appropriate locations of RSFCLs to be deployed to the network is at MV substations in series with outgoing MV feeders. The RSFCLs at such locations have shown a considerable improvement in the cells resilience levels by providing additional headroom against switchgear short-circuit ratings, and at the same time limiting the impact within the faulted cell and providing improved voltage sag performance to consumers connected to unfaulted cells.

The effectiveness of the RSFCLs located at the ongoing MV feeders on the microgeneration transient performance were tested by using developed transient models including RSFCL transient model based on real data of its resistance profile. Informative transient studies were conducted, and the results have shown that the RSFCL is a significant device that can enhance the fault ride through capabilities of small scale microgenerators during remote faults. The device could be seen as an important element that may take a place in the future power grids for improving distribution networks transient performance if the benefits and cost are balanced.

A new mathematical approach was developed in this chapter in order to determine the minimum required value of the resistive element of the resistance time curve of RSFCL by which the transient stability of downstream connected single-phase induction microgenerators can be improved. The approach is based on equation solution, and it was developed to determine the value of $R_{fcl\min}$ when the machine reached its critical speed. The value of $R_{fcl\min}$ would be determined by the system parameters and machine steady state parameters. The results have shown that when the resistance of the RSFCL was equal to $R_{fcl\min}$, a damping torque on the machine during the fault was applied, and this could hold the machine speed to be within the stability limit until the fault is cleared. This has assured that the post-fault electric torque to be always equal or higher than the mechanical torque, so there was no impact of the fault duration on the machine transient performance when $R_{fcl} > R_{fcl\min}$. When $R_{fcl} < R_{fcl\min}$, the limiter has presented a very limited impact on the microgeneration transient stability improvement, and the machine performance was highly dictated by the fault duration.

The mathematical method was tested on different single-phase induction machines with different parameters, and the method was validated by using the time-domain PSCAD/EMTDC simulation. The calculated $R_{fcl\min}$ from the method and simulated results compared and found to be close. The obtained results have shown that using the developed mathematical approach is an effective method to calculate $R_{fcl\min}$ and reduce the reliance on detailed transient models and studies to calculate $R_{fcl\min}$. However, because the error between the $R_{fcl\min}$ calculated from the approach (51) and the $R_{fcl\min}$ obtained from the simulation studies is about 20%, so it should be realised that further improvement for the mathematical approach is necessary to reduce such error that has resulted.

6.11 Chapter References

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Chapter Seven: Conclusions and future work

7.1 Conclusions

Moving to a low carbon environment, and reducing the reliance on large thermal power plants, whilst at the same time improving the sustainability of power systems, has motivated an increased interest in the integration of distributed energy resources (DERs) including microgeneration. Adding a high penetration of such technologies to a power system that has not been designed to accommodate such devices will bring a great change to the configuration of the host system. It becomes vital for such substantial amounts of microgeneration among other decentralised resources to be controlled so the local constraints are removed and the wider system is supported by the new devices aggregated response. In addition, for the support to be realised the characterisation behaviour of such penetrations requires to be understood under different system conditions to ensure benefits of DERs to be delivered.

Therefore in order to maximise the benefits of DERs, and minimise the adverse impacts that DERs may have on the system performance, this thesis presented three main contributions to support future attainment of sustainable power systems. Firstly a new conceptual control structure for a system incorporating a high penetration of DERs was developed. Secondly, the resilience level of an urban distribution network accommodating large amount of microgeneration as well as the resilience levels of microgeneration during large transient disturbances was evaluated and quantified. This included the increased fault level due to the presence of microgeneration, the impact of LV connected microgeneration on traditional LV protection performance, and the transient stability issues of LV connected microgeneration. Thirdly, a network technical solution that can support enhanced transient stability of a large number of LV connected microgenerators was introduced and demonstrated.

The system control structure based on a cell concept was proposed in the thesis as an alternative approach that can facilitate the management of the spread of heavy volumes of distributed energy resources (DERs). The proposed control structure built in hierarchical form consists of four main control levels starting from an individual device control level up to multi-cell control levels. Such hierarchical structure increases the possibility of exploiting the useful ancillary services features of local DER units in support of local and wider system. The structure also provides better coordination between DERs by allowing the inputs from DERs and groups of cells to be transferred as collective actions when it moves from a local to a wider system level.

Under fault conditions the impact of different penetrations of domestic and commercial scale microgeneration on the fault level of a typical HV-LV urban distribution network based on actual data was quantified. The results have proven that when the microgeneration have met 100% of the local domestic average load of the network, the fault level was increased by 24% of its original value at the main LV bus. Such increase forced the typical network to operate very close to its limit by lowering the fault level headroom from 26.28% to 8.2%. 65% of the contribution to the increase in the fault level was made by local microgeneration connected to the faulted cell, and the rest caused by microgeneration connected to the other adjacent LV cells. When larger microgenerators of commercial scale were added to the network with different penetrations, the available fault level headroom was significantly reduced to 2.3% when the penetration reached 100% of commercial average loads. From studying the impact of different penetrations of microgeneration on the fault level at the secondary LV bus, it has been found that the relationship between the microgeneration penetration and increased fault level is linear. Each 1kVA increase in local generation will lead to 0.0042MVA increase in the fault level at the main bus of the LV secondary substation.

Operating distribution networks very close to their short circuit limits due to lowering significantly their fault level headrooms by the connection of microgeneration (i.e. reduction up to 2/3 found by the studies based on actual data) stresses the network resulting in shorter component lifetimes to be experienced. This will increase the cost associated with connection of microgeneration as well as the cost of the space which can be an issue in urban substations. Therefore operating close to the short circuit rating can obstruct the spread of more microgeneration uptake at LV and DGs at MV level. For safe operation and to avoid setting-back the growth of microgeneration across LV distribution networks, managing the increase in the fault level due to microgeneration integration must be introduced.

The protection issues associated with an urban example of low voltage distribution network with a high penetration of microgeneration were outlined by the studies of the thesis. The obtained results have shown that with the existing arrangement of LV protection schemes, microgeneration can cause numbers of protection issues during upstream faults. For upstream faults, the results have shown that when the upstream fault on the main LV bus is cleared from the grid side, the downstream microgeneration continue to supply the fault by reverse fault current. The reverse fault current has led to blowing the feeder fuse within 5 seconds when 100% penetration of microgeneration was connected. So, downstream microgeneration must be disconnected before this time for such load, otherwise a healthy feeder can be disconnected and extra fuse can be lost due to nuisance blowing.

The minimum amount of microgeneration penetration that can cause the reverse fault current to exceed the fuse threshold current was identified by the studies to be 47% of microgeneration, and this penetration will require about 15 minutes for blowing the fuse. If the microgeneration do not themselves sense the loss of the grid, then safety issue can be caused by feeding the fault on the system for a long period of time. If the amount of microgeneration is less than 47%, the fuse will not detect the reverse fault current and the fault would be supplied until the microgeneration trip by their own protection. Supplying upstream faults by reverse current for a few seconds can also cause a delay in the restoration time, by impacting the quick reconnection of the system by the reclosers used for quick removal of temporary faults. This may impact sensitive equipment connected to the system. Furthermore, if the reverse current caused LV fuses to blow the time of the power cut will increase due to the request to replace the fuse unit. This can cause issues of undesirable features for future systems where sustainability of supply and the ability of privately owned generators to provide local energy needs during the power outage are one of future power systems objectives, and yet these would be countered by these effects.

The transient performance of a range of technologies of LV connected small scale microgeneration in response to realistic urban distribution network faults applied at different locations was examined. Two types of technologies were considered: a small scale CHP driving a three-phase synchronous machine connected within commercial premises; and a small microwind turbine interfaced directly within residential dwellings by a single-phase induction generator. The studies outlined under which circumstances such technologies with low inertia and limited controllability can be unnecessarily tripped due to unstable performance caused by system fault conditions.

The studies found that the transient stability of microgeneration is detrimentally affected by MV remote faults on urban distribution networks more than local faults. Local faults can be cleared very fast due to the low operating time of downstream protection, and their impact is limited to very limited number of microgenerators. While MV remote faults on urban networks at two different locations at the main MV bus and at remote location from the MV bus led to large voltage dips on the LV circuits resulting in instable performance of all the LV connected microgeneration interfaced by single-phase induction generators and meeting 90% of the local domestic average loads. It was observed that all these microgeneration will go unstable following the remote fault within 79-83msec. This is 17 to 21% less time than typical protection operating time. This was compared to a typical operating time of upstream protection devices at MV side equal to 100msec based on utilities experience.

The nuisance tripping as consequence of microgeneration instability due to remote MV faults has imposed numbers of issues including the result in impaired local power quality due to voltage fluctuation. Simultaneous disconnection and reconnection of microgeneration meeting 90% of the local load has impaired the network voltage at the main bus of the secondary substation (i.e. LV bus) by forcing voltage unbalance and voltage steps to be very close to the allowed limits identified in Engineering Recommendation P28 and P29. When all the amount of the LV connected microgeneration tripped due to instability caused by remote faults and reconnected simultaneously, the voltage step reached -2.3% which is just 0.7% under the normal limits.

The effect of the spread of reconnection time on the voltage of the LV bus at the secondary substation has also been demonstrated, and the results of the thesis studies have found that the intervals of reconnecting large numbers of microgenerators are very important. When the total amount of microgeneration is reconnected during spread of reconnection time, the impact on the local voltage profile is less compared to simultaneous reconnection if the intervals between the reconnections are larger than the starting time of the already connected microgeneration. When a high penetration of microgeneration is reconnected during the starting of other already connected microgeneration interfaced by induction machines where a large reactive power will be drawn, the larger voltage steps will emerge. Therefore, if a large penetration of microgeneration is disconnected due to unstable performance and reconnected again within very short period of time (i.e. during the starting period), the interaction between the already connected microgeneration and still starting and the new reconnected microgeneration can lead to voltage steps to become an issue, and degradation in the quality of the supply may emerge. To avoid such operation, microgeneration with a high penetration should be reconnected within suitable intervals.

To reduce the impact of remote faults at MV level on the microgeneration transient performance, the thesis proposed a network solution based on using superconducting fault current limiters (RSFCLs). The thesis has found that the most appropriate locations of the limiters to be deployed to the network to improve microgeneration transient stability are at MV substations in series with outgoing MV feeders. The limiters at these locations can significantly help the increased fault level to be controlled by providing additional headroom against switchgear short-circuit ratings, and at the same time help downstream connected microgeneration cope with external transient disturbances on the remote locations of the host network. The effectiveness of the RSFCLs on fault level limitation and microgeneration transient stability improvement were tested by conducting informative transient studies by using developed microgeneration transient models and RSFCL transient model with real resistance-time characteristics. The results of the studies have shown that the limiter can provide a reduction factor in the fault current ($I_{fault} / I_{\lim ited}$) up to 1.4 of the fault current peak make and 3.09 of the fault current peak break. This in turn will lead to numbers of advantages such as reducing the stress of the heat on the protected system component which helps the component to last longer, and reduces the need for larger component with larger rating, so smaller space will be required and the cost of land which is a significant issue in urban areas can be reduced. In addition, reduction in the fault current resulting in reduction in the voltage dips on the nearby areas to the fault location, and this can be seen as a significant measure to improve system power quality.

Using RSFCL as a solution to provide improved voltage sag performance to consumers connected to unfaulted cells has been shown to significantly enhance microgeneration stability and ensure they ride through remote faults. By using an example of RSFCL with resistance-time curve based on real data, the results of transient studies have shown that the transient stability of LV connected microgeneration has been significantly improved following remote faults. This is because the rise in the limiter resistance during the fault duration will improve the retained voltage on the microgenerators terminals. Improved terminals voltage and machines rotor speed are intrinsically related, and hence the acceleration in rotor speed of single-phase induction microgenerators is reduced when terminal voltages are improved. Improving the resilience level of the faulted cell by using RSFCL will improve the fault ride through capabilities, and hence no massive disconnection of microgeneration will happen due remote faults, and power quality issues caused by voltage steps can be avoided.

In order to ensure RSFCL will provide the required retained voltage, and hence a damping torque on microgenerators interfaced by single-phase induction generators to be applied during remote faults and stability to be maintained, the thesis has introduced a new mathematical approach to determine at which condition RSFCL can maintain the transient stability of LV connected microgeneration by calculating the minimum required value of the resistive element of RSFCL ($R_{fcl\min}$) to meet such purpose. The approach is based on equation solution, and it can be used to determine the value of $R_{fcl\min}$ from the host system parameters and microgenerator steady state parameters. $R_{fcl\min}$ is calculated from the developed approach when the machine reaches its critical speed, so as soon the resistance-time curve of RSFCL reaches this value the transient stability of the connected induction microgenerator is maintained regardless the fault duration.

The results from the transient studies have shown that when the resistance of the RSFCL is equal to $R_{fcl\min}$, a damping torque on the machine during the fault is applied, and this makes the machine speed to be within the stability limits until the fault is cleared. The $R_{fcl\min}$ has assured that the post-fault electric torque to be always equal or higher than the mechanical torque, and whenever the fault is cleared the stability will be maintained.

The mathematical approach to identify $R_{fcl\min}$ of RSFCL has been tested on different single-phase induction machines with different parameters, and the method has been validated by comparing the effectiveness of calculated $R_{fcl\min}$ from the approach to $R_{fcl\min}$ obtained by trial-and-error from detailed simulation transient studies by using the time-domain PSCAD/EMTDC simulation program. The calculated $R_{fcl\min}$ from the method and simulated results compared and found to be close. The obtained results have shown that using the developed mathematical approach is an effective method to calculate $R_{fcl\min}$.

The developed method to determine $R_{fcl\min}$ has offered numbers of advantages such as; a simple method to identify the resistance required to be developed by the limiter to ensure the transient stability of a large penetration of downstream connected microgeneration, and this will offer another added function of RSFCL by improving local system transient performance as well as fault level control. Another advantage of the method is to offer recommendation of the characteristics of the limiter that will suit a certain system to ensure the stability of LV microgeneration. This is because the analysis has shown that different systems with different short-circuit grid impedances will require different $R_{fcl\min}$ to maintain the stability of the connected microgeneration. In addition, the approach reduces the reliance on detailed transient models and informative transient studies to calculate $R_{fcl\min}$. By using the developed method to calculate $R_{fcl\min}$ and ensuring the RSFCL response during the fault reaches the required value, failure to clear remote faults quickly are no longer result in complete unnecessary disconnection of substantial amount of microgeneration connected to low voltage distribution networks. Furthermore, the impact of this method is to help RSFCL designers to consider the required transient characteristics of RSFCL for system transient stability improvement rather than just considering the characteristics that suit fault level limitations.

By proposing a new system control structure based on a cell concept as one of the solutions that can deliver the objectives of future power systems, and understanding the transient behavioural characteristics of a system incorporating a high penetration of microgeneration and quantifying the resilience level of the microgeneration that can be connected at LV level, and introducing a network solution based on using RSFCL to improve the transient stability of large amount of LV connected microgeneration the thesis has offered very valuable contributions that can support future sustainable power systems.

7.2 Future work

Based on the work presented in this thesis, the following points summarise the future work that can be conducted to increase the uptake of more renewable and low carbon microgeneration which has the potential to contribute positively to future sustainable power systems:

1- Demonstrating the cell concept by developing necessary dynamic decentralised control measures by which the negative impacts of local generation and dynamic loads on the system transient performance are minimised.

2- Evaluating the extent of the impact of tripping a high penetration of microgeneration on the system wide stability. Two emerging areas that may potentially be affected by microgeneration response under transient disturbances that require further research are: system frequency stability issue, and system transient stability issues.

   The impact of microgeneration response during transient disturbances on low frequency events is important to be understood in order to protect a large number of consumers from being disconnected by lowering the frequency further and initiating under frequency load shedding schemes (UFLS) due to the trip of a high penetration of microgeneration.

   In terms of system transient stability performance, most of the current approaches such as time domain simulation tools to analyse transient stability phenomena and identify the system transient stability boundaries use classical models to represent the system generators and constant impedances to represent the system loads. When large amount of microgeneration are added to distribution systems, such assumption may not be valid since the devices will impact the characteristics of distribution systems. Such new characteristics may impact the wider system stability margins. So, it may become important to investigate the impact of active distribution networks with different characteristics to traditional distribution networks due to the presence of a significant penetration of microgeneration on the wider system transient stability.

3- The impact of voltage steps caused by reconnection of a high penetration of microgeneration interfaced by single-phase induction generators on the performance of instantaneous overcurrent protection of low voltage feeders would require further investigation. This is because inrush currents caused by microgeneration reconnection may cause low set instantaneous overcurrent elements to unnecessarily trip. The impact of “cold load pickup” on the instantaneous overcurrent protection has received some research, and the impact of microgeneration reconnection would be an interesting area that needs further attention in order to make sure that undesirable protection performance will not result.

4- The interaction between the impact RSFCLs on the microgeneration stability performance and the existing protection performance will need to be investigated. This is because for traditional RSFCLs applications, only the interaction between protection and fault current limitation has been considered. So it is important to ensure that the minimum required value of the resistive element of RSFCLs to improve downstream connected microgeneration will not impact the operating time of the host system protection schemes.

5- In spite of the advantages that RSFCLs can offer as has been proven by this thesis, the devices are still considered as expensive elements. Therefore, balance between the cost and the benefits of RSFCLs needs further investigation so the cost can be justified, and how to share the cost based on the level of the gained benefits can be proposed.

Appendix A: The parameters of 28kVA 3-phase synchronous generator

Ta (s)	H (s)	Xd pu	Xd' pu	Xd'' pu	Td0' (s)	Td0'' (s)	Xq pu	Xq'' pu	Tq0'' (s)	X1 pu
0.0049	1	2.637	0.269	0.172	0.338	0.0307	1.335	0.301	0.041	0.054

Table 22: The impedances and time constants parameters of 28kVA 3-phase synchronous generator

AC1A Exciter Parameters	Values
Regulator gain (KA)	400 pu
Regulator time constant (Ta)	0.02s
Max reg. internal voltage (Vamax)	14.5 pu
Min reg. internal voltage (Vamin)	-14.5 pu
Max reg. output voltage (Vrmax)	3.95 pu
Min reg. internal voltage (Vrmin)	-3.85
Rate feedback gain (KF)	0.03 pu
Rate feedback time constant (T_F)	1.0 s
Exciter time constant (T_E)	0.80 s
Exciter constant related to field (KE)	1.0 pu
Field circuit commutating reactance	0.2 pu
Demagnitizing factor (KD)	0.38 pu
Saturation at VE1 (SE(VE1)	0.1 pu
Exciter voltage for SE1 (VE1)	4.18 pu
Saturation at VE2 (SE(VE2)	0.03 pu
Exciter voltage for SE1 (VE2)	3.14 pu

Table 23: AC1A Exciter Parameters

Woodward governor parameters	values
Gain G	1
Lead time constant T	0.25s
Lag time constant T	0.039s
Time constant of the actuator T	0.009s
Engine time delay (Td)	0.025s

Table 24: Woodward governor parameters

Appendix B: Transient model details of single-phase induction machine

The basic equations of single-phase machine stator and rotor voltages:

Voltage equations of the main and auxiliary windings can be written as follows:

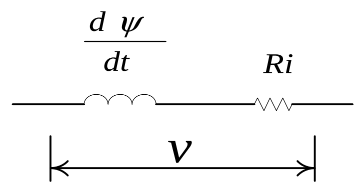

Figure 1: Voltage across winding carrying ac current

$$V_{ms} = p\psi_{ms} + R_{ms} i_{ms} \tag{58}$$

$$V_{as} = p\psi_{as} + R_{sa} i_{as} \tag{59}$$

V_{ms} is the voltage across the stator main winding.

V_{as} is the voltage across the stator auxiliary winding .

ψ is the flux linkage of the winding indicated by subscript ms for the main, and as for the auxiliary of the stator.

R_{sm} is the stator main winding resistance.

R_{sa} is the stator auxiliary winding resistance.

p is the differential operator d/dt.

The flux linkage equations of the stator main and auxiliary winding can be derived as follows:

The flux linkage of stator main windings:

$$\psi_{ms} = L_{msms} i_{ms} + L_{msmr}(i_{mr} \cos\theta_r) + L_{msar}(i_{ar} \cos(\frac{\pi}{2} - \theta_r)) \tag{60}$$

$$\psi_{ms} = L_{msms} i_{ms} + L_{msmr}(i_{mr} \cos\theta) - L_{msar}(i_{ar} \sin\theta) \tag{61}$$

Where, L_{msms} is the self-inductance of the stator main winding.

L_{msmr} is the mutual inductance between the stator main winding and the rotor winding referred to the stator main winding.

L_{msar} is the mutual inductance between the stator main winding and the rotor windings referred to the stator auxiliary windings.

The flux linkage of stator auxiliary windings:

$$\psi_{as} = L_{asas} i_{as} + L_{asms} i_{ms} + L_{asmr} (i_{mr} \cos(\frac{\pi}{2} - \theta) - L_{asar} i_{ar} \cos\theta \qquad (62)$$

$$\psi_{as} = L_{asas} i_{as} - L_{asmr} (i_{mr} \sin\theta) + L_{asar} (i_{ar} \cos\theta) \qquad (63)$$

Where L_{asas} is the self-inductance of the stator auxiliary winding.

L_{asmr} is the mutual inductance between the stator auxiliary winding and the rotor winding referred to the stator main winding.

L_{asar} is the mutual inductance between the stator auxiliary winding and the rotor windings referred to the stator auxiliary windings.

It is assumed that the current induced in the shorted rotor windings produce a field with the same number of poles as that produced by the stator. So, rotor winding is considered to be modelled of the same number of stator windings (i.e. main and auxiliary windings). The rotor voltage equations and rotor flux linkage can be written as follows:

Voltage equations of the rotor windings referred to the main and auxiliary windings:

$$V_{mr} = p\psi_{mr} + R_{mr} i_{mr} \qquad (64)$$

$$V_{ar} = p\psi_{ar} + R_{ar} i_{ar} \qquad (65)$$

R_{mr} is the main winding rotor resistance.

ψ_{mr} is the flux linkage of the rotor main winding.

R_{ar} is the auxiliary winding rotor resistance.

ψ_{ar} is the flux linkage of the rotor auxiliary winding.

Flux linkage equations of the rotor referred to main and auxiliary:

$$\psi_{mr} = L_{nrnr} i_{mr} + L_{mrms} i_{ms} + L_{mras} i_{as} \qquad (66)$$

$$\psi_{ar} = L_{arar} i_{ar} + L_{arms} i_{ms} + L_{aras} i_{as} \qquad (67)$$

The d-q transformation

The following mathematical equations reflect transformations of the ab variables to d-q frame values applied to the single phase induction generator. The variables represent voltages, currents and the flux linkages. All q variables refer to the main winding and d variables to the auxillary winding.

For the stator quantities:

$$\begin{bmatrix} V_{qs} \\ V_{ds} \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} \begin{bmatrix} V_{as} \\ V_{bs} \end{bmatrix} \tag{68}$$

For the rotor quantities:

$$\begin{bmatrix} V_{qr} \\ V_{dr} \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ -\sin\theta_r & -\cos\theta_r \end{bmatrix} \begin{bmatrix} V_{mr} \\ V_{ar} \end{bmatrix} \tag{69}$$

All the quantities are referred to the stator main and the auxiliary winding axes.

Stator main (ms) and auxiliary winding (as) transformation to d-q components

V_{qs} is on the same axis of the main winding, and V_{ds} is on the same axis of the auxiliary windings, and the angle between the main and the auxiliary winding axis is 90°. Thus the currents, voltages and flux linkage variables of the stator main and auxiliary windings can be transformed to d-q axes as follows:

Currents:

$$i_{qs} = i_{ms} \tag{70}$$

$$i_{ds} = -i_{as} \tag{71}$$

Flux linkages:

$$\psi_{qs} = \psi_{ms}$$

$$\psi_{ms} = L_{msms} i_{ms} + L_{msmr}(i_{mr}\cos\theta) - L_{msar}(i_{ar}\sin\theta)$$

$$\psi_{qs} = L_{msms} i_{qs} + L_{msmr}(i_{mr}\cos\theta) - L_{msar}(i_{ar}\sin\theta) \tag{72}$$

$$\psi_{ds} = -\psi_{as}$$

$$\psi_{ds} = L_{asas} i_{ds} + L_{asmr}(i_{mr}\sin\theta) + L_{asar}(i_{ar}\cos\theta) \tag{73}$$

Voltages:

$$V_{ms} = p\psi_{ms} + R_{ms} i_{ms}$$

$$V_{as} = p\psi_{as} + R_{as} i_{as}$$

$$V_{qs} = V_{ms} = R_{ms} i_{ms} + p\psi_{ms}$$

$$V_{ds} = -V_{as} = -R_{as} i_{as} - p\psi_{as}$$

$$V_{qs} = R_{ms} i_{qs} + p\psi_{qs} \tag{74}$$

$$V_{ds} = -R_{as} i_{ds} - p\psi_{ds} \tag{75}$$

Rotor main (mr) and auxiliary winding (ar) transformation to d-q components

The rotor of an induction machine does not have a fixed speed, and the d-q transformation for the rotor quantities should consider this fact. As mentioned aearly in this section, the θ_r is the angle by which the rotor winding axis leads q-axis. If the rotor rotates at slip *S*, then the rotor speed is equal to $S\omega_s$. So the speed will impact the angle between the rotor main winding and the q axis winding. The relationship between the induction machine rotor speed and this angle can be found from the equation below.

$$\frac{d\theta_r}{dt} = S\omega_s = p\theta_r = \omega_r \tag{76}$$

$$\theta = \omega_s t - \theta_r \tag{77}$$

By using the transformation of rotor quantities referred to the main and auxiliary of the stator to d-q frame of single phase machine as in (65) the d-q rotor currents, voltages and flux linkages can be written as follows:

d-q rotor currents components:

$$i_{qr} = i_{mr} \cos\theta_r - i_{ar} \sin\theta_r \tag{78}$$

$$i_{dr} = -i_{mr} \sin\theta_r - i_{ar} \cos\theta_r \tag{79}$$

d-q rotor flux linkage components:

$$\psi_{qr} = \psi_{mr} \cos\theta_r - \psi_{ar} \sin\theta_r \tag{80}$$

$$\psi_{dr} = -\psi_{mr} \sin\theta_r - \psi_{ar} \cos\theta_r \tag{81}$$

Where $\psi_{mr} = L_{nrnr} i_{mr} + L_{mrms} i_{ms} + L_{mras} i_{as}$ and $\psi_{ar} = L_{arar} i_{ar} + L_{arms} i_{ms} + L_{aras} i_{as}$

d-q rotor voltages components:

$$V_{qr} = R_{mr} i_{qr} + p\psi_{qr} + p\theta_r \psi_{dr} \tag{82}$$

$$V_{dr} = R_{ar} i_{dr} + p\psi_{dr} + p\theta_r \psi_{qr} \tag{83}$$

Appendix C: Transient paramaeters of single-phase induction machines

V=230, N=1, and the number of the poles =4

kVA	*Rqs* (*Ω*)	*Rds* (*Ω*)	*Rqr* (*Ω*)	*Rdr* (*Ω*)	*Xqs* (*Ω*)	*Xds* (*Ω*)	*Xqr* (*Ω*)	*Xdr* (*Ω*)	*Xmqs* (*Ω*)	*Xmds* (*Ω*)	J Kg.m2
1kVA	4	4	3.29	5	4.5	6.95	6.95	6.95	135	77	0.0146
1.5kVA	2.2	7.62	1.3	3.5	5	2.5	6.95	6.95	180	100	0.029

Table 25: Tranient stability data of 1kVA and 5kVA single-phase induction machines

Data of a typical small scale wind turbin that

Average wind speed	16.5m/s
Rotor radius	1m
Rotor area	3.4m2
Air density	1.229 [kg/m^3]

Appendix D: Steady state model of single-phase induction machines

Steady state equivalent circuit of an induction machine:

During the steady state operation the transient term $p\psi$ is equal to zero. Therefore the equations of the stator d and q axes of the voltages of the transient equivelant circuit of an induction machine as discussed previously in appendix B five can be rewritten as following.

$$V_{ds} = R_s i_{ds} + p\psi_{ds} - \omega_s \psi_{qs} = R_s i_{ds} - \omega_s (L_{ss} i_{qs} - L_m i_{qr})$$
$$V_{qs} = R_s i_{qs} + p\psi_{qs} + \omega_s \psi_{ds} = R_s i_{qs} + \omega_s (L_{ss} i_{ds} + L_m i_{dr})$$

$$V_s = V_{ds} + jV_{qs} = R_s (i_{ds} + ji_{qs}) + \omega_s L_{ss} (ji_{ds} - i_{qs}) + \omega_s L_m (ji_{dr} - i_{qr})$$

$$V_s = R_s (i_{ds} + ji_{qs}) + j\omega_s L_{ss} (i_{ds} + ji_{qs}) + j\omega_s L_m (i_{dr} + ji_{qr}) = R_s I_s + j\omega_s L_{ss} I_s + j\omega_s L_m I_r$$

By adding the term $jL_m I_s$ *and* $- jL_m I_s$ to the equation the Vs will be equal to

$$V_s = R_s I_s + j\omega_s (L_{ss} - L_m) I_s + j\omega_s L_m (I_s + I_r)$$

The steady state voltage of the stator will be equal to

$$V_s = R_s I_s + jX_s I_s + jX_m (I_s + I_r) \qquad (84)$$

Where R_s is the stator, $X_s = \omega_s (L_{ss} - L_m)$ is the stator leakage reactance, and $X_m = \omega_s L_m$ is the magnetizing reactance.

The rotor d and q voltages Vdr and Vqr are equal to zero since the rotor circuits are shorted, therefore the d and q voltages can be written as follows:

$$V_{dr} = 0 = R_r i_{dr} - S\omega_s \psi_{qr} = R_r i_{dr} - S\omega_s (L_{rr} i_{qr} - L_m i_{qs})$$

$$V_{qr} = 0 = R_r i_{qr} + S\omega_s = R_r i_{qr} + S\omega_s (L_{rr} i_{dr} + L_m i_{ds})$$

$$V_r = V_{dr} + jV_{qr} = 0 = R_r (i_{dr} + ji_{qr}) + jS\omega_s L_{rr} (i_{dr} + ji_{qr}) + jS\omega_s L_m (i_{ds} + ji_{qs})$$

Dividing the equation by the slip S

$$V_r = V_{dr} + jV_{qr} = 0 = \frac{R_r}{S} I_r + j\omega_s L_{rr} I_r + j\omega_s L_m I_s$$

$$V_r = \frac{R_r}{S} I_r + j\omega_s (L_{rr} - L_m) I_r + j\omega_s L_m (I_s + I_r)$$

$$V_r = \frac{R_r}{S} I_r + jX_r I_r + jX_m (I_s + I_r) \qquad (85)$$

Where R_r is rotor resistance and $X_r = \omega_s (L_{rr} - L_m)$ is the rotor leakage reactance.

From the equations (84) and (85) the steady state equivalent circuit with all the values referred to the stator can be drawn as in the figure below.

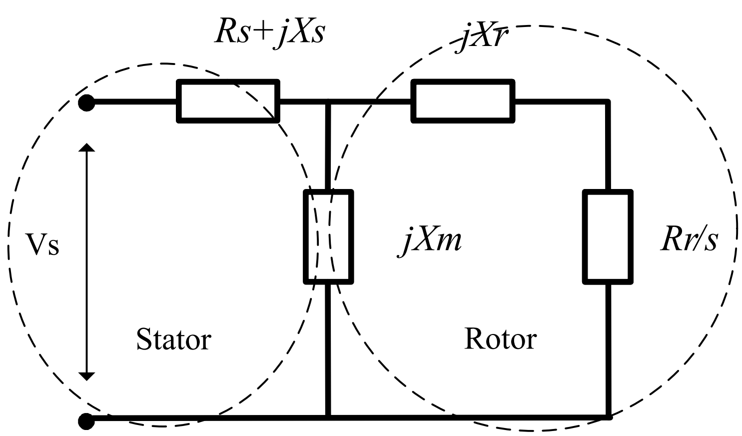

Figure B- 1: The steady state equivalent circuit of an induction machine

The power transferred across the air-gap is $P_{ag} = \frac{R_r}{S} I_r^2$, and the rotor resistance loss is equal to $P_{lr} = R_r I_r^2$.

Appendix E: Steady state and transient parameters of single-phase induction machines with different ratings

Rating	Rg (Ω)	Xg (Ω)	Xt (Ω)	Rl (Ω)	Xl (Ω)	Rs (Ω)	Xs (Ω)	Xr (Ω)	Rr (Ω)	Xm (Ω)
1.5kVA	0.018	0.2684	0.0182	0.0117	0.0035	4.03	7.38	8.92	5.98	155.4
1hp	0.018	0.2684	0.0182	0.0117	0.0035	2.87	2.282	2.211	1.49	122
700W	0.018	0.2684	0.0182	0.0117	0.0035	4.0	4.5	4.5	3.29	129
1.1Kw	0.018	0.2684	0.0182	0.0117	0.0035	2.556	2.02	1.244	3.733	152.4

Table 26: Steady state data of numbers of single-phase induction generators with different ratings used for calculating $R_{fcl\min}$ from equation (51)

Rating	Rsm (Ω)	Rsa (Ω)	Rrm (Ω)	Rra (Ω)	Xsm (Ω)	Xsa (Ω)	Xrm (Ω)	Xra (Ω)	Xsm (Ω)	Xsa (Ω)
1.5kVA	2.2	4	3.29	5	2.5	6.95	6.95	6.95	135	77
1hp	3.14	11.22	4.37	8.01	3.99	6.433	3.99	6.433	122	76.65
700W	4.0	5.0	3.4	3.4	4.5	6.95	4.5	4.5	100	90
1.1kW	2.2	7.62	3.5	1.3	3.97	2.97	0.87	0.78	32	24

Table 27: Transient data of numbers of single-phase induction generators with different ratings used with transient simulation studies to identify $R_{fcl\min}$

Appendix F: Derivative of the mathematical approach to identify the values of R_{fclmin}

By substituting the values of $V_{th\min}$ from (31) and $R_{th\min}$ and $X_{th\min}$ from (41) in (49) above the following equation is resulted.

$$\left(\frac{A_2R_{fcl}^2+B_2R_{fcl}+C_2}{(R_{fcl}+R_g)^2+(X_g)^2}\right)^2+2\frac{A_2R_{fcl}^2+B_2R_{fcl}+C_2}{(R_{fcl}+R_g)^2+(X_g)^2}(X_s+X_r)+(X_s+X_r)^2-$$
$$V_g^4\frac{R_{fcl\min}^4}{(2\omega T_m)^2[(R_{fcl}+R_g)^2+(X_g)^2]^2}+V_g^2\frac{R_{fcl\min}^2}{\omega T_m[(R_{fcl}+R_g)^2+(X_g)^2]}R_s+$$
$$V_g^2\frac{R_{fcl\min}^2}{\omega T_m[(R_{fcl}+R_g)^2+(X_g)^2]}\frac{A_1R_{fcl}^2+B_1R_{fcl}+C_1}{(R_{fcl}+R_g)^2+(X_g)^2}=0 \quad (86)$$

$$[A_2R_{fcl}^2+B_2R_{fcl}+C_2]^2+2[(R_{fcl}+R_g)^2+(X_g)^2](X_s+X_r)[A_2R_{fcl}^2+B_2R_{fcl}+C_2]+$$
$$[(R_{fcl}+R_g)^2+(X_g)^2]^2(X_s+X_r)^2-V_g^4\frac{R_{fcl\min}^4}{(2\omega T_m)^2}+$$
$$V_g^2[(R_{fcl}+R_g)^2+(X_g)^2]\frac{R_{fcl\min}^2}{\omega T_m}R_s+V_g^2\frac{R_{fcl\min}^2}{\omega T_m}[A_1R_{fcl}^2+B_1R_{fcl}+C_1]=0 \quad (87)$$

$$A_2^2R_{fcl}^4+2A_2B_2R_{fcl}^3+(2C_2A_2+B_2^2)R_{fcl\min}^2+2B_2C_2R_{fcl}+C_2^2+$$
$$2[A_2R_{fcl}^2(X_s+X_r)(R_{fcl\min}^2+2R_{fcl}R_g+R_g^2)+B_2R_{fcl}(X_s+X_r)(R_{fcl\min}^2+2R_{fcl}R_g+R_g^2)+$$
$$C_2(X_s+X_r)(R_{fcl\min}^2+2R_{fcl}R_g+R_g^2)+A_2(X_s+X_r)(X_g)^2R_{fcl}^2+$$
$$B_2(X_s+X_r)(X_g)^2R_{fcl}+C_2(X_s+X_r)(X_g)^2]+$$
$$[R_{fcl\min}^2+2R_{fcl}R_g+R_g^2+(X_g)^2]^2(X_s+X_r)^2-V_g^4\frac{R_{fcl\min}^4}{(2\omega T_m)^2}+$$
$$V_g^2[R_{fcl\min}^2+2R_{fcl}R_g+R_g^2+(X_g)^2]\frac{R_{fcl\min}^2}{\omega T_m}R_s+$$
$$V_g^2\frac{R_{fcl\min}^2}{\omega T_m}[A_1R_{fcl}^2+B_1R_{fcl}+C_1]=0 \quad (88)$$

$$\begin{aligned}
&A_2^2R_{fcl}^4+2A_2B_2R_{fcl}^3+(2C_2A_2+B_2^2)R_{fcl\min}^2+2B_2C_2R_{fcl}+C_2^2+\\
&2[A_2(X_s+X_r)R_{fcl\min}^4+2A_2(X_s+X_r)R_gR_{fcl}^3+A_2(X_s+X_r)R_g^2R_{fcl}^2+B_2(X_s+X_r)R_{fcl\min}^3+\\
&2B_2(X_s+X_r)R_gR_{fcl\min}^2+R_g^2B_2(X_s+X_r)R_{fcl\min})+\\
&C_2(X_s+X_r)R_{fcl\min}^2+2C_2(X_s+X_r)R_{fcl}R_g+C_2(X_s+X_r)R_g^2+\\
&A_2(X_s+X_r)(X_g)^2R_{fcl}^2+B_2(X_s+X_r)(X_g)^2R_{fcl}+C_2(X_s+X_r)(X_g)^2]+\\
&[R_{fcl\min}^4+2R_{fcl\min}^2(2R_{fcl}R_g+R_g^2+(X_g)^2)+(2R_{fcl}R_g+R_g^2+(X_g)^2)^2](X_s+X_r)^2-\\
&V_g^4\frac{R_{fcl\min}^4}{(2\omega T_m)^2}+V_g^2[R_{fcl\min}^2+2R_{fcl}R_g+R_g^2+(X_g)^2]\frac{R_{fcl\min}^2}{\omega T_m}R_s+V_g^2\frac{R_{fcl\min}^2}{\omega T_m}[A_1R_{fcl}^2+B_1R_{fcl}+C_1]=0
\end{aligned}\tag{89}$$

$$\begin{aligned}
&A_2^2R_{fcl}^4+2A_2B_2R_{fcl}^3+(2C_2A_2+B_2^2)R_{fcl\min}^2+2B_2C_2R_{fcl}+C_2^2+\\
&2[A_2(X_s+X_r)R_{fcl\min}^4+2A_2(X_s+X_r)R_gR_{fcl}^3+A_2(X_s+X_r)R_g^2R_{fcl}^2+B_2(X_s+X_r)R_{fcl\min}^3+\\
&2B_2(X_s+X_r)R_gR_{fcl\min}^2+R_g^2B_2(X_s+X_r)R_{fcl\min})+\\
&C_2(X_s+X_r)R_{fcl\min}^2+2C_2(X_s+X_r)R_{fcl}R_g+C_2(X_s+X_r)R_g^2+\\
&A_2(X_s+X_r)(X_g)^2R_{fcl}^2+B_2(X_s+X_r)(X_g)^2R_{fcl}+C_2(X_s+X_r)(X_g)^2]+\\
&[(X_s+X_r)^2R_{fcl\min}^4+4R_gR_{fcl\min}^3(X_s+X_r)^2+2R_{fcl\min}^2(R_g^2+X_g^2)(X_s+X_r)^2+\\
&4R_g^2(X_s+X_r)^2R_{fcl\min}^2+4R_{fcl}R_g(R_g^2+X_g^2)(X_s+X_r)^2+(X_s+X_r)^2(R_g^2+X_g^2)^2]-\\
&V_g^4\frac{R_{fcl\min}^4}{(2\omega T_m)^2}+\frac{V_g^2}{\omega T_m}R_sR_{fcl\min}^4+2\frac{V_g^2}{\omega T_m}R_sR_{fcl\min}^3R_g+\frac{V_g^2}{\omega T_m}R_sR_g^2R_{fcl\min}^2+\frac{V_g^2}{\omega T_m}R_s(X_g)^2R_{fcl\min}^2+\\
&A_1\frac{V_g^2}{\omega T_m}R_{fcl}^4+B_1\frac{V_g^2}{\omega T_m}R_{fcl\min}^3+C_1\frac{V_g^2}{\omega T_m}R_{fcl\min}^2=0
\end{aligned}\tag{90}$$

$$\begin{aligned}
&[A_2^2+2A_2(X_s+X_r)+(X_s+X_r)^2-V_g^4\frac{1}{(2\omega T_m)^2}+\frac{V_g^2}{\omega T_m}R_s+A_1\frac{V_g^2}{\omega T_m}]R_{fcl}^4+\\
&[2A_2B_2+4A_2(X_s+X_r)R_g+2B_2(X_s+X_r)+4R_g(X_s+X_r)^2+2\frac{V_g^2}{\omega T_m}R_sR_g+B_1\frac{V_g^2}{\omega T_m}]R_{fcl\min}^3+\\
&(2C_2A_2+B_2^2)+2A_2(X_s+X_r)(R_g^2+(X_g)^2)+4B_2(X_s+X_r)R_g+2C_2(X_s+X_r)+\\
&2(R_g^2+X_g^2)(X_s+X_r)^2+4R_g^2(X_s+X_r)^2+\frac{V_g^2}{\omega T_m}R_sR_g^2+\frac{V_g^2}{\omega T_m}R_s(X_g)^2+C_1\frac{V_g^2}{\omega T_m}]R_{fcl\min}^2+\\
&2B_2C_2+2R_g^2B_2(X_s+X_r)+4C_2(X_s+X_r)R_g+2B_2(X_s+X_r)(X_g)^2+4R_g(R_g^2+X_g^2)(X_s+X_r)^2]R_{fcl\min}+\\
&C_2^2+2C_2(X_s+X_r)R_g^2+2C_2(X_s+X_r)(X_g)^2+(X_s+X_r)^2(R_g^2+X_g^2)^2=0
\end{aligned}$$

$$F(R_{fcl\min}) = D_1 R_{fcl\min}^4 + D_2 R_{fcl\min}^3 + D_3 R_{fcl\min}^2 + D_4 R_{fcl\min} + D_5 = 0$$

Where the coefficients *D1*, *D2*, *D3*, *D4*, and *D5* are constants, and can be calculated from the following formulae.

$$D_1 = A_2^2 + 2A_2(X_s + X_r) + (X_s + X_r)^2 - V_g^4 \frac{1}{(2\omega T_m)^2} + \frac{V_g^2}{\omega T_m} R_s + A_1 \frac{V_g^2}{\omega T_m}$$

$$D_2 = 2A_2B_2 + 4A_2(X_s + X_r)R_g + 2B_2(X_s + X_r) + 4R_g(X_s + X_r)^2 + 2\frac{V_g^2}{\omega T_m} R_s R_g + B_1 \frac{V_g^2}{\omega T_m}$$

$$D_3 = (2C_2A_2 + B_2^2) + 2A_2(X_s + X_r)(R_g^2 + (X_g)^2) + 4B_2(X_s + X_r)R_g + 2C_2(X_s + X_r) + 2(R_g^2 + X_g^2)(X_s + X_r)^2 + 4R_g^2(X_s + X_r)^2 + \frac{V_g^2}{\omega T_m} R_s R_g^2 + \frac{V_g^2}{\omega T_m} R_s (X_g)^2 + C_1 \frac{V_g^2}{\omega T_m}$$

$$D_4 = 2B_2C_2 + 2R_g^2B_2(X_s + X_r) + 4C_2(X_s + X_r)R_g + 2B_2(X_s + X_r)(X_g)^2 + 4R_g(R_g^2 + X_g^2)(X_s + X_r)^2$$

$$D_5 = C_2^2 + 2C_2(X_s + X_r)R_g^2 + 2C_2(X_s + X_r)(X_g)^2 + (X_s + X_r)^2(R_g^2 + X_g^2)^2$$

A1, *B1*, *C1*, *A2*, *B2*, and *C2* are constants which consist of the parameters of the system, and their formulae are given above in equations (35) to (40).