Assessment of Novel Distributed Control Techniques to Address Network Constraints with Demand Side Management

Tianyu Luo

A thesis presented in fulfilment of the requirements
for the degree of Doctor of Philosophy

Advanced Energy System Group
Institute for Energy and Environment
Department of Electronic and Electrical Engineering
University of Strathclyde
Glasgow, G1 1WX
Scotland UK

2015

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: *Date:*

“Success is the ability to go from failure to failure without losing your enthusiasm.”

Sir Winston Leonard Spencer Churchill

(1874-1965)

This Thesis is dedicated to my loving parents

for their

constant encouragement and sincere support.

Contents

Figures

Tables

Glossary of Abbreviations

AC	Alternating Current
AD	Active Demand
AES	Advance Electrical System
AIS	Air Insulate Switchgear
AuRA-NMS	Autonomous Regional Active Network Management System
ANM	Active Network Management
AVC	Automatic Voltage Control
BMUs	Basic Measurement Units
CAES	Compressed Air Energy Storage
CDM	Clean Development Mechanism
CHP	Combined Heat and Power
CLASS	Customer Load Active System Services
CLNR	Customer-Led Network Revolution
CP	Constraint Programming
CP-DC	Constraint Programming for Distributed Control
CSP	Constraint Satisfaction Problem
CVPP	Commercial VPP
DC	Direct Current
DCC	Distribution Control Center

DECC	Department of Energy and Climate Change
DERs	Decentralized Energy Resources
DERMS	Distributed Energy Resources Management System
DFS	Depth-First Search
DG	Distributed Generator/Dispersed Generation
DMS	Distribution Management System
DNO	Distribution Network Operator
DR	Demand Response
DR-PFM	Demand Response for Power Flow Management
DRM	Demand Response Module
DSE	Distribution State Estimator
DSM	Demand Side Management
ECU	Electronic Control Unit
EDLCs	Electrochemical Double-Layer Capacitors
EMR	Electricity Market Reform
EMS	Energy Management System
ENW	Electricity North West
EPSRC	Engineering and Physical Sciences Research Council
ESCO	Energy Service Company
ESS	Energy Storage System
ETYS	Electricity Ten Years Statement
FACTS	Flexible AC Transmission System

FALCON	Flexible Approaches for Low Carbon Optimized Networks
FAN	Field Area Network
FCs	Fuel Cells
FES	Future Energy Scenarios
FESSs	Flywheel Energy Storage Systems
FIPA	Intelligent Physical Agent
FiT	Feed-in Tariff
GHG	GreenHouse Gas
GIS	Gas Insulate Switchgear
GUI	Graphical User Interface
HC-PFM	Hybrid Control for Power Flow Management
HESDs	Hybrid Energy Storage Devices
HiDEF	Highly Decentralized Energy Future
HIL	Hardware-In-the-Loop
HMI	Human Machine Interface
I&C	Industrial and Commercial
IDMS	Integrated Distribution Management System
IED	Intelligent Electronic Device
IPM	Interior Point Method
IT	Information Technology
IT and OT	Information Technology and Operation Technology
JI	Joint Implementation

LA	Lighting Authority
LAN	Local Area Network
LCNF	Low Carbon Networks Fund
LCT	Low Carbon Technology
LDC	Line Drop Compensation
LP	Linear Programming
LV	Low Voltage
MIP	Mixed Integer Programming
MMS	Market Management System
	Manufacturing Message Specification
Mtoe	Million Tons of Oil Equivalent
MV	Medium Voltage
MW	Mega Watt
NAN	Neighborhood Area Network
NLP	Non-Linear Programming
NMT	Network Modelling Tool
NSG	Non-Synchronous Generation
OECD	Organization for Economic Co-operation and Development
Ofgem	Office of Gas and Electricity Markets
OLTC	On-Load Tap Changer
OPC	Open Process Control
OPF	Optimal Power Flow

PBDR	Price-Based Demand Response
PFM	Power Flow Management
PLC	Power Line Carrier
PME	Protective Multiple Earth
PMU	Phasor Measurement Units
PV	Photovoltaic
QP	Quadratic Programming
RESs	Renewable Energy Sources
RESS	Renewable Energy Support Schemes
RF	Radio Frequency
RIIO	Revenue = Incentives + Innovation + Output
RMS	Root Mean Square
RTP	Real Time Pricing
SCADA	Supervisory Control and Data Acquisition
SDRC	Successful Delivery Reward Criteria
SIM	Scenario Investment Model
SME	Small to Medium Sized Enterprise
SMES	Superconductive Magnetic Energy Storage
SO	System Operator
STES	Seasonal Thermal Energy Storage
TEES	Thermoelectric Energy Storage
TGC	Tradable Green Certificates

TOU	Time Of Use
TPES	Total Primary Energy Supply
TSO	Transmission System Operator
TVPP	Technical VPP
UNSCC	United Nations Framework Convention on Climate Change
VPP	Virtual Power Plant
VSC	Voltage Source Converter
WAN	Wide Area Network
WPD	Western Power Distribution

Abstract

The development of sustainable generation, a reliable electricity supply and affordable tariffs are the primary requirements to address the uncertainties in different future energy scenarios. Due to the predicted increase in Distributed Generation (DG) and load profile changes in such future scenarios, there are significant operational and planning challenges facing network operators. These changes in the power system distribution network require a new Active Network Management (ANM) control system to manage distribution constraint issues such as thermal rating, voltage, and fault levels.

The future smart grid focuses on harnessing the control potential from demand side via bidirectional power flow, transparent information communication, and contractual customer participation. Demand Side Management (DSM) is considered as one of the effective solutions to defer network capacity reinforcement, increase energy efficiency, facilitate renewable access, and implement low carbon energy strategy. From the Distribution Network Operator's (DNO) perspective, the control opportunity from Demand Response (DR) and Decentralized Energy Resource (DER) contributes on capacity investment reduction, losses reduction, energy efficiency, and enable low carbon technologies.

This thesis develops a new decentralized control system for dealing effectively with the constraint issues in the Medium Voltage (MV) distribution network. In the decentralized control system, two novel control approaches are proposed to autonomously relieve the network thermal constraint via DNO's direct control of the real power in network components during the operation period. The first approach, Demand Response for Power Flow Management (DR-PFM), implements the DSM peak clipping control of Active Demand (AD), whilst the second approach, Hybrid

Control for Power Flow Management (HC-PFM), implements the hybrid control of both AD and DER. The novelty of these two new control algorithms consists in the application of a Constraint Satisfaction Problem (CSP) based programming model on decision making of the real power curtailment to relieve the network thermal overload. In the Constraint Programming (CP) model, three constraints are identified: a preference constraint, a contractual constraint, and a network constraint. The control approaches effectively solve the above constraint problem in the CSP model within 5 seconds' time response. The control performance is influenced by the pre-determined variable, domain and constraint settings. These novel control approaches take advantages on flexible control, fast response and demand participation enabling in the future smart grid.

Acknowledgement

My sincerest and deepest gratitude goes first and foremost to my academic supervisor, Professor Graham Ault, for providing the research opportunity in Highly Decentralized Energy Future (HiDEF) works streams in Advanced Electrical System (AES) group. His valuable supervision and patient guidance inspired me through the duration of my research project.

I also wish to acknowledge the contribution of Dr Michael Dolan, Mr Euan Davidson and Mr Finlay McNicol for their kind help and support on this project. Thanks also go to all my colleagues within the AES research group for every discussion, seminar, and conference that we experienced.

And in the end, I would like to express my special thanks to my love parents. Thank you for all your understanding, encouragement, and selfless support to me in every small progress I have made. Your love always brightens up my life and helps me get through those tough days. Thank you so much!

Chapter 1

Introduction

1.1 Overview of Chapter 1

This Chapter introduces background, objectives, methodology, and simulation activities of the presented research project which focuses on the application of Demand Side Management (DSM) to achieve the objectives of network capacity reinforcement deferral and constraint management in distribution networks. In the background, world energy profile, environmental issues, renewable energy development and official policies are reviewed to identify the current and future challenges of demand growth and energy profile change. The objectives of this research is to investigate the control potential from the demand side to provide supports for Distribution Network Operator's (DNO) network issues. The issues include thermal rating, voltage, and fault levels. The original contribution of this research is to develop a Constraint Satisfaction Problem (CSP) based on-line demand control approach to relieve the network thermal constraints in a Power Flow Management (PFM) scheme. This thesis is organized with an introduction chapter, a background chapter, a methodology chapter, two case study chapter, and a conclusion and future work chapter. During the research period, 4 publications have been composed with 1 conference paper and 3 journal transaction papers.

1.2 Thesis Background and Motivation

1.2.1 World Energy Outlook

World energy has experienced tremendous change since the 1970s. Energy crisis and climate change arouse international concerns on exploration of new energy type, development of sustainable technology, and improvement of energy efficiency. Technical innovation in energy production, transportation, distribution and utilization requires a new vision of energy management system. Emerging environmental issues also stimulate the development of renewable energy. World energy tends to reform its profile to renewable sources as alternatives to traditional carbon intensive energy resources. However, the increasing demand for electrical energy challenges the existing energy consumption status. Therefore, the development of a new effective energy management system on both traditional centralized generation and renewable energy resources has been put on the agenda in a sustainable future.

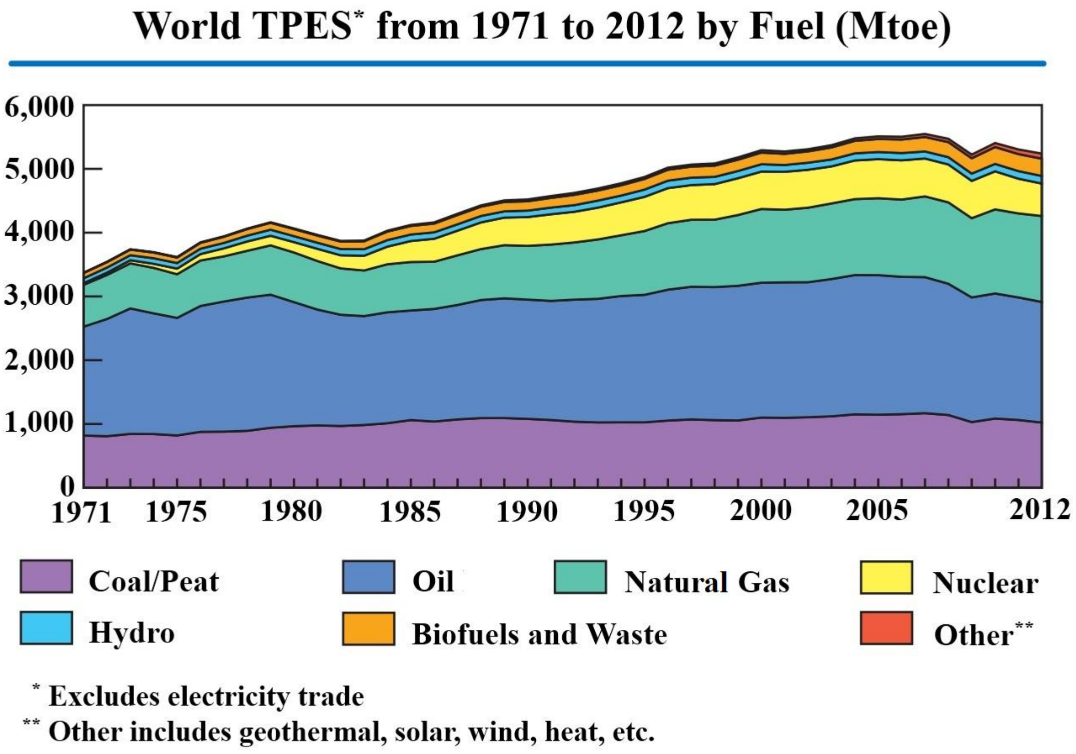
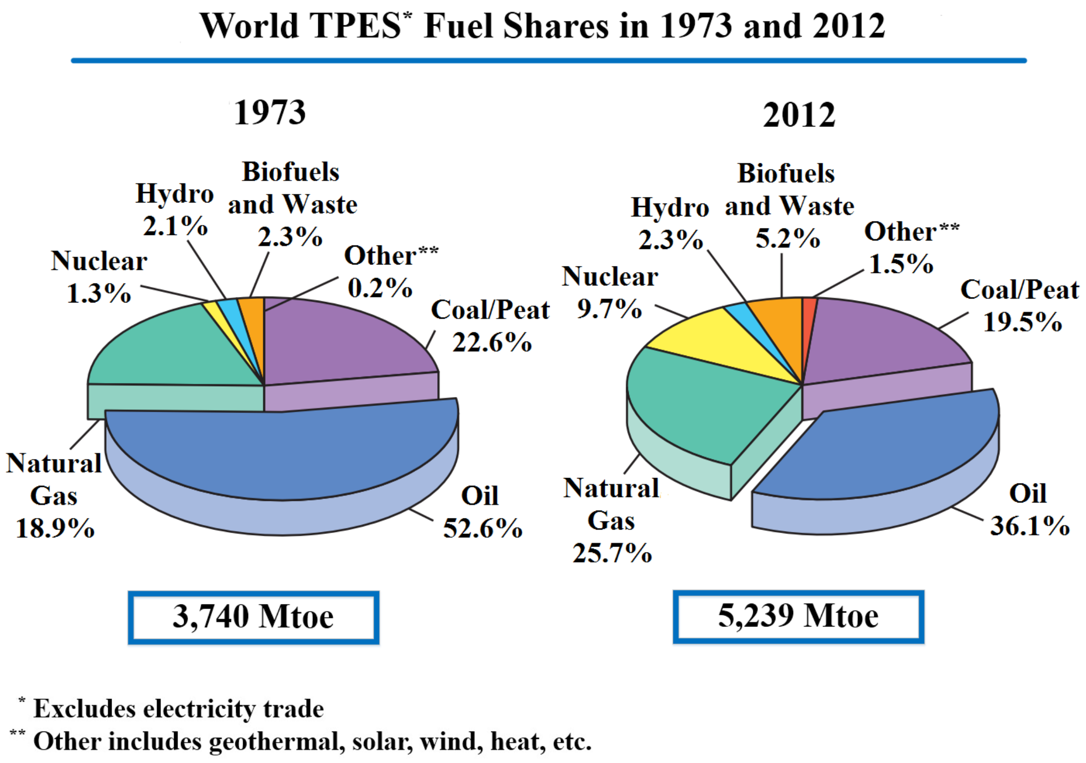


Figure 1-1: World Energy Trend from 1971 to 2012 [1]

World energy trend is characterized in various phenomena that are continuously evaluated by global researchers based on updating statistics over time. The world Total Primary Energy Supply from 1971 to 2012 is shown in Figure 1-1 [1]. The quantity is evaluated by fuel in Million Tons of Oil Equivalent (Mtoe). It is illustrated that the traditional carbon intensive fossil energy resources such as coal/peat and oil maintains a slow and steady growth. As energy resources with low environmental impact, natural gas and nuclear energy experienced rapid development during the investigation period. Supplies of power by nuclear energy and natural gas play important roles in future highly liberalized and diversified energy market. Energy harvested from biofuels and waste doubles its capacity for sustainable purpose, but remains constrained by technical obstacles to spread the application range. However, renewable energy resources from geothermal, solar, wind, heat, etc. are widely explored in developed and some developing countries. It is believed that renewable energy is one of the main solutions to energy crisis after the exhaustion of fossil resources. The figure also indicates two large energy crises in 1975 and 2008 respectively. Vigorous expansion of renewable generation and electrification in all scales with decentralized energy management approach are concerned as one of the potential solutions to deal with next energy crisis.

To make a better illustration of energy development trend, a pie comparison chart of world TPES fuel shares between 1973 and 2012 is presented in Figure 1-2 [1]. The comparison chart indicates that the fossil energy share decreases by 19.6%, with coal/peat by 3.1% and oil by 16.5%. Meanwhile, the natural gas and nuclear power increase the fuel share to approximate a third in total. Although the potential high risk of nuclear power leads to recession in relevant industry in some developed country, most effective energy generation still dominates the energy market share in many regions owing to the fact of technical and natural barriers in renewable energy development. The renewable energy shown in red area experiences the highest development rate from 0.2% to 1.5%. It has large potential to facilitate the energy system decentralization and make low environmental impact in future clean smart grid.


World TPES* Fuel Shares in 1973 and 2012

* Excludes electricity trade

** Other includes geothermal, solar, wind, heat, etc.

Figure 1-2: World Energy Profile Contrast between the Year 1973 and 2012 [2]

A prediction has been made in an Energy Information Administration (EIA) report “International Energy Outlook 2013” for energy development between 2010 and 2040 [2]. It indicates that world energy demand will increase by 56%, half of which is attributed to China and India during the period. Although renewable energy and nuclear power are concerned as the energy with highest development rate of 2.5% per year respectively, fossil fuels will continue to dominate almost 80% of world energy use through the next 30 years. Natural gas will maintain a fast growing rate in fossil fuels supported by increasing exploration of shale gas, particularly in the U.S. Coal/peat consumption will exceed petroleum consumption by approximately 2030 because of an increasing consumption of coal energy in developing countries and a stagnant oil market in Organization for Economic Co-operation and Development (OECD) member countries. As to energy environmental impact, global energy-related carbon dioxide emission tends to increase by 46% and reach 45 billion metric tons in 2040.

Therefore, issues derived from energy exploration and consumption still challenge the speed of our development process in all regions. It is a large project which requires contributions from industrial, commercial, governmental, and other relevant organizations. International collaboration is essential to obtain potential solutions on the following aspects [3]:

- Significant energy demand growth in most regions, especially developing countries, which increases pressure on global fossil fuel consumption
- Rapid deterioration of environment resulted from global diversification of fossil fuel extraction and transportation
- Resistance from existing systems and infrastructure to renewable adoption and sustainable development
- Disagreement on responsibility in different regions to transform the way of energy production and utilization
- Insufficient collaboration or co-ordination of energy policy and regional energy plan among countries
- Difficulties on mitigation of short and long term risk associated with nuclear power generation and waste disposal
- Lack of competitiveness in renewable energy in comparison with current carbon intensive energy sources
- Confliction between policies and market-based mechanisms which impedes the process of decentralization in a sustainable future

- Low public awareness and lack of sustainable vision creates barriers to long-term consideration on energy development

1.2.2 Environmental Issues and Sustainable Development

The previous subsection presented a general outlook of world energy trend which indicates unprecedented changes on world energy map. This brings far-reaching consequences to technical and commercial activities. Such changes focus on performances in environmental issues which include climate change, resource depletion, energy shortage, and pollution impacts. During the process of energy production and consumption, environmental pressures are inevitably imposed on human activities shown in Table 1-1 [4].

It is indicated from Table 1-1 that the most frequent and influential issues consist in greenhouse gas emissions, air pollution, and nuclear waste disposal. In addition, accidental events and technical failure may also result in disastrous impacts, such as Deepwater Horizon 172 million gallons oil spill incident in Gulf of Mexico 2010 and Fukushima Daiichi nuclear disaster initiated by earthquake and tsunami in east coast of Japan 2011. Furthermore, other environmental pressures also arise from land pollution, noise pollution, visual pollution, and ecological pollution.

Extraction of Primary Energy Sources	Transportation of Primary Energy Sources	Energy Conversion	Energy Transmission and Distribution	Energy Consumption
Methane emissions from coal mining, natural gas and oil extraction	Methane emissions from pipeline leakage	Greenhouse gas and air pollutant emissions from fuel combustion	Methane emissions from natural gas transmission and distribution	Greenhouse gas and air pollutant emissions from fuel combustion
Solid wastes from mining	Oil spills	Solid waste from coal combustion	Spills and leakages of liquid fuels	Other emissions, such as lead, cadmium and mercury
Ground water contamination from mining	Emissions greenhouse gases and air pollutants from energy consumption in transportation	Noise and visual intrusion	Emissions greenhouse gases and air pollutants from energy consumption in transportation	
Radon from uranium extraction		Nuclear waste from power production		
Oil discharges		Other emissions, such as lead, cadmium and mercury		
Air pollution from flaring		Oil discharges from oil refineries		
Ecosystem degradation		Risk of accidental radioactive release		

Table 1-1: Environmental Pressures on Energy Utilization [4]

Therefore, the development of energy sustainable development has been put on the agenda to deal with these issues as well as energy market reformation issues. Sustainable development can be broadly defined as “living, producing and consuming in a manner that meets the needs of the present without compromising the ability of future generations to meet their own needs” [5]. It combines the carrying capacity of ecological support systems to quality of life in human society. It aims to improve human activities in four constituent aspects: environmental sustainability, economic sustainability, sociopolitical sustainability, and cultural sustainability [6]. It is a provision of energy with reasonable investment and extensible application from renewable energy resources that result in negative societal impacts over a relatively long-term [7]. Therefore, technical innovation on the next generation energy system is considered as one solution to alleviate the theoretical and practical limitations of energy supply efficiency and environmental impacts. Sustainable energy is defined as the effective provision of energy conversion and utilization which satisfies the requirements of sustainable development in dynamic harmony between equitable availability of energy-intensive products and services to current development and future conservation [8]. It is noted that renewable energy and energy efficiency are the two key components of sustainable energy [9].

Regulation of GreenHouse Gas (GHG) emissions is one sustainable development strategies. The Kyoto Protocol is an amendment to the United Nations Framework Convention on Climate Change (UNFCC) which aims to set binding obligations on industrialized countries to reduce the emission of the gases that contribute to climate change [10]. The Treaty is implemented in ways that impose different levels of GHG reduction responsibility on the member countries based on national differences in emission quantities, wealth, and capacity. As an effective tool for emission reduction commitment of developed countries, trading of emissions certification, usually named as Emissions Trading System (ETS), are allowed as one of the three flexible market-based mechanisms in this protocol, in which the other two mechanisms are Joint Implementation (JI) and Clean Development Mechanism (CDM).

ETS is an administrative approach which provides economic incentives and market competition mechanisms for the main objective of CO_2 emissions mitigation. A limit or cap is imposed to ETS members by a central regulation authority on the CO_2 emission quantity. Any firms covered by the ETS treaty are allocated or sold an equivalent amount of emission allowance, also known as carbon credit, which indicates the permission to emit a specific volume of a certain pollutant. In this case, the exceeding quantity has to be purchased as a product from other firms in ETS market. Researches have been proposed on the influence of ETS on market clearing and prices which is evaluated in a two-step procedure: environmentally constrained generation scheduling and optimal power flow [11]. Other researches have been developed on investigating the impact of ETS-based generation scheduling [12] and renewable energy support schemes [13].

In order to facilitate ETS implementation, Renewable Energy Support Schemes (RESS) have also been developed to promote the rapid development of renewable energy sources in many countries [14]. It is traditionally based on three marketing mechanisms: Feed-in Tariff (FiT), Tradable Green Certification (TGC), and bidding system. Other complementary instruments are also applied in this scheme such as investment subsidies, fiscal and financial incentives, and green pricing [15].

1.2.3 Development of Renewable Energy Resources

Renewable energy is defined as “energy obtained from natural and persistent flows of energy occurring in the immediate environment” [5]. It can be constantly harvested and replenished from the environment with low impact, which is an attractive characteristic to meet the increasing demand with green energy as an alternative to traditional fossil energy. Renewable energy resources derived either directly or indirectly from the sun comprise solar, wind, geothermal resources, biofuels, marine energy, and hydropower. Development trend of world renewable energy investment by type and total generation is shown in Figure 1-3 [16].

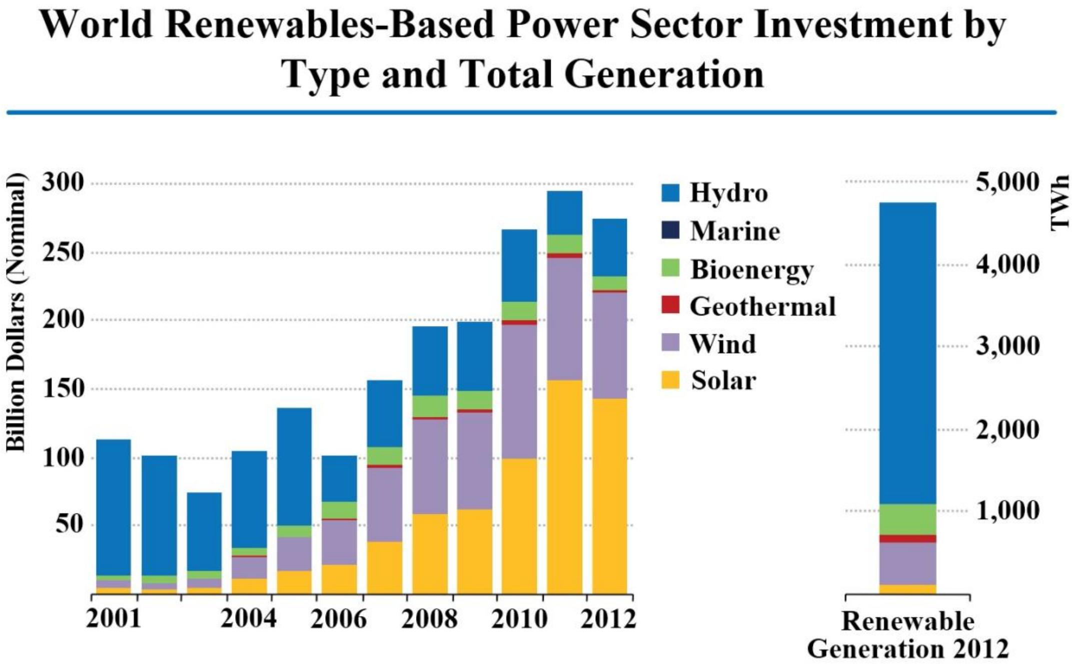


Figure 1-3: World Renewable Energy Investment Investigation [16]

The figure indicates that solar and wind energy has gained large quantity of investment since the beginning of this century. They are concerned as the main renewable investment target because of adequate resource distribution and advanced technical innovation. However, development of such new energy resources still requires large investment to gain more share of energy market. Geothermal and bioenergy are invested in relatively small amounts owing to barren resources and low energy conversion efficiency. The investment in hydropower decreases gradually, but it still maintains most share of global renewable generation, over 3,600 TWh, in 2012.

Renewable energy has potential to replace conventional fuels in electricity generation, hot water/heating system, fuels for transportation, and rural energy services. However, such energy is intermittently harvested from the rapidly changing environment which may mismatch energy consumption requirements in various demands. Additionally, the connection between widely deployed renewable generation and the main grid may also result in serious security of supply issues in the power system. Therefore, quality of renewable energy supply is of significant importance in energy consumption section. As to mismatch problem between supply and demand, the surplus energy should be either sold to a utility or stored in local storage facilities. However, power flow congestion, network destabilization, and storage capacity issues are the main obstacles. Alternatively, a power sharing approach with a hybrid design of energy transmission system which contains both the traditional Alternating Current (AC) line and a small community level Direct Current (DC) line will provide an effective solution to this mismatch problem in a smart microgrid [17]. As to grid connection problem, a multi-terminal High Voltage Direct Current (HVDC) system with autonomous converter control is an applicable solution with stable power curve and low investment cost [18]. This thesis also provides another solution from the demand side to deal with power flow stability issues in large renewable DG access environment. The approaches are presented in Chapter 3, Chapter 4, and Chapter 5.

1.2.4 UK Policies on Energy and Environment

Sustainable development can be extended to some specific meanings supported by the corresponding criteria and policies in different application environment. The UK government has set out the international and domestic energy strategy to address potential the long term energy challenges in 2007 White Paper, and delivered 4 key energy policy goals [19]:

- To put the UK on a path to cut carbon dioxide emissions by some 60% by about 2050, with real progress by 2020
- To maintain reliable energy supplies
- To promote competitive markets in the UK and beyond, helping to raise the rate of sustainable economic growth and to improve productivity
- To ensure that every home is adequately and affordably heated

This means the energy issue becomes one of the key points in future sustainable development. Energy consumption has been brought into a new era of sustainable development, smart management, and active participation. The long term energy challenges can be concluded as 4 aspects:

- Tackling the climate change by low carbon strategy and ensuring a secure, clean, and affordable energy future
- Two-way energy flow by demand side participation and active load management
- Energy market promotion by two-way energy information communication and improving the role of market aggregator
- Introduction of decentralized energy resources

Climate change resulted from carbon intensive energy consumption is one of the main challenges in the long term energy plan. The UK Low Carbon Transition Plan was published on 15 July, 2009, which refers to the details on reducing carbon emissions that satisfies the global strategies on ETS implementation. The 2020 plan details are shown as follows [20]:

- Carbon emissions will be cut by 34%, based on 1990 levels.
- Over 1.2 million people will be employed in green jobs.
- The efficiency of 7 million homes will have been upgraded, with over 1.5 million of them generating renewable energy.

- 40% of electricity will be generated from low carbon sources (renewable, nuclear power, and clean coal).
- Gas imports will be 50% lower than would otherwise have been the case.
- The average new car will emit 40% less carbon compared to 2009 levels.

Clarification has also been made by the current government on increasing the deployment of renewable energy across the UK in the sectors of electricity, heat, and transport [21]. This contributes on protecting consumers from fossil fuel price fluctuation, providing new jobs and businesses in the renewable energy sector, and tracing the progress of carbon reduction objectives. The UK renewable energy target to 2020 made in 2011 is shown in the following roadmap [21]:

- Although starting low, the UK can meet the target to deliver 15% of the total energy consumption from renewable sources by 2020.
- 8 technologies are capable of delivering more than 90% of the renewable energy required for 2020, which include onshore wind, offshore wind, marine energy, biomass electricity, biomass heat, ground source, air source heat pumps, and renewable transport.
- The pipeline for large-scale renewable electricity project is well established and has the potential to deliver a total of 29 GW of operational capacity by 2020.
- Although the pipeline for renewable heat projects is less well developed, it aims to deliver as many as 124000 renewable heat installations under the introduction of renewable heat incentives.
- Road transport biofuels have already achieved over 3% by volume of all road transport fuels and are proposed to increase to 5% by 2014.
- The costs of renewable energy technologies are expected to fall over time because of the development of supply chain, technical innovation, and risk reduction.

- Specific barrier of renewable energy technology and cross cutting barriers are required to be addressed to achieve the aims for deployment and cost reduction.

Furthermore, UK Department of Energy and Climate Change (DECC) believes that Electricity Market Reform (EMR) will enable large-scale investment in low-carbon generation in the UK and deliver security of supply in a cost-effective way. EMR aims to achieve the targets on security of supply, renewable development, and consumer affordability.

1.2.5 Demand Side Management Opportunities in Active Network Management

Sustainable development in future distribution network requires renewable means of generation, an economic method of transmission, and reliable delivery of power supply. However, deployment of distribution network with large DG penetration leads to challenges such as thermal overload, over/under voltage and fault level issues. For instance, installation of large-scale Photovoltaic (PV) units in LV level, 230 V, will cause local voltage rise in the off-peak summer time that may influence the electrical assets’ lifecycle within the area. Introduction of DG and demand units may lead to power flow problem in a low thermal rating network.

Active Network Management (ANM) is considered as one of the main solutions to deal effectively with voltage rise and congestion issues while optimizing large access of renewable DG units. It is defined as “a network where real-time management of voltage, power flows, and even fault levels is achieved through a control system either on site or through a communication system between the network operator and the control devices” [22]. It applies a range of simulation, automation and communication technologies to monitor and control the grid in real time. The ANM control target focuses on providing real time technical support to maintain power system operating parameters which mainly comprise generator output, nodal voltage, reactive power flow, dynamic ratings, distribution losses, islanding issues, fault location, and automatic synchronization [23]. This new management approach of the power delivery system is widely concerned for its robust characteristics of flexibility, extensibility, intelligence, and co-operation. However, large penetration of Decentralize Energy Resources (DER) still challenge the control system of future distribution network with control efficiency, operational cost, and network impact.

DSM provides solutions to the power network by seeking to avoid constraints in real time by harnessing the management potential from the demand side. It can be defined as planning, evaluation, implementation, and monitoring of electric utility activities to obtain the desirable demand response via “a deliberate intervention in the marketplace so as to alter energy use” [24]. It contributes on energy efficiency improvement, Green House Gas (GHG) emission reduction, and network reinforcement deferral by balancing the relationship between supply and demand. It can be integrated with ANM in the control platform for novel development and deployment.

From the DNO’s perspective, DSM takes advantage on capacity investment reduction, losses reduction, energy efficiency improvement, low carbon activities, and renewable generation enhancement. The implementation of DSM could be realized by means of DNO’s direct control, indirect control, and direct appliance schedule [25] to realize the DSM functions of peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape [26]. Besides the innovation of control principles, the program planning and market application of DSM schemes which focuses on the social awareness and commercial realization are of significant importance in the development progress [27].

Implementation of DSM control function has potential to influence the activities in demand, network, and generation, and balance the relationship between consumer, suppliers, and the operator. In general, 8 DSM potential opportunities in power system active network have been posted in Figure 1-4 [28]:

- Better consumer deals from suppliers
- Improvement of domestic demand response
- Provision of local network capacity support
- Provision of regional and national network capacity support
- Variable generation balance at the national level
- Better services from suppliers in electricity market
- Investment in new generation deferral
- Increased commercial models for consumer, suppliers, and DNO

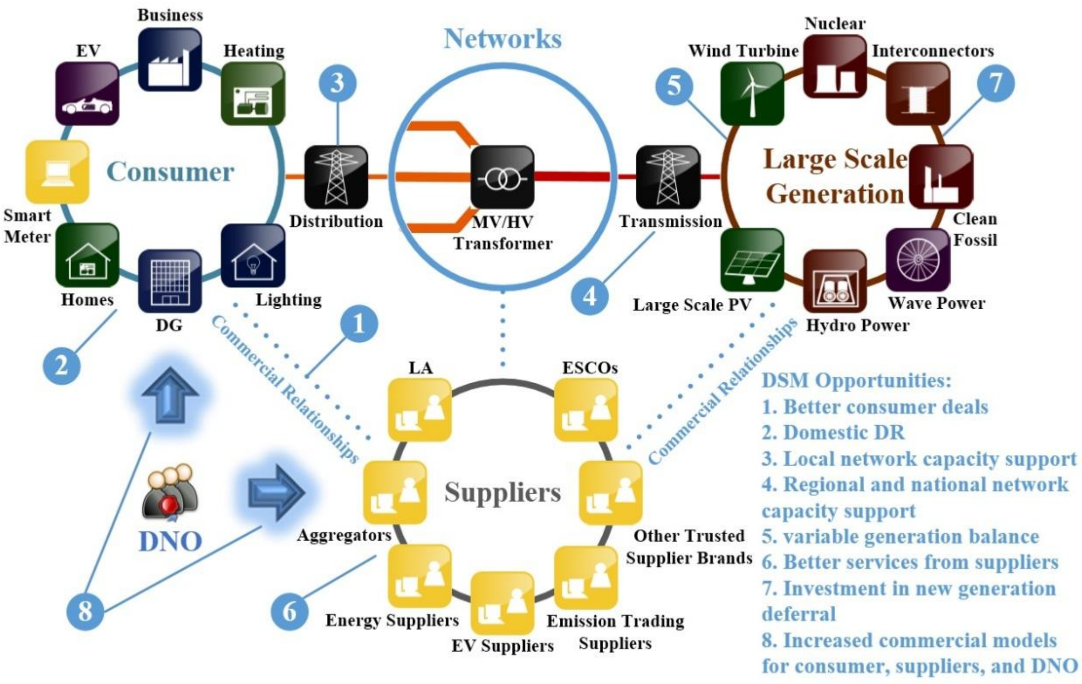


Figure 1-4: DSM Potential Opportunities in Power System Active Network [28]

Implementation of DSM control function can be realized in two broad stages in an active network, offline schedule and online control. Offline schedule requires investigation on the historical data base of the target demand profile related to the planning results such as project identification, load-shape objectives, cost control/consumer options, cost-effectiveness determination, demand-side alternatives, and other processing issues. DNO indirect control and direct schedule control schemes are applied in this stage in day-ahead market. Online control focuses on the real-time control activities based on advanced monitoring technology and smart meter system. DNO direct control scheme is applied to contractual or preferred objectives of constraint management in this stage.

In this thesis, the proposed DSM principle is applied in distribution network control system to provide DNO direct control support from the demand side, shown as the second and third opportunity in Figure 1-4. Two DSM based online distributed control approaches are developed to relieve the network thermal overload constraint with DSM peak clipping and flexible load shape objectives. An objective function solver, Constraint Programming (CP) solver, is adopted in the approaches to realize constraint satisfaction targets in ANM autonomously regional control environment. Three constraints are identified in a CSP based power flow problem, which are preference constraint, contractual constraint, and network constraint. Control models are designed to evaluate the DR curtailment control performance and effectiveness of constraint relief in both approaches.

1.3 Research Objectives

DNOs are interested in the network constraint issues under the impact of large DG penetration and uncertainties. DSM has its own cases to provide solutions to the above issues. Customer participation from the demand side has potential to offer many advantages to the overall power system operation and in particular in the MV/LV distribution networks where network constraints and network objectives can be addressed through harnessing the potential from demand side. Demand side participation is both an operational issue (e.g. data processing, control application, decision making, incentives, etc.) and a planning issues (e.g. network capacity requirement, constraints, etc.). This project aims to exploit control opportunities for future network challenges and model demand side participation fully to demonstrate the DSM functions from DNO perspective.

The objectives can be summarized as follows:

- Perform literature review of DSM opportunities in the new areas and identify DSM application potential for DNO’s network issues such as investment deferral and constraint management in the future distribution network

- Develop a DSM based active control model with the identified input, output, constraints, and control functions to effectively achieve the DNO’s network objectives in the on-line environment

- Demonstrate the feasibility of the active demand control functions and evaluate the effectiveness of the control performance in Hardware-In-the-Loop (HIL) simulation cases

1.4 Original Contribution

The original research contribution and novelty of this thesis based on the previously presented research project can be summarized in the following aspects:

- Further integration of DSM principles in future active distribution networks; identification of DSM/DR control schemes for DNO’s network issue support which include capacity reinforcement deferral, distribution loss reduction and constraint management

- Development of Constraint Satisfaction Problem (CSP) control algorithm for DSM flexible demand objective which includes variable definition, domain selection, and constraint identification in the application of on-line demand control; designed two active demand control approaches to relieve the network thermal overload in on-line cases.

- Evaluation of developed control performance metrics for CSP based distributed control through interconnected distribution network case studies in Hardware-In-Loop (HIL) simulation and demonstration of DSM contributions under the influence factors

These contributions mainly focus on the DSM applications in active distribution network in the future smart grid. The research investigates and analyzes the DSM control performance and impact on the MV distribution network from the demand side.

1.5 Thesis Organization

This thesis is composed in 6 chapters. Each chapter is presented with sections of overview, main body, summary, and reference. The organization is described into details as follows:

Chapter 1 provides an introduction of the research project and whole thesis presentation which comprise world energy profile analysis, sustainable development trends, research project objectives and motivation, original knowledge contribution, thesis organization, and publications. In this chapter, the problem is clarified to be the impact of renewable generation connection that aims to satisfy the requirement of environment issues and sustainable development. The motivation of this research is to investigate the DSM control opportunities to the announced impacts in distribution network and develop DSM based control approach as non-build solutions to the DNO concerned issues such as thermal rating, voltage, and fault levels.

Chapter 2 presents literature review of the DSM principles and the ANM control projects. The DSM principles provide the background understanding of demand control which includes DSM objectives, demand side alternatives, DSM benefits and impacts, DNO perspective of DSM, DSM application in smart grid, and DSM practical demonstrations. The ANM control projects provide the DNO’s on-line autonomously regional control approaches which include steady-state voltage control, automatic restoration, power flow management and network optimization. The on-line demand control approaches developed in this thesis are based on the above theories: DNO-DSM direct load control with flexible demand in an existing on-line distribution control platform.

Chapter 3 is the methodology chapter. It develops a new CSP based load/DR control model in the existing ANM control platform. The DR control model aims to relieve the on-line regional thermal overload with preferred control depth and contractual priority. The objective function is to minimize the curtailed real power in constraint condition. The control environment for this new CSP based DR control approach is established in a distribution network model. To evaluate the control performance, a simulation model is designed with a PC simulator connected to an ABB COM600 controller. Furthermore, the active DR control realization problem is discussed in demand requirement, communication system, and DNO’s implementation. Two DR control approaches are developed with the above methodology: CSP based Demand Response for Power Flow Management (DR-PFM) and CSP based Hybrid Control for Power Flow Management (HC-PFM). The structure of this chapter can be concluded as mathematical model, control function design, distribution application model, performance simulation model, and DNO’s realization problem.

Chapter 4 simulates the DR-PFM control approach in a Medium Voltage (MV) interconnected distribution network. In the distribution network, 8 controllable loads are assigned as DR units to perform the CSP based DR control approach. 4 on-line case study tasks (two single load control cases and two multiple load control cases) are simulated to examine their feasibility, effectiveness, and time response for the same thermal overload constraint. The control performance is evaluated by the parameters of control range, curtailment index, duration factor, and control efficiency. Finally, discussions are presented to analyse the key findings from the tests.

Chapter 5 simulates the HC-PFM control approach in the same MV interconnected distribution network. Since the control actions are performed by both DR and DG units in this approach, the controllable units are assigned to 5 DR units and 3 DG units. In this scenario, 5 on-line study tasks are simulated which include two DG supported DR control cases, two DR supported DG control cases, and a DG only control case. The control performance is evaluated by the same parameters as the ones defined in the previous chapter. Discussions are presented not only to analyse the HC-PFM control performance, but also to compare the cases between DR-PFM and HC-PFM control approaches in the end.

Chapter 6 summarizes the demand control performance in distribution network constraint management activities. It provides the conclusions and highlighted key findings with recommendations as future work.

1.6 Associated Publications

The author’s associated publications in academic journals and conferences during the research period are list in the following sub-sections.

1.6.1 Journal Paper Publications

The following academic journal papers have been published by the author as the main author of the original work:

1. Tianyu Luo, Michael J. Dolan, Euan M. Davidson, Graham W. Ault, “Assessment of a New Constraint Satisfaction Based Distribution Control Technique for Power Flow Management in Distribution Networks of Generation and Demand Response”, IEEE Transactions on Smart Grid, Vol. 6, No. 1, January 2015, *published.*

2. Tianyu Luo, Michael J. Dolan, Euan M. Davidson, Graham W. Ault, “A New

CSP Based Demand Side Control Approach for Power Flow Management", IET Transactions on Generation Transmission Distribution, *under review, last submission November 2014.*

3. Tianyu Luo, Di Cao, Brain O'Reilly, Bruce Stephen, Stuart Galloway, Graham W. Ault, "Assessment of Electrical Energy Saving from a Novel Occupancy Measurement and Adaptive Smart Decision Making System", IEEE Transactions on Instrumentation and Measurement, *under preparation, expected submission July 2015.*

1.6.2 Conference Paper Publications

1. Tianyu Luo, Stuart Galloway, Graham W. Ault, "Demand Side Management in a Highly Decentralized Energy Future", 45th International Universities' Power Engineering Conference (UPEC), Cardiff, 2009, *published.*

1.7 Summary

The last decades have witnessed large changes on world energy developing trend from the traditional carbon intensive fossil energy to a more renewable, reliable, and affordable energy form in the sustainable development. Environmental issues inevitably occurred during the process of energy production and consumption so that government energy policies and international treaties have to put reduction of carbon dioxide emissions on the agenda. In sustainable development, ANM is concerned as one of the effective solutions to deal with network issues with large penetration of DG in a flexible and extensive way. As an alternative control option in ANM control platform, DSM provides supplementary control opportunities to influence the response of energy usage profile that contributes on energy efficiency improvement, exhausted emission reduction, and network reinforcement deferral by harnessing the control/balancing potential from the consumption terminal. Functions and benefits are also identified from the DNO perspective. This chapter also introduces the content of research project, specification of objectives, and contributions to knowledge. In addition, the thesis organization is described with the detail of each chapter. And the author's publications in academic journals and conferences are listed at the end.

1.8 References for Chapter 1

[1] International Energy Agency, "2013 Key World Energy Statistics," OECD/IEA, France, 2013.

[2] A. Sieminski, "International Energy Outlook 2013," U. S. Energy Information Administration, Washington DC, 2013.

[3] M. Jaccard. (2011). *10 Unsolvables Energy Problems the World must Solve*. Available: http://10unsolvables.org/

[4] P. Andea, D. Mnerie, D. Cristian, O. Pop, and D. Jigoria-oprea, "Conventional vs. alternative energy sources overview. Part I. Energy and environment," in *Computational Cybernetics and Technical Informatics (ICCC-CONTI), 2010 International Joint Conference on*, 2010, pp. 595-600.

[5] J. Twidell and T. Weir, *Renewable Energy Resources* vol. 1. the U.S. and Canada: Talyor and Francis Ltd., 2006.

[6] R. Goodland, "Sustainability: Human, Social, Economic and Environmental," John Wiley & Sons Ltd., World Bank, Washington, DC, USA, 2002.

[7] M. A. Rosen, "Energy efficiency and sustainable development," *Technology and Society Magazine, IEEE,* vol. 15, pp. 21-26, 1996.

[8] J. Tester, E. Drake, M. Driscoll, M. Golay, and W. Peters, *Sustainable Energy - Chossing Among Options* vol. 1: Massachusetts Institute of Technology, 2005.

[9] X. Lemaire, "Glossary of Terms in Sustainable Energy Regulation," Warwick Bussiness School, UK, Renewable Energy and Energy Efficiency Partnership, 2010.

[10] S. Walker, K. W. Hipel, and T. Inohara, "Strategic analysis of the Kyoto Protocol," in *Systems, Man and Cybernetics, 2007. ISIC. IEEE International Conference on*, 2007, pp. 1806-1811.

[11] I. Kockar, A. J. Conejo, and James R. McDonald, "Influence of emissions trading scheme on market clearing and prices," in *Power & Energy Society General Meeting, 2009. PES '09. IEEE*, 2009, pp. 1-5.

[12] Ivana Kockar, Antonio J. Conejo, and James R. McDonald, "Influence of the Emissions Trading Scheme on generation scheduling," *International Journal of Electrical Power & Energy Systems,* vol. 31, pp. 465-473, 10// 2009.

[13] G. Z. Liu, C. W. Yu, X. R. Li, and F. S. Wen, "Impacts of emission trading and renewable energy support schemes on electricity market operation," *Generation, Transmission & Distribution, IET,* vol. 5, pp. 650-655, 2011.

[14] Theocharis Tsoutsos, Eleni Papadopoulou, Alexandra Katsiri, and Agis M. Papadopoulos, "Supporting schemes for renewable energy sources and their impact on reducing the emissions of greenhouse gases in Greece," *Renewable*

and Sustainable Energy Reviews, vol. 12, pp. 1767-1788, 9// 2008.

[15] P. Gonzalez, H. Hernandez, and M. Gual, *The Implications of the Kyoto Project Mechanisms for the Deployment of Renewable Electricity in Europe* vol. 33, 2005.

[16] International Energy Agency, "Redrawing the Energy- Climate Map," OECD/IEA, France, 2013.

[17] Zhu Ting, Huang Zhichuan, A. Sharma, Su Jikui, D. Irwin, A. Mishra, *et al.*, "Sharing renewable energy in smart microgrids," in *Cyber-Physical Systems (ICCPS), 2013 ACM/IEEE International Conference on*, 2013, pp. 219-228.

[18] C. D. Barker and R. Whitehouse, "Autonomous converter control in a multi-terminal HVDC system," in *AC and DC Power Transmission, 2010. ACDC. 9th IET International Conference on*, 2010, pp. 1-5.

[19] Department of Trade and Industry, "UK Energy White Paper: Meeting the Energy Challenge," ed: the Stationery Office, 2007.

[20] Department of Energy and Climate Change. (2009). *UK at Forefront of a Low Carbon Economic Revolution*. Available: http://webarchive.nationalarchives.gov.uk/20121217150421/http://www.decc.gov.uk/en/content/cms/news/pn081/pn081.aspx

[21] Department of Energy and Climate Change, "UK Renewable Energy Roadmap," DECC, London, 2011.

[22] S. N. Liew, A. Beddoes, and G. Strbac, "Ancillary Services Market Opportunities in Active Distribution Networks," presented at the Proceeding

Second International Symposium on Distributed Generation: Power System and Market Aspects, Session 9: Active Network, 2002.

[23] D. Popovic, "A Technical Review and Assessment of Active Network Management Infrastructures and Practices," EA Technology DG/CG/00068, 2006.

[24] C. W. Gellings, K. E. Parmenter, and P. Hurtado, "Efficient Use and Conservation of Energy," in *Efficient Use and Conservation of Energy*. vol. 2, C. W. Gellings, Ed., ed: Eloss, 2008.

[25] X. Zhu, "Electricity Demand Side Management and its Different Promotion Measures," in *Power and Energy Engineering Conference, 2009. APPEEC 2009. Asia-Pacific,* 2009, pp. 1-6.

[26] C. W. Gellings, "The concept of demand-side management for electric utilities," *Proceedings of the IEEE,* vol. 73, pp. 1468-1470, 1985.

[27] D. Y. Goswami and F. Kreith, *Energy Management and Conservation Handbook* vol. 13: CRC Press, 2008.

[28] Energy Networks Association, "GB Demand Response Report 1: The Opportunities for Demand Response," KEMA Ltd., 2011.

Chapter 2

Demand Side Management in Active Network Control Platform

2.1 Overview of Chapter 2

The previous chapter has presented world energy background and thesis introduction, whilst this chapter provides a literature review on Demand Side Management (DSM) and active network control projects. First, the principles of DSM is introduced on 6 DSM objectives, demand side alternatives, DSM benefits and impacts, the DNO perspective of DSM, DSM application in Smart grid, and the UK DSM demonstration projects. On one head, as one of the supports in the future distribution network, the above issues should be essentially considered in the marketing and implementation planning of DSM schemes. On the other hand, however, Demand Response (DR) control also has potential to contribute to on-line network constraint issues from the DNO’s perspective.

Secondly, an active network control platform is introduced for autonomous control schemes in a distribution network. The autonomous control schemes include steady-state voltage control, automatic restoration, power flow management, and network optimization strategies. They are designed to effectively solve the network constraint issues voltage fluctuation, frequency drop, power flow congestion, and large distribution loss before the activation of the protection system. Therefore, the active network control platform is also concerned as a potential platform for the implementation of the on-line demand response control.

The research of new DR control approaches is based on both DSM principles and on-line control integration. Comparison of the relevant projects is discussed for the new DR on-line control approach developed in this thesis.

2.2 Principles of Demand Side Management

In modern power industry, Demand Side Management (DSM) is given new concept on various areas for the change of future energy scenarios. The change involves the increasing off-shore wind turbines, decentralized control, customer energy profiles, network energy losses, raise quality of supply and resilience, central and dispersed distributed generation, micro-generation, and decentralized energy resources such as EV charging, heat pumps, and CHP. The universal focus of network planning and operational activities has shifted to build a two-way grid which requires demand side participation on power flow, data communication, and market negotiation. Another important point consists in reducing the energy consumption as well as mitigating the impact of environment.

The UK government has introduced a series of financial incentives for DSM and low carbon policies, such as renewable obligation, feed-in tariffs (FIT), and renewable heat incentives. Meanwhile, the EU commission has also introduced the 20-20-20 targets to a 2020 plan that involves a 20% cut in greenhouse gas emissions, a 20% increase in use of renewable energy, and a 20% cut in energy consumption through improved energy efficiency. Principles of DSM will be introduced to the detail in this subsection.

2.2.1 Overview of Demand Side Management

DSM is based on the purpose of the planning, implementation and monitoring of the activities of electric power companies focused on altering customer electricity consumption patterns to produce desired changes in the load shape of the distribution system [1]. The DSM is applied with power saving technologies, tariffs and incentives, and government policies to mitigate the peak demand instead of enlarging the generator capacity or reinforcing the network [1]. The aim of the DSM activities is to change the load shape by making a reduction of the total load demand of the distribution system during the periods of peak time (and other appropriate times) in order to reduce the planning and operational cost of the network and wholes system [2]. This requires carefully balancing of the relationship between the network operators and network using customers. The load shape that indicates the daily or seasonal electricity demand of industrial or residential consumers between peak time and off peak time can be altered by means of six broad objectives: peak clipping, valley filling, load shifting, strategic conservation, strategic load growth, and flexible load shape [3]. Such objectives are illustrated in Figure 2-1.

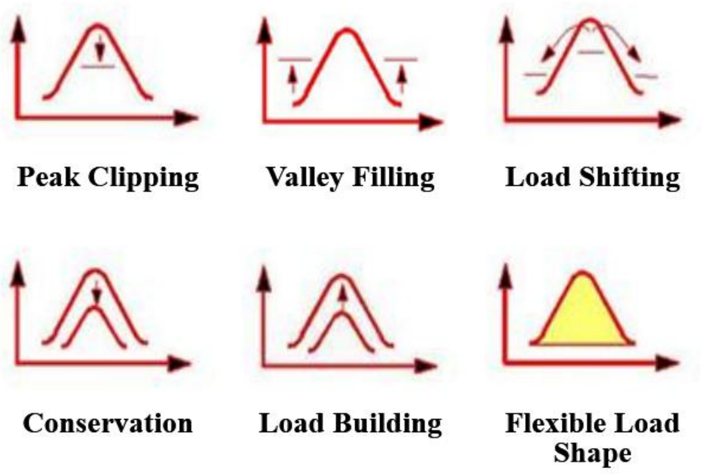


Figure 2-1: 6 Main Objectives of DSM [3]

Peak clipping refers to direct load control to make reduction of the pick loads, while valley filling focuses on constructing the off-peak demand by applying direct load control. These two approaches focus on reducing the difference between the peak load level and the valley load level in order to mitigate the burden of peak demand and increase the security of the distribution network. Load shifting combines the previous classic load management forms and shifts loads from peak time to off-peak time. This approach is widely applied as a most effective load management strategy in current distribution networks and it takes advantage of time independence (or flexibility) of loads. Storage heating or cooling systems based on the concept of shifting electricity usage period can be implemented to ameliorate the high peak demand condition by energy storage in the form of heat/cold. In the highly decentralized energy future, smart electrical devices such as schedulable refrigerator and washing machine will also contribute to optimizing electrical energy dispatch in the concept of customers' participation in the electricity market.

Strategic conservation indicates the load shape optimization through applying demand reduction methods directly at customer premises. 'Strategic' indicates that the consideration focuses on purposely designed utility programs instead of naturally occurring actions. It decreases the total energy consumption from the demand by improving the efficiency of energy utilization that leads to load shape changes via programs driven by utilities. This also involves a reduction in energy sales and a change of energy usage pattern, which reduces the average fuel cost and defers the requirement of utility capacity reinforcement. In reality, it is unlikely that the DNO would have enough incentive to engage in this activity. The DNO would have to consider the longer term implications of demand reduction in network planning and operation.

Strategic load growth optimizes the daily response in the circumstance of large demand access beyond the valley filling strategy in the future distribution networks. It is based on increasing the market share of loads supported by energy conversion and storage systems or decentralized energy resources, such as small-scale renewable or CHP. Electrification is a future tendency of sustainable development on the new emerging electric technologies which are modified to operate using electricity that will increase the energy intensity as well as motivation on reducing the usage of fossil fuels and other raw materials. It is an option to balance the increasing demand with processes for constructing the necessary infrastructure that accompanies applying strategic load growth. In the current context, it is expected that strategic load growth in the areas of electrification of transport and heating can be considered as strategic load growth.

Flexible load shape relates to the reliability of energy supply supported by controllable loads in distribution networks. The control approaches include variations of interruptible load control, contractual consumption schedule, and service constraints offered by individual customer arrangements. DNO identify customers with the flexible loads which are willing to be controlled in critical periods in exchange for various incentives. Studies should be conducted to identify the anticipated load shape which includes demand side activities forecasted over the planning horizon. Variations of interruptible load, integrated energy management system, and individual customer load control device are suitable to implement this strategy.

The presented DSM objectives are usually integrated with practical implementation targets in various areas. The principle consists in rational utilization of existing resources in certain time duration. Researches have been developed to evaluate active Demand Response (DR) activities in the area of system planning and operation [4], active market participation [5], renewable energy source integration [6], and household energy management [7]. However, the adoption of demand side alternatives to achieve one or more DSM objectives requires investigation in responsive application environments.

2.2.2 Demand Side Alternatives

Demand side alternatives refer to effective products or services that influence the consumer use of energy or change the pattern of demand in DSM applications. They can be characterized by the following criterion [8]:

- The intended load shape objective of the demand side program
- The consumer end-use that is affected
- The technology or equipment involved
- The manner in which market implementation is achieved

It is demonstrated practically in power system that the application of demand side alternatives in power supply and relevant services is financial profitable in numerous cases. Cost reductions resulted from changes in the load shape occurs primarily from three conditions [8]:

- Requirements reduction for new assets and critical energy purchases
- Higher efficiency of utilization on existing and planned facilities
- Higher efficiency of operating activities on existing and planned facilities

Deferral of system expansion and reduction of the critical fuel usage can be achieved by significant elimination of peak energy consumption utilizing active network control equipment, energy efficient appliances, adaptive weatherization programs, and energy efficient guidelines for new assets constructions. Increasing utilization efficiency of existing and planned facilities can be realized through the programs of deliberate load growth that reduce local unit costs by extending the fixed cost from debt service and dividends to other units in the market at the expense of total fuel and operating costs. Improved operating activity efficiencies are feasible by shifting the load from peak to off-peak to make an adequate usage of existing generating units and transmission capacities with optimal operating calculations and well-planned control schedule. The typical electric load changes resulting from selective demand side alternatives are shown in Table 2-1 [8].

Table 2-1 lists 4 demand side alternatives which are energy and demand control equipment, thermal storage equipment, efficiency equipment and appliance options, and building envelope alternatives. Typical cases are introduced with their respective achievements in different DSM objectives. Technologies involved comprise direct load control, storage devices, heat pumps, dual-fuel system, and passive building system. Additionally, incentive-based indirect load control and direct schedule planning have large potential, if predictable, on application of demand side alternatives in practise. DSM impacts in the perspective of consumers and utilities are introduced in the following subsections.

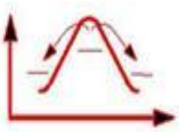
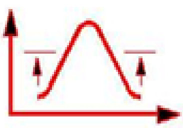
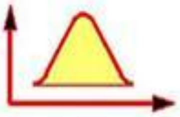
Demand Alternatives	Typical Cases	Load Shape Changes	Demand Objectives
Energy and demand control equipment	Direct load control of residential water heaters	Reduction in coincident demand ranging from 0.3 kW to 1.6 kW per control per unit with a clustering of reduction around 0.5 - 1.9 kW	Load shifting 
	Direct load control of residential central air conditioners	Reduction in coincident demand ranging from 0.6 kW to 2.0 kW per unit, averaging around 1.0 kW	Peak clipping 
Thermal storage equipment	Central Ceramic Heat Storage	Completely eliminate peak period heating demands (4- 6.5 kW in test homes) and result in increase of off-peak demand ranging from 200% to 330% of conventional equipment demands	Valley filling 
Efficient equipment and appliance options	Add-on heat pump	Provide roughly two-thirds of customers' heating requirements in cold climate (Basically in off-peak sale)	Strategic load growth 
	Dual-fuel heating systems	Produce both valley filling with new customers and flexible load shape with existing customers. Typical reported demand impacts range from 7 kW to 10 kW and all new consumption is completely off-peak.	Flexible load shape 
Building envelope alternatives	Incorporating passive solar design in residential buildings	Energy saving range from 25% to 40% of annual space conditioning consumption compared to conventional designs. Variations are due to designs and climate.	Strategic conservation 

Table 2-1: Typical Electrical Load Shape Changes Resulting from Selected Demand Side Alternatives [8]

2.2.3 Demand Side Management Benefits and Impacts

DSM applies a wide range of technical alternatives for network planning, evaluation, implementation and monitoring activities in selective areas, which aims to balance the relationship among consumers, supplies and DNO. Such DSM-based technical alternatives are increasingly concerned in consumers, utilities, and regional energy planning programs. Development of large amount of technical alternatives requires a proper assessment of selection instead of a trivial task. The adoption of alternatives are generally determined by specific local or regional factors, such as generating dispatches, expected load growth, capacity reinforcement plans, load factor requirements, load shapes for average and extreme periods, regulatory climate, and reserve margins [8]. Opportunities of mutual benefits are investigated for DSM scope between customers/consumers and utilities, which are shown in Figure 2-2.

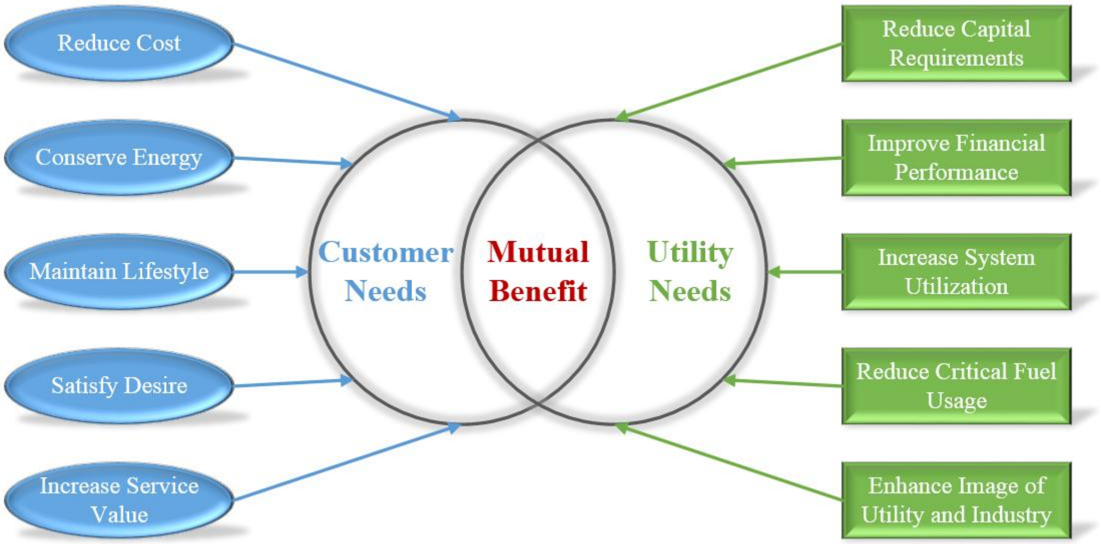


Figure 2-2: DSM Scope for Customer and Utility Requirements [8]

From the customer perspective, the blue section in the figure, the application of DSM has potential benefits on cost reduction, energy conservation, matching better lifestyle, energy consumption satisfaction, and improvement of service value. In this case, the most concerned issue can be concluded as financial benefit and convenient application. Thus, more affordable consumption price and acceptable incentives for load shedding or scheduled appliances are essential in DSM schemes' planning. The requirement of various demand profile should be categorized and investigated respectively in a wide application range. And from the electric utility perspective, the green section in the figure, the desirable benefits involves reduction of capital requirements, improvement of financial performance, increasing system utilization, reduction of critical fuel usage, and image of utility and industry enhancement. In this case, the most concerned issue can be concluded as financial cost and energy transfer balance from the demand side. Thus, more economic system utilization and reliable power supply to support DSM schemes are of significant importance for utility benefits. Therefore, the mutual benefits between custom and utility, the red section in the figure, have to be investigated for a certain DNO-DSM scheme to establish Active Demands (AD).

Active Demand Options	Main Objectives	Householder Activity	Comments
Demand reduction (all seasons)	Energy management; investment and design for efficiency	Question and change practice, invest in efficiency, develop energy literacy	The most conscious and 'active' option. Enabling technology can be very simple.
Static Time-Of-Use (TOU) Tariffs (day to day)	System management to reduce peak load	Choose tariff, and whether utility can control your usage; possible change in practices	Must have 'smart' metering. Some equity and data management issues. May assist micro-generators.
Real-Time Pricing (RTP) (hour to hour)	System management to reduce peaks and use variable generation efficiently	Choose tariff/contract, and enabling technologies	More risky than TOU, but required for variable supply. Central to idea of the smart grid.
Dynamic Demand and Smart Appliances	Network Management to maintain grid frequency	Choose smart appliances	Least problematic option. Needs very liable technology.

Table 2-2: Domestic Active Demand Options from the Customers' Perspective

AD units are the interruptible or controllable loads that are contractually controlled or scheduled to achieve DSM objectives. Domestic AD units participate DSM schemes indirectly with different tariff options in Price-Based Demand Response (PBDR). PBDR is an incentive based dynamic pricing DSM application which contributes on system cost and customer bill reduction by providing higher price during peak periods and lower price during off-peak periods [9]. The application also achieves the load shape objective that consists in decreasing the deviation of demand response curve either by reducing peak loads or by shifting them to off-peak period. Currently, the tariff system in PBDR can be classified to Time-Of-Use (TOU), Critical Peak Pricing (CPP), Extreme Day Pricing (EDP), Extreme Day Critical Peak Pricing (ED-CPP), and Real Time Pricing (RTP) [10]. The typical domestic AD options in PBDR from the customers' perspective are shown in Table 2-2.

2.2.4 Distribution Network Operator's Perspective of Demand Side Management

DSM has potential to provide network support/solution from the Distribution Network Operator's (DNO) perspective. It can be implemented by the DNO according to indirect load control, direct load control, and direct appliance schedule. Incentives and tariff schemes are also required to be considered in a DSM commercial model.

2.2.4.1 Demand Side Management Contribution

DNO companies are incented by different drivers for applying DSM schemes in consideration of their own preference. They own and operate the distribution network of towers and cables (voltage level less than 132 kV) that bring electricity from transmission network to domestic and commercial demands. They plan the distribution networks with DG connection, network wider works, and asset replacement to face current and future challenges. They also operate the network between transmission network and demands in a secure and reliable manner. There are currently 15 DNO license areas operated by 7 DNO companies in the UK which are Scottish and Southern Energy, Scottish Power, Electricity North West Ltd., Northern Powergrid, Western Power Distribution, UK Power Networks, and Northern Ireland Electricity, shown in Figure 2-3 [11].

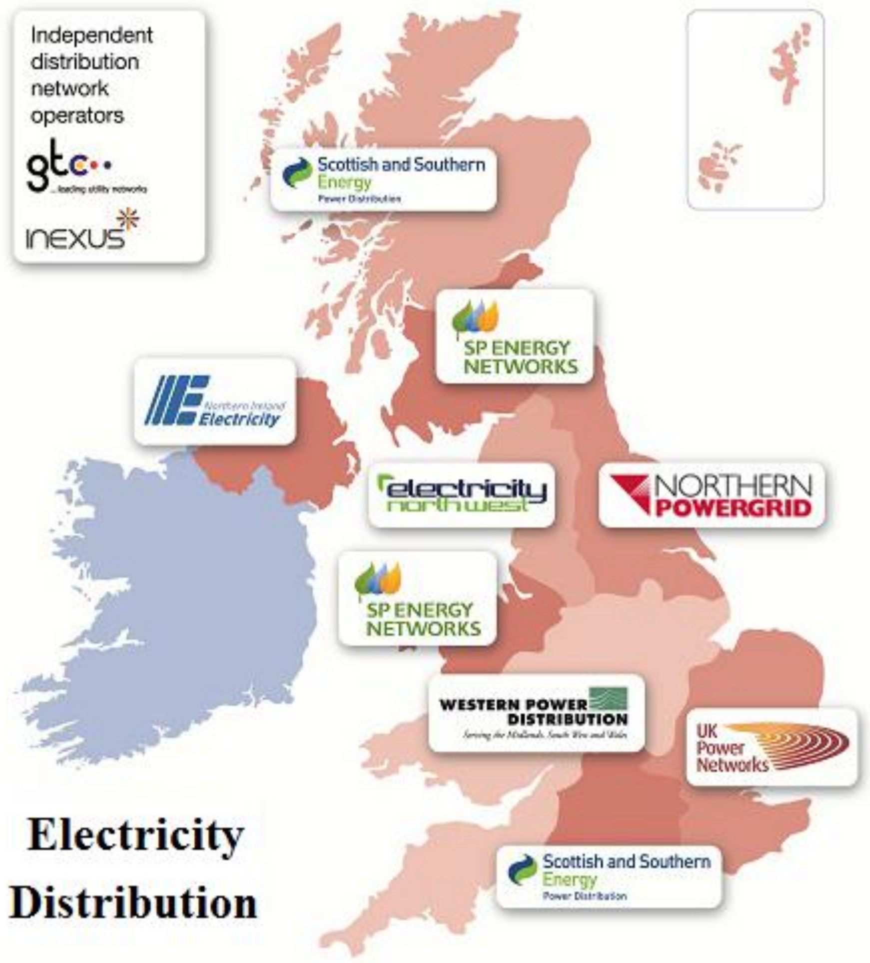


Figure 2-3: UK DNO Distribution [11]

The "Electricity Distribution Price Control Review Initial Proposals", recently published by Ofgem, proposes incentives to encourage DNO companies to consider non-build solutions (including DSM) to solve capacity constraints, as an alternative to making capital investment in reinforcing the network [12]. The requirements of DNO companies have fundamental differences from those of the suppliers and System Operator (SO). The former specifically are localized to a particular network area, possibly restricted to an individual feeder, whereas the latter focus on the local agnostic within Basic Measurement Units (BMUs). DNO has its own preferences on network planning and operation which can be realized by the DSM schemes which are introduced in previous sections. The DNO-DSM functions can be identified as:

capacity investment reduction, losses reduction, increasing energy efficiency, enabling low carbon transport, enabling low carbon heating, and enabling renewable generation, which are shown in Figure 2-4 [13].

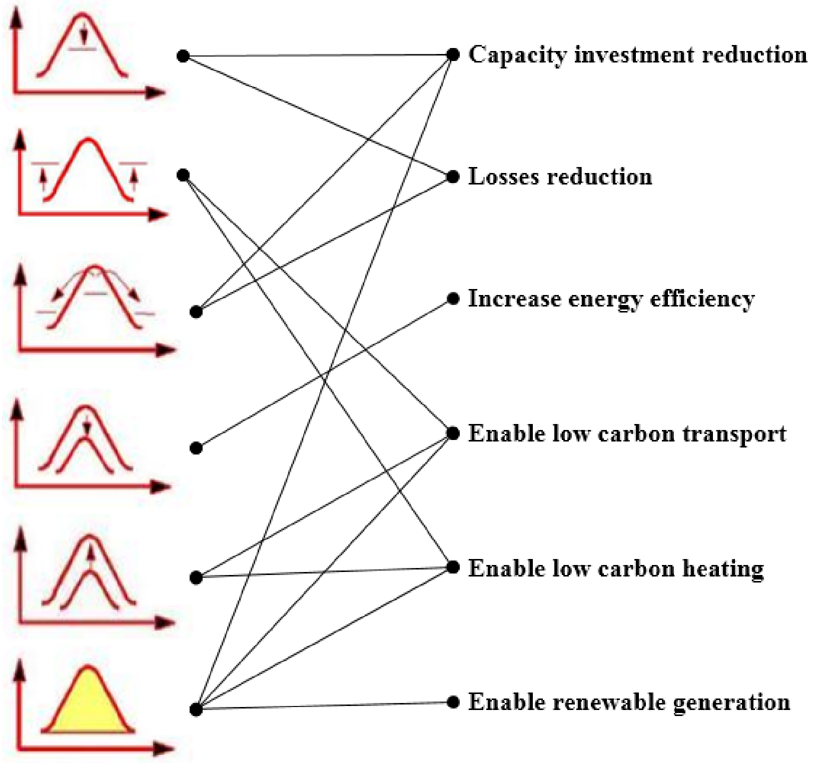


Figure 2-4: DNO Perspective of DSM Benefits [13]

The DNO takes the responsibility on providing network constraints and power flow information and supplying technical support on maintenance and reinforcement of distribution network to ensure the system security, power quality and optimal power flow. They also in charge of the network usage cost which will be coordinated with the suppliers and transmission system operator (TSO) in tariff system. Furthermore, the improvement of load response and energy efficiency should also be considered when applying DSM programs.

From the DNO perspective, DSM projects are of most interest in supporting network operations but this is combined with the energy efficiency and system level response functionality. Furthermore, the LV network constraints in relation to decentralized energy resources and electrification demand growth, such as electric vehicles and smart rechargeable devices should be balanced with the increasing loads.

2.2.4.2 Demand Side Management Application

As a robust power consumption management strategy for low cost power service, energy saving method, and environment conservation, DSM is implemented to improve the load curve and energy efficiency by indirect load control, direct load control and direct schedule of appliance, which could be implemented by Distribution Network Operations (DNOs) [14].

Indirect load control indicates the financial incentives that include bonus payment, real time pricing, and even tariff penalties. In this case, the network constraint issues and DSM objectives are identified by DNO in consideration of demand prediction. Flexible customer participation is performed with the pre-signed contract or real time tariff information posted on the internet or smart meter. The realization of DSM indirect load control relies on bidding based liberalized electricity market which requires transparent price and power flow information on the electricity auctions. However, flexible demand may result in unpredictable response which should be adjusted by smart control system.

On the contrary, direct load control indicates DNO direct intervention to the network control activities. In this case, financial incentive and pre-contracted tariff are applied to the targeted demand side. DSM schemes are invoked by the DNO real time demand control that is implemented to suppliers or even customers [15]. The appropriate real time load curtailment or adjustment efficiently and promptly relieves the network constraints such as thermal limit, voltage drop, and security issues. However, this may result in large operational cost and network transient impact. Therefore, the maximum demand limit which requires political and commercial acceptance will be a feasible alternative in this control scheme [16].

The last DSM control method, direct schedule of appliance, shifts the appliance demand for a better DR by direct customer contracts during the control period. As for large non-domestic demand, energy storage devices such as batteries, fuel cell, and industrial cooling or heating system are applied for energy transformation and off-peak usage. And as for domestic demand, smart metering based appliances with timer options are applied for customer choice of load shifting participation. For instance, the contracts will be made between DNO and customers or suppliers to recharge the EV batteries in certain off-peak times. Construction of EV battery stations instead of petrol stations is recommended for load shifting use. In addition, smart house-hold appliances which can be controlled by timers will also play an important role in combination with smart meters.

2.2.4.3 Demand Side Management Commercial Model

A commercial model for DSM application is established to clarify the commercial relationships among customers, suppliers and DNO in decentralized scenario. It is assumed that information transparency and control signal communication are achieved by a market aggregator and wide spread smart meters in this model, shown in Figure 2-5.

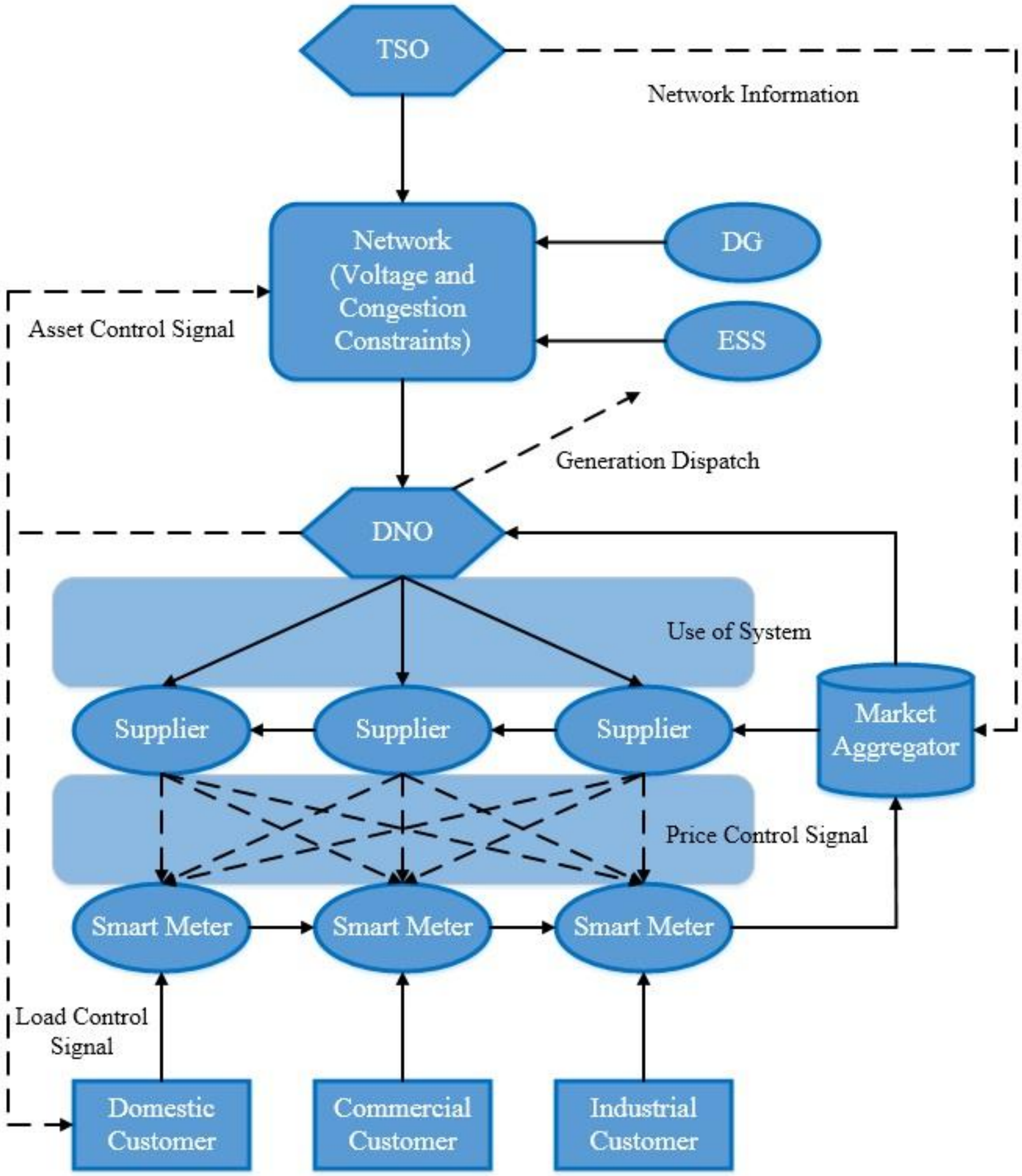


Figure 2-5: DSM Commercial Model

In the DNO-DSM commercial model, the DNO provides information of system usage and relevant charges to suppliers in electricity market. The DNO owns the whole distribution network of electrical energy supply in the district, but it won't attend the market issues which set contract directly to customers. Suppliers sell electricity and set commercial contract to domestic customers, commercial customers, and industrial customers with tariff scheme options. Smart meters are applied in demand terminals to receive price control signals from suppliers while collecting data of energy consumption DR. Such DR information is transmitted to the market aggregator data base that differentiates DSM products of power supplies and services to a broad opportunity of customer satisfaction targets. Transmission network information which contains network usage and transmission charges from the Transmission System Operator (TSO) is transmitted to the DNO and suppliers together with the DR feedback via market aggregator. Another branch of information from distribution network monitoring system is also transmitted to the DNO for stability and security purposes. In this case, DSM indirect control method is implemented by the DNO via price control signal from suppliers to customers and obtains feedback via smart meters. Meanwhile, direct load control method and direct schedule of appliance method are implemented by the DNO via load control signal which derives from the contract directly signed between the DNO and domestic customers. Additionally, generation dispatch control signal is also transmitted to distribution substation control center for the adjustment of DG, ESS, and other components, which improves the electrical distribution efficiency and prevents the instable issues.

There are 5 separate DSM commercial schemes based on this commercial model:

- TOU tariff scheme
- RTP scheme
- Maximum demand scheme
- Supplier business scheme
- DNO direct control scheme.

In TOU tariff scheme, the suppliers provide the information about generation costs and take TOU contract directly with the customers. DSM scheme is applied to introduce the tele-switching loads for shifting and smoothing the demand response in the rate with hour intervals. The DNO plays an normal role in network planning, operating, and regulating, and benefits from the reduction of peak load.

In RTP scheme, the DNO deploys dynamic pricing capability via smart meters and collects information from data feedback. The DNO also provides the network information on constraint issues and use of system charges in the two-way communication system. The pricing signal are transmitted from suppliers to customers in real time to the desirable load profile with the support of smart meters.

The maximum demand scheme is dictated by the suppliers or the DNO for industrial loads. In this scheme, the customers are obligated to operate normally within maximum demand constraints. The network limits information from suppliers are delicately identified for DSM purposes. In addition, the tariff penalties are applied to limit the exceeding demand from industrial customers.

In the supplier business scheme, the competitive market of the suppliers is constructed according to their contractual arrangements with multiple parties. The DNO provides network limits on constraints and use of system charges to the suppliers. Financial incentives are applied to the customers in this DSM scheme. As a result, commercial benefits are gained by avoiding the peak generation purchase.

DNO direct control scheme refers DNO direct control signals to the customer load. Load profile research should be implemented before the scheme application. The customers contract with the DNO and the suppliers to allow the direct access to the appliances. The DNO should also coordinate with the suppliers for the responsibility of commercial incentive arrangements.

2.2.5 Demand Side Management in Smart Grid

The main vision for future power industry is driven by the technology of intelligent automation and the concept of demand side management in electrical distribution networks (as well as major infrastructure investments at the transmission level). This will lead to a major change in distribution network design and operation, in which the concept “smart” will be considered for a new type of power network.

Smart grid is a broad concept which is proposed to improve the power system reliability and performance by optimizing the relationship between supply and demand. Utilities, suppliers, and consumers are all involved in this large environment and require gaining benefits which is suitable to their investments. Researches and reviews have been developed for smart grid technologies, such as communication and standards [17], flexible device control [18], DG connection regulation [19], DR impact in the market [20], and customer active participation [21].

Generally, the key market drives for smart grid are concluded as follows:

- Provision of renewable power (sustainability)
- Provision of reliable power (reliability)
- Provision of affordable power (affordability)

Provision of renewable power, also known as sustainability, relates to the integration of carbon dioxides free energy that enables access and dispatch of renewable DERs and develops flexibility and extensibility of back up energy assets. In addition, integration of renewable distribution, energy positive buildings and EVs are also developed in this case. This key driver focuses on smart grid objectives from the energy generation aspect.

Provision of reliable power, also known as supply security, relates to the maintenance of grid stability while enabling the network decentralization. It contributes on operational decision support improvement, constraint management implementation, blackout and outages impact mitigation, and aging assets management. This key driver focuses on smart grid objectives from the transmission and distribution network aspect.

Provision of affordable power, also known as price stability, relates to customer acceptance and energy efficiency improvement under the application of DSM schemes. It aims to reduce the influence that smart technology imposed on energy price fluctuation by maximizing energy flows in constrained and aging grids. Enabling end-users' decentralized energy resource (DER) accesses with the energy system is another challenge to the future distribution network. The end-users are required to be professional in market participation, which are also called "Prosumers". Furthermore, it also leverage information across business silos which bridging IT and OT (Information Technology and Operation Technology). This key driver focuses on smart grid objectives from the consumer acceptance and participation aspect.

Smart grid technology is the term given to the integration of electrical power distribution network solutions to meet the future challenges such as increasing electric demand, LV/MV power network infrastructure and work force management, DER, smart house-held devices installation, and the environmental impact of greenhouse gas produced during electric generation [22]. It focuses not only on innovation in advanced control and metering technologies, but also on the decisions regarding appropriate investments. On one hand, implementation of the smart grid concept should contribute to higher availability of power supplies as well as the reduction of primary equipment investment. On the other hand, wide application of decentralized energy resource, such as small scale wind turbine, combined heat and power, and biomass generation, and the increased electrification of electric vehicle and increased penetration of smart house-held devices in LV/MV networks require more complex and robust control and operational approaches to balance the supply and demand.

Integrated smart grid solutions combine advanced sensing technology, two-way high speed communications using the DNO assets, condition monitoring and enterprise analysis software and related services to provide location-specific, real-time actionable data as well as home energy management solutions to provide enhanced services for the end-users. Smart grid solutions, including distribution automation, asset management, DSM, DR control, facilitation of decentralized energy, advanced metering infrastructure, and commercial aggregator control. They allow DNO, supply company and customer participation in the electricity network and market through a single integrated, robust, and scalable smart grid platform. This has the potential to enhance the performance of the distribution power system. These solutions have the potential to increase the efficiency and reliability of the electricity system while reducing the environmental impact of electric usage benefiting utilities, their customers, and the environment. These solutions prospectively also benefit energy users on energy efficiency, cost reduction and transparency/visibility.

Demand side management plays an important role in smart grid application, which brings large impacts to the modern energy market. Controlling and influencing energy demand can reduce the peak demand and reshape the domestic load profile, which could increase the grid sustainability by reducing the overall cost and carbon emission level. This will also lead to the avoidance of the redundant or under-utilized infrastructure: generation capacity, transmission lines and distribution networks.

Smart pricing is an application of DSM in smart grid using smart metering devices in automatic metering infrastructure. It could contribute to cost-reflective pricing based on the entire supply chain of delivering electricity at a certain location, quantity, and period. Customer control of their energy usage is influenced by the penalty and incentive regime at all levels of the supply chain. However, the essence of DSM in the smart grid is to promote the overall system in efficiency, security and sustainability by making a full utilization of the existing network infrastructure and facilitate low carbon technology integration into the network [22].

2.2.6 Demand Side Management Demonstration

DSM researches and trials have been implemented around the world with international collaborative projects. However, the most innovative and typical cases are supported by governments, operators, and manufacture companies within the EU. Meanwhile, the UK government has established the Low Carbon Networks Fund (LCNF) with up to 500 million pounds to support DNO projects for new trials of technology, operating and commercial arrangements to push the UK energy market to a low carbon economy. Thus, the author investigates the UK LCNF researches and demonstrations to evaluate the DSM contributions in reality.

2.2.6.1 Overview of Low Carbon Networks Fund

The future challenges of UK power network identified in National Grid ‘2013 Electricity Ten Years Statement (ETYS)’ include the delivery of economic and efficient investment decisions to address the potential transmission solutions of commercial services, operational constraints, and asset investment [23]. In addition, UK Future Energy Scenarios (FES) has modeled non-progression, slow progression, low carbon and gone green scenarios for the future energy development trend [24]. It also indicates that the future decentralized trend of intermittent generation requires more flexible and extensible management approaches such as demand curtailment and reactive power services to alleviate the network constraint impacts and realized a sustainable energy future.

The Low Carbon Networks Fund (LCNF) is one of the UK sustainable realization plan for DNOs to "explore how networks can facilitate the take up of low carbon and energy saving initiatives such as electric vehicles. Heat pumps, micro and local generation and demand side management" [25]. The LCNF was set up with 500 million pounds in total by Ofgem to meet Britain's low-carbon energy sector targets in a 5 years period from 2010 to 2015. It provides valuable researches for industry to establish a better understanding of new requirements from both generators and consumers for future investment. The goal of this fund is to "distribute relevant technical know-how and expertise acquired from trials across the industry, with the hope of transitioning to a low carbon economy in the most cost-effective and efficient manner possible" [26]. Thus, the main objectives of the fund is to help DNOs to meet the challenges of a predictable low-carbon world [27]:

- Efficiently connecting renewable generation
- Meeting the needs of small-scale and intermittent generation
- Addressing an increase in the use of electric vehicles, heat pumps, smart domestic appliances and other low-carbon technologies
- Using smart meter data to improve network performance and costs
- Incentivizing customers to reduce their carbon footprint and cut bills, by managing their energy demand

The above challenges indicate that the management of DG connections and DR behaviors is mainly concerned in LCNF projects. Most importantly, exploration of demand side alternatives is required to enlarge network capacity and defer costly investment. DNOs are also encouraged to explore solutions on impact of climate change initiatives, energy efficiency measures, flexible demand arising, DR impact of tariffs, and large DG penetration. In addition, a new price control model, RIIO (Revenue = Incentives + Innovation + Output) [28], has been created by Ofgem to provide remarkable incentives to environmental challenges and network services delivery.

2.2.6.2 DNO-DSM Trials in the UK Low Carbon Networks Fund Projects

The implementation of DNO-DSM trials is one of the main objectives of the UK LCNF which are listed in the above subsection. In such trials, DNOs are responsible to the adoption and evaluation of demand side alternatives which aims to deal with specific network requirements. The benefits can be summarized as financial and technical which include avoiding frequency drop blackout, deferring capital expenditure investment for infrastructure, supporting development of low carbon technologies, and delivering additional support to future smart grid. 3 typical DNO-DSM trials are introduced to the detail and the other relevant trials in the UK LCNF projects are listed and discussed in the following part.

- **Flexible Approaches for Low Carbon Optimised Networks (FALCON)**

The Flexible Approaches for Low Carbon Optimised Networks (FALCON) is a Western Power Distribution’s (WPD) program which applies demand response trials in the Milton Keynes area coinciding with the triad season. It adopts 6 alternative techniques to the conventional reinforcement, one of which is demand response trial to build a new Scenario Investment Model (SIM) for planning on the 11 kV network and creating an energy model which provides a forecast of peak demand situations in the UK Future Energy Scenarios (FES) [29]. The purpose of such intervention techniques also consists in network capacity support without resorting to traditional investment of network reinforcement. The underpinning principle of FALCON is to leverage technology and innovation to evaluate the potential benefits that can be accrued to customers through making efficiency savings or business policy changes [29].

Customer engagement is one of the novel outcomes supported by balancing and energy avoidance techniques in the commercial trials. Load estimation system is established to predict customer load status based on a set of historical data or new developed ‘Energy Model’ in different pre-determined demand scenarios. Such demand scenarios contribute to analyse the impact that the demand side alternatives produce to the other low carbon technologies. The recent Successful Delivery Reward Criteria (SDRC) from WPD-FALCON report indicates that the Network Modelling Tool’s (NMT’s) capability of process half hourly data in volume and calculating the required values for voltage and thermal headroom slightly reduced the accuracy risk resulted from the ‘Energy Model’ [29].

The main outcome of the FALCON DNO-DSM trials is concluded as successful delivery of required capacity by contracting strong relationships with third parties to sign Industrial and Commercial (I&C) users up for the trials [29]. These contracts have explicitly identified the DSM implementation details that clarify the significant weighted split between generation dispatch and load curtailment. However, this project did not focus on developing an autonomous control that actively realizes the control functions to DG and DR units in a relatively short time response. Meanwhile, the report also indicates that customer engagement is less considered by the DNO in comparison with other participants of the network, such as suppliers and utilities. It is because of the lack of interaction requirement with the demand side. At this stage, customer participation is only considered as reactive behaviours to DNO's direct load control other than active behaviours to DNO's indirect DSM plans.

- **Customer-Led Network Revolution (CLNR)**

The Customer-Led Network Revolution (CLNR) project is developed to assess the potential for new network technology and flexible customer DR in the process of moving to a low-carbon economy. It aims to facilitate speedier and more economic take-up by customers of Low-Carbon Technologies (LCT) and the connection to the distribution network of increasing amounts of low carbon or renewable energy generation [30]. The objectives are focus more on demand side customer participation and tend to figure out the increasing benefit to the development of smart-grid solutions that contributes to both customers and DNOs.

To achieve the objectives of LCNF, this project integrates network management experience and DR technologies by bringing together GB's largest regional wires-only distributor (Catering Equipment) and largest national unaffiliated energy retailer (British Gas) to evaluate a range of demand side innovations (innovative tariffs and load control incentives in association with different LCTs) [31]. These DNO-DSM trials are also applied along and in combination with network-side technology including voltage control, real time thermal rating and Energy Storage System (ESS).

The learning outcomes of this project include: demand profile research, customer flexibility, network technology, optimum solution, and most effective delivery [30]. The trials have identified the demand profiles based on general load case and new electrical load and generation types defined in LCTs. In customer flexibility research, an interim analysis of domestic customer participation subject to demand intervention are also investigated according to customer behaviours influenced or modified by technical, social or economic means. In addition, 4 test cell propositions for Small to Medium Sized Enterprises (SMEs) are designed and launched which includes disaggregated load monitoring, Time-of-Use (ToU), restricted hours and direct control [30]. However, the term report also points out that even though significant findings have been achieved on suitability of detailed quantitative and qualitative, challenges still exist in all trials , particularly large multi-partner trials, in terms of technology, IT, customer recruitment, development of partner relationships, and sourcing products from suppliers [30]. Furthermore, customer flexibility is also pointed out to be a complex problem which includes time flexibility, location flexibility, process flexibility, and practice abstention or curtailment [30].

- **Customer Load Active System Services (CLASS)**

The Customer Load Active System Services (CLASS) project is a new project funded by the second tier of Ofgem’a LCNF mechanism. It is an Electricity North West’s (ENW) project which takes academic partnership with University of Manchester. It aims exploit the relationship between demand and voltage to cost-effectively solve the demand issues caused by increasing connections of LCT [32]. The solution has potential to provide a new autonomous control mechanism for DNO companies to achieve voltage control and frequency management targets and support the system operator at GB level.

The CLASS project focuses on maximizing the use of existing assets and minimizing the capital investment requirement to achieve the following objectives: peak demand reduction at primary substations, reactive power absorption for voltage regulation, and provision of fast reserve/frequency response [32]. In this research, autonomous control solutions have been developed for the network congestion issue based on the load profile definition models that include a time-independent load model and a time-vary load model through On-Load Tap Changer (OLTC) actions at primary substation level [33]. Otherwise, reactive power absorption is also investigated to relieve the high voltage issue from the demand side in the low demand environment through tap staggering actions at primary substation level [33].

The research has successfully demonstrated that autonomous control from primary substation level effectively contributes to network issues such as network congestion and high voltage regulation. It also takes advantages in eliminating discernible impacts to LV customers while implementing voltage control actions. However, customer phase connection, cable information, and Protective Multiple Earth (PME) are required to be concerned for realization problem. In this research, the real and reactive power of DR is influenced by the autonomous control from the network substation. However, there is another potential opportunity to control the DR devices or appliances which, oppositely, contributes to the network by dealing with the on-line constraint problem. This provides a new research area for the control approaches presented in this thesis.

- **Other Relevant Projects with DSM Involvement**

Other relevant DNO-DSM projects include low carbon London [34], Capacity to Customers (C2C) [35], Thames Valley visions [36], Solent Achieving Value from Efficiency (SAVE) [37], Smart Street [38], Vulnerable Customers and Energy Efficiency (VCEE) [39], etc. In the plans of these DNO-DSM projects, demand side alternatives and customer participation impacts are carefully reviewed to provide potential solutions for Ofgem’s desirable scenario of low carbon economy. From the trials’ learning, DSM is broadly concerned by the DNOs as an indispensable solution to the future more flexible and extensible smart grid. However, most of the

LCNF-DSM trials have put great weight on the market based DNO's indirect influence of energy usage behaviours from the demand side. The increasing capacity requirements and constraint challenges from distribution network require a new decentralized control method from the demand side that can be implemented by DNO as a supplementary option. Therefore, the novel demand side control approach presented in this thesis investigates the feasibility and performance of the DNO's direct demand control for network constraints.

2.3 Active Network Control Platform

Active Network Management (ANM) aims to achieve DNO objectives of flexibility and extensibility in power network plan and operation process by implement active control functions to decentralized components. It has potential to provide effective autonomous control environment for DR on-line control approaches in the DNO's direct load control scheme.

2.3.1 Overview of Active Network Management

The development of the UK distribution network brings a significant improvement on Network Management System (NMS) which introduces a series of monitoring and administration approaches in combination of control algorithms, communication standards, and network infrastructures. The NMS improvement provides supports to various areas of next generation power network such as Energy Management Solutions (EMS), Distribution Management Solutions (DMS), Market Management Solutions (MMS), Demand Response Modules (DRM), etc. The importance of an effective planning for NMS can be summarized as the network inventory discovery, health monitoring, devices status, and outage alert and control activity. Recently, however, the traditional distribution networks which have been designed to operate passively and deliver unidirectional power flows to dispersed end users were challenged by the proliferation distributed generator connection and disparate load introduction.

Active Network Management (ANM) solutions are being developed to enable the increasing connection of DG, often on a case by case basis as an economically preferable alternative to network reinforcement [40]. The concept of an Active Network has been defined as “a network where real-time management of voltage, power flows and even fault levels is achieved through a control system either on site or through a communication system between the network operator and the control devices” [41]. Currently, from the DNO perspective, the main driver for the deployment of ANM in the UK is the necessity to counteract the network issues which commonly arise alongside the connection of distributed generation, which would otherwise require costly and sometimes controversial network reinforcement [42]. As a result, utilities are looking to active network management solutions which allow generators to connect to existing networks under a range of connection agreements, while avoiding, or at least reducing or deferring, the costs associated with network reinforcement [43].

ANM solutions are applied in a broad area of smart grid which contains generation, transmission, distribution, and demand side participation to deal with issue for DNO, utilities, suppliers, and customers. It requires technical innovation in grid constructions, network management, substation automation, high voltage technology, and advanced protection system. In the UK, technical innovation is encouraged through two financial incentive schemes offered to network operators by the industrial regulator, Ofgem: The Innovation Funding Initiative (IFI) scheme encourages the research and development of innovative grid technologies, whereas the Registered Power Zone initiative offers incentives for DNOs who implement such technologies onto the network, facilitating the connection of DG that has previously been blocked by technical barriers [40].

There are mainly two aspects in ANM application which are network planning and on-line operation. The ANM on-line control platform in power network operating process is of significant importance to implement “active” performance for network automation and management. The role of the on-line power network simulator is to re-create network conditions suitable for testing the control algorithms, which is done by feeding the algorithms with on-line measurements from the network and also by applying to the network any control actions taken by the algorithms in real time [44]. The control algorithms are realized by activating controllable parameters identified by ANM components. The network controllable parameters, such as flexible loads, distributed generators, circuit breakers/protection relays, and transformer tap-changers, are altered in real time by either predefined test profiles or programmed control actions.

One of the important aspects of on-line control preparation is to perform Hardware-In-the-Loop (HIL) simulation as an inevitable aspect in the research and development of complex process systems before implementation in the real world. It provides an extensive platform by increasing the complexity of the plant under control to the test platform which is included in test and development by adding a mathematical representation of all related dynamic systems, named as the plant simulation [45]. Besides the feature of simulation in on-line environment, HIL simulation has its own characteristic which can be identified as the integration of a real component, identified as an Electronic Control Unit, in the loop for control performance testing and evaluation. The application of HIL enhances the quality and safety of the testing environment while providing more tolerance to the network violation. Therefore, the main procedure of developing a new ANM control algorithm is: mathematical model design, HIL Simulation, and Real Process Implementation.

2.3.2 An Active Network Management Control System

The DSM control algorithm in this thesis is integrated in a large ANM control platform, Autonomously Regional Active Network Management System (AuRA-NMS). Many of components in AuRA-NMS were developed as part of a three and half year research program involving seven universities in UK, two DNOs (EDF Energy and SP Energy Networks) and a major manufacturer (ABB) [46]. The program has a number of different facets: the research and development of the ANM system itself; the testing of the resulting system; research into communications underpinning AuRA-NMS and ANM per se; and a dedicated stream assessing the economic benefits of AuRA-NMS and different ANM functions in general [46].

2.3.2.1 Control Environment in Autonomously Regional Active Network Management System

The ANM control functions are integrated in the AuRA-NMS control platform for the HIL simulation that requires RT test environment to realize the function of close loop calculation solvers. The solvers are developed as the essential part of the control algorithms to perform constraint identification, objective function calculation, and problem reduction. The control algorithms are installed in an ABB COM6xx series substation automation controller, shown in Figure 2-6.

Figure 2-6: ABB COM600 Substation Automation Simulator

One of the ABBCOM6xx series hardware, ABBCOM600 box, is a robust substation automation controller integrated with functions of communication gateway, automation platform, and user interface solution in an all-in-one manner for utility and industrial distribution substations. The communication gateway provides connectivity functions between substation Intelligent Electronic Devices (IEDs) and network-level management systems via IEC61850 servers. The automation platform supported by its logic processor facilitates the implementation of substation-level automation tasks in a flexible way which can be realized with various control functions and application environments. And the user interface solution is achieved by Information Technology (IT) based functionalities which enable remote access to the substation controller and process via a web browser based Human Machine Interface (HMI) [47].

The COM600 controller is a Windows XP Embedded industrial computer which is based on ruggedized mechanics for robustness, and has no moving parts to wear or tear [47]. It has been designed to act in part as a substation gateway which translates between various legacy master/intra and slave/inner substation protocols using IEC61850 servers as a common data model and Open Process Control (OPC) technologies. These local and remote substation communication protocols include: DNP3; MODBUS; PROFIBUS; and IEC61850 using OPC and Manufacturing Message Specification (MMS) clients [47]. The COM600 comes with a readymade software interface to existing protection, control and monitoring systems as well as existing communication networks [48]. The structure of HIL test environment is shown in Figure 2-7, consisting of a RT power network simulator and two COM600 communication gateways (hosting the control algorithms) [44].

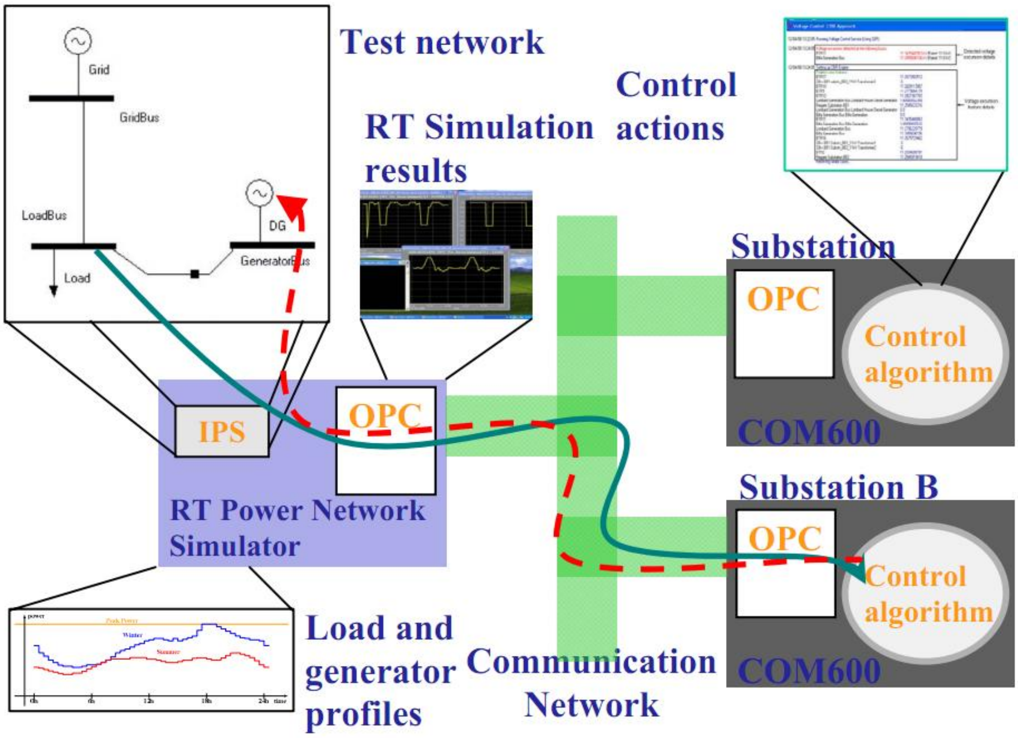


Figure 2-7: HIL Simulation Model for the ANM Control Platform [44]

The HIL simulation operates in C++ script and applies embedded Python script interface to IPSA software for the load-flow engine and manipulation. During the HIL simulation process, the test network is operating on-line load flow simulation in IPSA software which provides the profiles of load and generator. The on-line simulation results are transmitted to the substation automation controllers as the network response via OPC IEC61850 servers and Wide Area Network (WAN) communication network. Meanwhile, the ANM control algorithms are running in the substations to analyze the network response information and calculate the solutions for DNO network objectives. The control signals for different ANM control functions are transmitted back to the network simulator to implement the relevant operating activities according to the IEDs. The control loop keeps running for both problem solving and system recovering process. In addition, a Multi-Agent system (MAS) approach is adopted for the system flexibility and extensibility. The Foundation for Intelligent Physical Agent (FIPA) standards are deployed for interoperability assistance between multi-agent systems. Furthermore, a Distribution State Estimator (DSE) is applied for measurement reduction by the underlying control approaches.

2.3.2.2 Active Network Control Platform

The proposed architecture of the ANM control platform on a COM600 substation simulator is shown in Figure 2-8 [46]. The DSM control function is also integrated in this ANM control platform. The ANM control platform aims to integrate disparate control functions and network management tasks in a “plug and play” manner including:

- Steady-state voltage control: CBR [49] and CSP [48]
- Automatic restoration [50]
- Power flow management [51]
- Network optimization strategies [52]

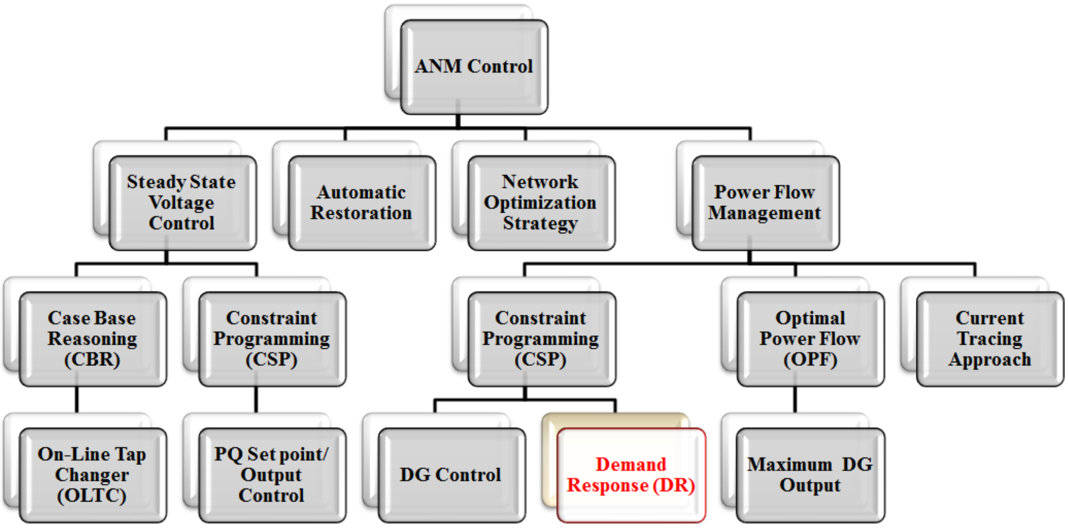


Figure 2-8: Control Function Integration in ANM Control Platform

The steady-state voltage control applies Case-Based Reasoning (CBR) data base technology to regulate the network voltage within statutory limits or DNO specific limits in a way that maximises DG energy yield under normal and abnormal conditions proactively and responsively of a potential voltage excursion without compromising security of customer supplies. The automatic restoration refers to the determination of reconfiguration in order to minimize the number of disconnected customers based on knowledge of the fault location and the pre-fault loading of feeders, which usually indicates the reduction of Customer Interruptions (CI) and Customer Minutes Lost (CML). The power flow management adopts the current tracing, the Constraint Satisfaction Problem (CSP), and Optimal Power Flow (OPF) control algorithms to alleviate the network overload within the network thermal limits when large amount of demand is introduced in the circumstance of increasing DG connections. And the network optimization strategies, also refers to the minimization or reduction of loss, focuses on the centralized Loss of Mains (LOM) by applying local active islanding detection techniques and remote control schemes such as transfer trip scheme, and power line signalling scheme.

As an optional support to the DNO's network constraint management, the DR on-line control function is also integrated in this platform. It implements direct demand control approaches to relieve the temporary thermal overload from the network. The control system autonomously curtails the contracted DR units within the scheme on the detection of overload constraint. It also takes consideration on other constraints such as contractual control priority and preferred curtailed amount of the DR units. It makes decision in the real time to obtain an optimal solution to satisfy all identified constraints. Thus, the CSP model is also adopted for this approach. As the essential part of this thesis, it will be presented in the follow chapters.

2.3.2.3 Steady-State Voltage Control

Three main control methods considered for coordinated steady-state voltage control within AuRA-NMS include: changing transformer tap position, changing power flow set-point, and control of real power output of distributed generator. The most common voltage control measure employed on distribution networks is the use of an On-Load Tap Changer (OLTC) to regulate the secondary voltage (reactive power provision or absorption) by selecting the appropriate tap position for a range of power flow conditions [53]. This control scheme is usually implemented according to an Automatic Voltage Control (AVC) relay and Line Drop Compensation (LDC) equipment. The line output voltage is continuously monitored for any voltage excursion by the AVC relay, while the voltage drop on the line between the transformer and loads situated toward the far end of the feeder is compensated by the LDC equipment [44].

Case Based Reasoning (CBR), which is applied to solve problems by retrieving the matched cases in the case base library, is a potential Artificial Intelligence (AI) technique being investigated for identifying possible voltage control solutions and providing the flexible voltage control required in the AuRA-NMS environment [54]. Compared to online control techniques, such as Optimal Power Flow (OPF), the CBR system can manage different types and sizes of network without risks of non-convergence: it can cope with network data corruptions and model errors; and it also can provide more practical solutions than deriving from first principle [44]. The retrieved cases are supposed to achieve a solution that can be reused and simulated for accesses. Furthermore, it is crucial to construct a thoroughly designed case based library, in which the voltage control parameters, such as voltage excursion location, the network topology information, and the tap changer position, are conserved. The operating principle of CBR on voltage control approach is shown in Figure 3-4 [48].

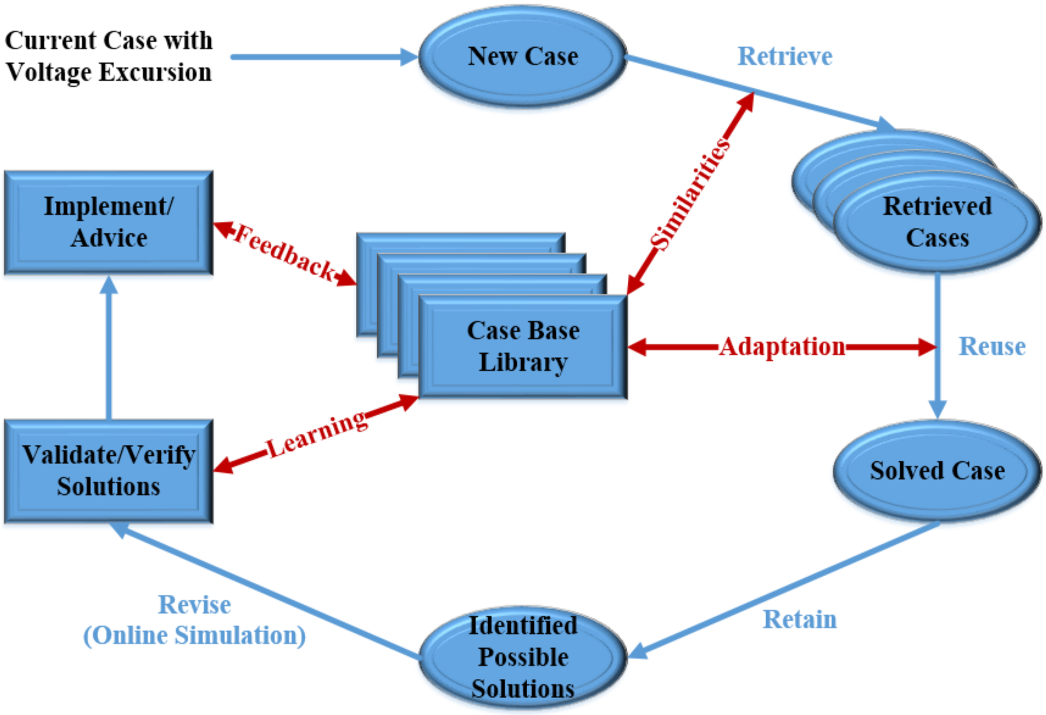


Figure 2-9: CBR Flowchart for AuRA-NMS Steady State Voltage Control [48]

When a new case with voltage excursion occurs, the attributes of the current case are compared with the cases in the case based library by CBR engine and similar cases are retrieved, ranked by the similarity. Then the solutions in these retrieved cases are reused to solve the current problem case. An online simulation tool is implemented to rank the effectiveness of all available credible control solutions, which will be measured against network criteria and DNO preferences, such as acceptable voltages, losses, and network securities, in response to the problem case. During the process, the unsuitable candidate solutions will be modified and recognized as a new one to update the case based library. The solutions which successfully pass online verification are given to the AuRA-NMS system for decision making [55]. The final implementation on the network will be deployed afterward.

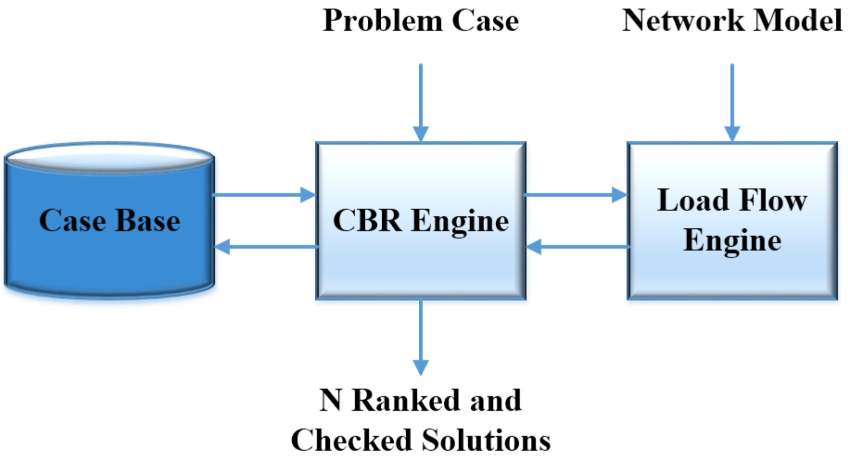


Figure 2-10: CBR Model for AuRA-NMS Steady-State Voltage Control [46]

The CBR control model for ANM steady-state voltage control is shown in Figure 3-5 [46]. The problem case is identified from DNO desirable objective functions and input to the CBR engine. The network model is simulated in a load flow engine for steady-state voltage violation detection with the problem case identification from the CBR engine. The network load flow response is returned to the CBR engine for control solution calculation. Then the CBR engine performs retrieve, reuse, retain, and revise actions with the case base library, shown in Figure 3-4, to obtain the N ranked solutions for the current case. Additionally, problem reduction algorithm is also required for the final solution output.

2.3.2.4 Power Flow Management

Electrical Power flowing within current distribution networks, with increasing distributed generation, can be unpredictable and variable due to the numerous power injection points [56]. Power flow management entails the management of DG in a manner such that thermal ratings of plant are not exceeded due to DG output [43]. The thermal rating limits constrain the DG connections in current network without further reinforcement. Besides the large cost of the network reinforcement, the time for seeking an appropriate network reinforcement plan and the correspondent technical supports will be a disincentive issue. An effective solution is to offer generators non-firm connections so that the power output of those distributed generators can be curtailed under network thermal conditions.

In the UK, current suggested practice is to use “Last in First Off” (LIFO) access rights for non-firm connections, under which regime the most recently connected DG must be curtailed first when a thermal excursion is detected [57]. Currently, the DNOs’ main practical techniques for dealing with thermal excursions are remedial schemes in particular cases. However, the proliferation of DG connections requires the incremental complexity and effectiveness control schemes, multiple remedial schemes, for a single power flow management solution from DNO perspective. Therefore, ANM-PFM approaches are developed: the current tracing approaches, the Optimal Power Flow (OPF) based approach, and the Constraint Programming (CP) based approach.

The OPF approaches have been investigated as minimization techniques in dealing with the constraints that are developed to achieve the objective of certain function associated with the most economic operation of the system. The minimization functions are usually relates to total cost of system operation, total system losses, and reactive requirements [58]. The analytical tool of OPF can be either on-line or off-line. The optimization techniques applied to solve the OPF problem can be summarized as: Non-Linear Programming (NLP), Quadratic Programming (QP), Linear Programming (LP), Mixed Integer Programming (MIP), and Interior Point Methods (IPM) [59]. However, limitations of the above techniques exist in terms of flexibility, adaptability and feasibility for ANM-PFM requirements. The OPF generation dispatch algorithm is a combination of the economic dispatch and the load flow problems which seek to find generation outputs that minimize a cost function. Simultaneously, satisfaction condition is made not only on the power balance equations but also on some additional network equality and inequality constraints representing the power system operating limits [56]. From the DNO perspective, the requirement energy loss and export curtailment minimization should be achieved while implementing the OPF generation dispatch algorithm to relieve PFM thermal constraint.

The Constraint Programming (CP) approach in generation dispatch based PFM involves modeling the power flow problem as a Constraint Satisfaction Problem (CSP) such that each controllable item of plant is considered as a variable in the problem [56]. It has its roots in the logic programming sub-field of artificial intelligence and has been applied in a number of different fields: its use in operations research as a means of solving scheduling problems and configuration problems in electronic serve [60]. The main objectives of CSP approach is to satisfy the power flow and contractual constraints as well as meet the DNO preference constraints when maximizing the DG accesses. To achieve these objectives, an off-the-shelf CSP solver and an off-the-shelf load flow engine are integrated with the COM600 simulator in figure 3-6 [46].

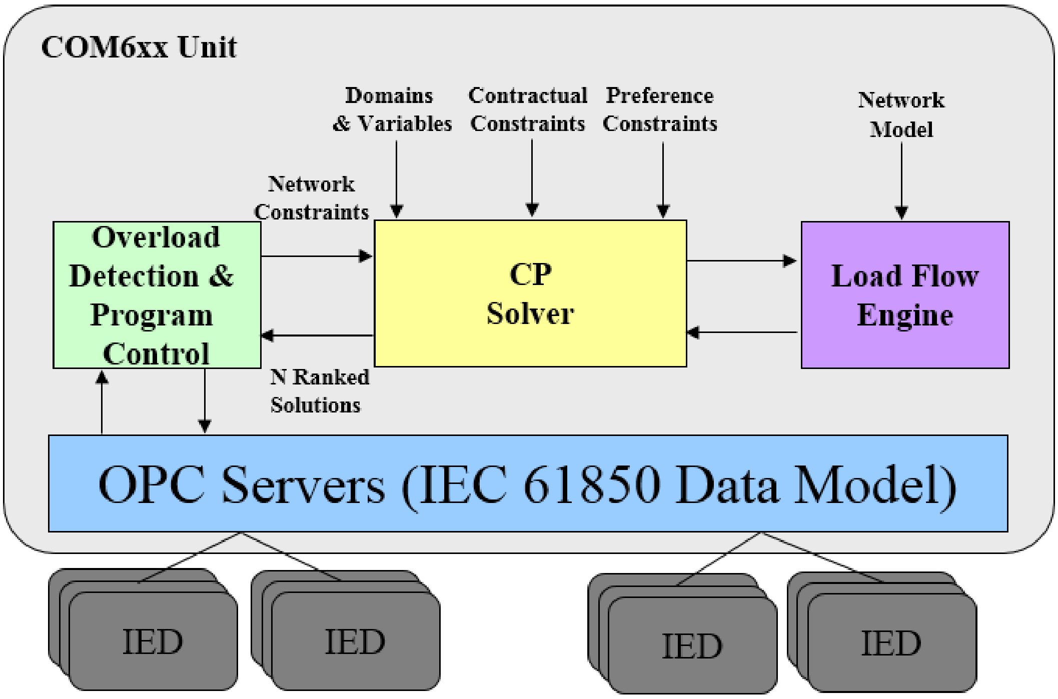


Figure 2-11: CSP Based Control Model for AuRA-NMS PFM [46]

The contractual constraints limit the DG access rights on possible solutions. Currently in the UK, LIFO network access rights are adopted for non-firm DG units. According to LIFO scheme, the priorities and the curtail bandings of each non-firm connection DG are ruled. An automatic curtailment algorithm will be implemented in the CSP solver for decision making in load flow engine. The load flow constraints limit the potential solutions in the form of control actions sent to the generators to ensure the thermal overload in any plant will not occur. In addition, the CSP solver also requires DNO preference constraints for the most feasible solution, i.e. maximize the DG access while meeting the contractual constraints.

2.3.3 Flexibility and Extensibility for Demand Response

The capacity reinforcement deferral and network constraint management are the main incentives for employing a novel network agnostic platform, AuRA-NMS, to realize active control of power flow within LV/MV distribution networks. It deploys a number of embedded generators by applying various control algorithms and the artificial intelligence technique of constraint programming for decision making in network planning problems. Through the adoption of Multi-Agent System (MAS) technologies, AuRA-NMS aims to provide a flexible and extensible means of developing solutions for a range of different types of network [48].

Flexibility is one of the most crucial attributes in a practical active network management system which must be adaptable for the control schemes that satisfies the existing network planning and operational agreement as well as the one in the future on both technical and commercial facets. It connotes the facilitation of system control reconfiguration and market participation rules, such as alternation of network topology and plant ratings, connection or removal of distribute generators and storage devices, changes of control and protection devices, installation and removal of measurement and monitoring equipment, regulatory framework adjustment, and the market in which generators connected to the network participation. Extensibility, otherwise, connotes the ability to adjust the network control and management functions for existing and future plans. As well as being flexible and extensible, AuRA-NMS is required to be safe, secure, tolerant to failure, and to possess the ability to exhibit graceful degradation in performance during adverse network conditions [61].

The requirement of flexibility and extensibility makes the ANM control platform in AuRA-NMS suitable for DR on-line control approaches. First of all, the control platform is designed to implement regional autonomous control with fast response time. It is applicable to realize DR on-line curtailment control approaches. Secondly, the capability of integrating various control functions provides a suitable environment to develop and deliver direct load control function. Thirdly, the substation automation controller and Open Process Control (OPC) based communication technology make it feasible to manage the Intelligent Electric Devices (IED) remotely while monitoring the network condition. Finally, the HIL simulation provides a safe and efficient evaluation to the control feasibility and performance.

2.4 Summary

This chapter has reviewed the principles of DSM and the active network control platform. DSM is considered as a non-build solution in DNO's network planning and operation activities. It contributes to network investment deferral, energy efficiency improvement, network constraint management and low carbon energy strategies. Demand side alternatives are the effective products or services that influence the consumer use of energy or change the pattern of demand in DSM applications. The adoption of demand side alternatives is considered with the cost-benefit analysis in various DSM schemes. The LCNF projects have implemented DSM based trials for practical demonstration. Meanwhile, the active network control platform provides an on-line autonomous control support to the distribution network constraints. The platform, AuRA-NMS, integrates multiple control functions in a substation automation controller with flexible design of the hardware and extensible development of the software. Therefore, it is applicable to integrate the on-line DR control function to relieve the network thermal overloads. This control approach aims to implement direct DR control actions to the flexible demand alternatives. It is an optional solution in the DNO's network constraint management activities.

2.5 Reference for Chapter 2

[1] L. Y. Seng and Philip Taylor, "Innovative Application of Demand Side

Management to Power Systems," in *Industrial and Information Systems, First International Conference on*, 2006, pp. 185-189.

[2] H. Yang, Y. Zhang, and X. Tong, "System Dynamics Model for Demand Side Management," in *Electrical and Electronics Engineering, 2006 3rd International Conference on*, 2006, pp. 1-4.

[3] C. W. Gellings, "The concept of demand-side management for electric utilities," *Proceedings of the IEEE,* vol. 73, pp. 1468-1470, 1985.

[4] C. E. Murillo-Sanchez, R. D. Zimmerman, C. Lindsay Anderson, and R. J. Thomas, "Secure Planning and Operations of Systems With Stochastic Sources, Energy Storage, and Active Demand," *Smart Grid, IEEE Transactions on,* vol. 4, pp. 2220-2229, 2013.

[5] V. J. Martinez and H. Rudnick, "Active Participation of Demand Through a Secondary Ancillary Services Market in a Smart Grid Environment," *Smart Grid, IEEE Transactions on,* vol. 4, pp. 1996-2005, 2013.

[6] O. Malik and P. Havel, "Active Demand-Side Management System to Facilitate Integration of RES in Low-Voltage Distribution Networks," *Sustainable Energy, IEEE Transactions on,* vol. 5, pp. 673-681, 2014.

[7] Wang Zhimin, Gu Chenghong, Li Furong, P. Bale, and Sun Hongbin, "Active Demand Response Using Shared Energy Storage for Household Energy Management," *Smart Grid, IEEE Transactions on,* vol. 4, pp. 1888-1897, 2013.

[8] C. W. Gellings, K. E. Parmenter, and P. Hurtado, "Efficient Use and Conservation of Energy," in *Efficient Use and Conservation of Energy*. vol. 2,

C. W. Gellings, Ed., ed: Eloss, 2008.

[9] J. Hong, "The Development, Implementation, and Application of Demand Side Management and Control (DSM+C) Algorithm for Integratiing Micro-Generation System within Build Environment," PhD, Department of Mechanical Engineering, University of Strathclyde, 2009.

[10] Charles River Associates, "Primer on Demand-Side Management with an Emphasis on Price-Responsive Programs," Washington, 2005.

[11] Energy Networks Association. (2013). *Independent Distribution Network Operators*. Available: http://www.energynetworks.org/

[12] EA Technology, "Operating the Electricity Transmission Networks in 2020—EA Technology's submission to National Grid's Consultation," 2009.

[13] Luo Tianyu, G. Ault, and S. Galloway, "Demand Side Management in a highly decentralized energy future," in *Universities Power Engineering Conference (UPEC), 2010 45th International*, 2010, pp. 1-6.

[14] X. Zhu, "Electricity Demand Side Management and its Different Promotion Measures," in *Power and Energy Engineering Conference, 2009. APPEEC 2009. Asia-Pacific*, 2009, pp. 1-6.

[15] M. S. Majid, H. A. Rahman, M. Y. Hassan, and C. A. Ooi, "Demand Side Management Using Direct Load Control for Residential," in *Research and Development, 2006. SCOReD 2006. 4th Student Conference on*, 2006, pp. 241-245.

[16] J. Fraisse, "Distributed generation relationship between producers, DNO,

TSO," in *Electricity Distribution - Part 2, 2009. CIRED 2009. The 20th International Conference and Exhibition on*, 2009, pp. 1-13.

[17] V. C. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, *et al.*, "Smart Grid Technologies: Communication Technologies and Standards," *Industrial Informatics, IEEE Transactions on,* vol. 7, pp. 529-539, 2011.

[18] G. Koutitas, "Control of Flexible Smart Devices in the Smart Grid," *Smart Grid, IEEE Transactions on,* vol. 3, pp. 1333-1343, 2012.

[19] M. Brenna, F. Foiadelli, P. Petroni, G. Sapienza, and D. Zaninelli, "Distributed generation regulation for intentional islanding in Smart Grids," in *Innovative Smart Grid Technologies (ISGT), 2012 IEEE PES*, 2012, pp. 1-6.

[20] F. Rahimi and A. Ipakchi, "Demand Response as a Market Resource Under the Smart Grid Paradigm," *Smart Grid, IEEE Transactions on,* vol. 1, pp. 82-88, 2010.

[21] N. Zafar, E. G. A. Phillips, H. Suleiman, and D. Svetinovic, "Smart grid customer domain analysis," in *Energy Conference and Exhibition (EnergyCon), 2010 IEEE International*, 2010, pp. 256-261.

[22] R. E. Brown, "Impact of Smart Grid on distribution system design," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century, 2008 IEEE*, 2008, pp. 1-4.

[23] Phil Sheppard, "2013 Electricity Ten Year Statement," National Grid, 2013.

[24] National Grid. (2014). *UK Future Energy Scenarios*. Available:

http://www2.nationalgrid.com/uk/industry-information/future-of-energy/future-energy-scenarios/

[25] Ofgem. (2014). *Low Carbon Networks Fund*. Available: https://www.ofgem.gov.uk/electricity/distribution-networks/network-innovation/low-carbon-networks-fund

[26] Kiwi Power. (2013). *Distribution Network Operators Trial Demand Side Response in the UK*. Available: http://demandresponseblog.com/tag/low-carbon-network-fund/

[27] Ofgem. (2010). *Creating Britain's Low Carbon Future and Today*. Available: https://www.ofgem.gov.uk/ofgem-publications/64028/lcnbro.pdf

[28] Ofgem. (2014). *Network Regulation - the RIIO Model.* Available: https://www.ofgem.gov.uk/network-regulation-%E2%80%93-riio-model

[29] Western Power Distribution, "FALCON Developing Future Power Networks," Ofgem, 2013.

[30] L. Sidebotham, "Customer-Led Network Revolution Progress Report 5," Northern Powergrid and Ofgem, 2013.

[31] Northern Powergrid, "Low Carbon Networks Fund - Full Submission Pro-forma," Ofgem, 2010.

[32] A. J. Howard, "Class Project Progress Report," University of Manchester, Electricity North West, 2014.

[33] A. Ballanti, L. F. Ochoa, Y. Guo, and H. Li, "Interim Report: Voltage Profile

Modeling and Study, Part A and Part B," University of Manchester, Electricity North West - Customer Load Active System Services, 2015.

[34] UK Power Networks, "Low Carbon London Project Progress Report June 2013," Ofgem, 2013.

[35] C. McNicol, "Project Progress Report for Capacity to Customers (C2C) Project," Ofgem, 2012.

[36] Scottish and Southern Energy, "New Thames Valley Vision Project Progress Report," Ofgem, 2013.

[37] Southern Electric Power Distribution, "Solent Achieving Value from Efficiency," Ofgem, 2014.

[38] K. Hoban, "Smart Street Project Progress Report," Manchester University and Queens University Belfast, Electricity North West, 2014.

[39] UK Power Networks, "Vulnerable Customers and Energy Efficiency," Ofgem, 2014.

[40] R. MacDonald, G. Ault, and R. Currie, "Deployment of Active Network Management technologies in the UK and their impact on the planning and design of distribution networks," in *SmartGrids for Distribution, 2008. IET-CIRED. CIRED Seminar*, 2008, pp. 1-4.

[41] S. N. Liew, A. Beddoes, and G. Strbac, "Ancillary Services Market Opportunities in Active Distribution Networks," presented at the Proceeding Second International Symposium on Distributed Generation: Power System and Market Aspects, Session 9: Active Network, 2002.

[42] D. Popovic, "A Technical Review and Assessment of Active Network Management Infrastructures and Practices," EA Technology DG/CG/00068, 2006.

[43] E. M. Davidson, M. J. Dolan, S. D. J. McArthur, and G. W. Ault, "The Use of Constraint Programming for the Autonomous Management of Power Flows," in *Intelligent System Applications to Power Systems, 2009. ISAP '09. 15th International Conference on*, 2009, pp. 1-7.

[44] P. C. Taylor, T. Xu, N. S. Wade, M. Prodanovic, R. Silversides, T. Green, *et al.*, "Distributed voltage control in AuRA-NMS," in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1-7.

[45] H. Halvorsen, "Hardware-In-the-Loop Simulation," Faculty of Technology, Telemark University College, 2011.

[46] E. M. Davidson, M. J. Dolan, G. W. Ault, and S. D. J. McArthur, "AuRA-NMS: An autonomous regional active network management system for EDF energy and SP energy networks," in *Power and Energy Society General Meeting, 2010 IEEE*, 2010, pp. 1-6.

[47] ABB Webpage. (2012). *Station Computer COM6xx*. Available: http://www.abb.com/product/db0003db004281/c12573e700330419c1257188002facd2.aspx

[48] P. Taylor, T. Xu, S. McArthur, G. Ault, E. Davidson, M. Dolan, *et al.*, "Integration Voltage Control and Power Flow Management in AuRA-NMS," presented at the Cired Seminar 2008: Smart Grid for Distribution, Frankfurt, 2008.

[49] X. Tao, P. Taylor, M. Prodanovic, T. Green, E. Davidson, and S. McArthur, "Case based reasoning for distributed voltage control," in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, pp. 1-4.

[50] J. V. C. Barros, R. F. Sampaio, R. P. S. Leao, L. S. Melo, and G. C. Barroso, "A multiagent approach to automatic restoration of distribution network," in *Innovative Smart Grid Technologies Latin America (ISGT LA), 2013 IEEE PES Conference On*, 2013, pp. 1-7.

[51] M. Dolan, E. Davidson, G. Ault, and J. McDonald, "Techniques for managing power flows in active distribution networks within thermal constraints," in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, pp. 1-4.

[52] L. McDonald, R. L. Storry, A. Kane, F. McNicol, G. Ault, I. Kockar, *et al.*, "Minimisation of distribution network real power losses using a smart grid Active Network Management System," in *Universities Power Engineering Conference (UPEC), 2010 45th International*, 2010, pp. 1-6.

[53] F. A. Viawan, A. Sannino, and J. Daalder, "Voltage control with On-Load Tap Changers in Medium Voltage Feeders in Presence of Distributed Generation," *Power Engineering Journal*, vol. 77, pp. 1314 - 1322, 2007.

[54] G. M. West and J. R. McDonald, "An SQL-Based Approach to Similarity Assessment within a Relational Database," presented at the 5th International Conference on Case-Based Reasoning, 2003.

[55] E. Davidson, S. McArthur, J. McDonald, and P. Taylor, "An architecture for

flexible and autonomous network management systems," in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, pp. 1-4.

[56] M. J. Dolan, E. M. Davidson, G. W. Ault, F. Coffele, I. Kockar, and J. R. McDonald, "Using optimal power flow for management of power flows in active distribution networks within thermal constraints," in *Universities Power Engineering Conference (UPEC), 2009 Proceedings of the 44th International*, 2009, pp. 1-5.

[57] D. Roberts, "Network Management Systems for Active Distribution Networks – a Feasibility Study," SP Power Systems LTD, Scottishpower PLC, DTI K/EL/00310/REP URN 04/1361, 2004.

[58] B. Weedy and B. Cory, *Electric Power Systems* vol. 6. Imperial College, London: John Wiley & Sons, 2004.

[59] J. A. Momoh, R. Adapa, and M. E. El-Hawary, "A review of selected optimal power flow literature to 1993. I. Nonlinear and quadratic programming approaches," *Power Systems, IEEE Transactions on*, vol. 14, pp. 96-104, 1999.

[60] K. R. Apt, *Principles of Constraint Programming* vol. 2. the Pitt Building, Trumpington Street, Cambridge, UK: Cambridge University Press, 2003.

[61] E. M. Davidson, S. D. J. McArthur, C. Yuen, and M. Larsson, "AuRA-NMS: Towards the delivery of smarter distribution networks through the application of multi-agent systems technology," in *Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century,*

2008 IEEE, 2008, pp. 1-6.

Chapter 3

Active Demand Control Technologies in Distribution Network

3.1 Overview of Chapter 3

The previous chapter has presented the principles of DSM and the active network control functions. An opportunity exists in integrating the DR on-line control function into the active network control platform to provide distribution network support. Thus, in this chapter, active demand control opportunity is discussed from the DNO's perspective. It includes network issue identification, demand side alternative selection, problem model design, and platform integration. A Constraint Satisfaction Problem (CSP) model is adopted to deal with the multiple constraint issues. Two new DSM based on-line control approaches are developed based on the CSP model. They are Demand Response for Power Flow Management (DR-PFM) and Hybrid Control for Power Flow Management (HC-PFM). DR-PFM implements DR curtailment control to relieve the network thermal overloads while considering the contractual priority and the preferred control depth of each DR units. HC-PFM investigates the further network solutions based on hybrid control of both DG and DR units. The control environment is identified for both of the approaches in a real distribution network. The control cycle and simulation model is also designed to evaluate the feasibility and effectiveness of the control performance. In the end, the realization problem of active demand response is discussed from 3 aspects: controllable demand, communication realization, and commercial model. This chapter provides methodology of the new DR on-line control approaches.

3.2 Active Demand Control Opportunity

The DNO focuses on the development of economic solutions to maintain a safe and reliable distribution network. The network thermal overload is one of the most concerned issues among the network constraints resulted from large DG connections within the future distribution network. The Power Flow Management scheme within the ANM control project (AuRA-NMS) provides autonomous control solutions to relieve the thermal constraint from the thermal overload issue. Although CSP based DG control, Optimal Power Flow (OPF), and current tracing approaches have been developed to solve this problem, opportunity exists from the demand side as an optional support. DSM has potential to benefit the DNO in managing the network constraints and deferring the capacity investment. Therefore, the problem solution is identified as DNO’s application of DSM control schemes to support the constraint management in distribution network.

As one of the DSM objectives (see Figure 2-1), flexible load shape contributes to energy supply support via adjustment of controllable loads such as interruptible load control, contractual consumption schedule, and service constraints from individual customer. As for adoption of demand side alternatives (see Table 2-1), dual-fuel heating systems in the category of efficient equipment and appliance options effectively support DNO’s direct load control (see DNO’s Perspective of DSM). It can be implemented in combination with electricity market based indirect load control and direct appliance schedule to obtain a satisfied demand response (DR) in the future smart grid. However, as for dealing with on-line network constraints, the controllable units that are available to provide DR curtailment control support are required to contract for this DSM scheme. Options exist in the arrangement of contractual priority and preferred control depth for each DR unit. Therefore, integration of this on-line DR control function into the existing ANM control platform is a new task. Additional, further control potential exists in the combination of control actions on both DG and DR units. The DG curtailment control is available to provide full range of curtailed amount from each unit, while the DR curtailment control is suitable to provide a flexible control pattern from diversified location.

Active demand control technologies is defined as the control approaches that fully or partially adopt the on-line DR control function to achieve the DNO's network objectives. The author's contribution is to develop new control approaches (both DR control and hybrid control) and integrate them into the ANM control platform, which is shown in Figure 3-1.

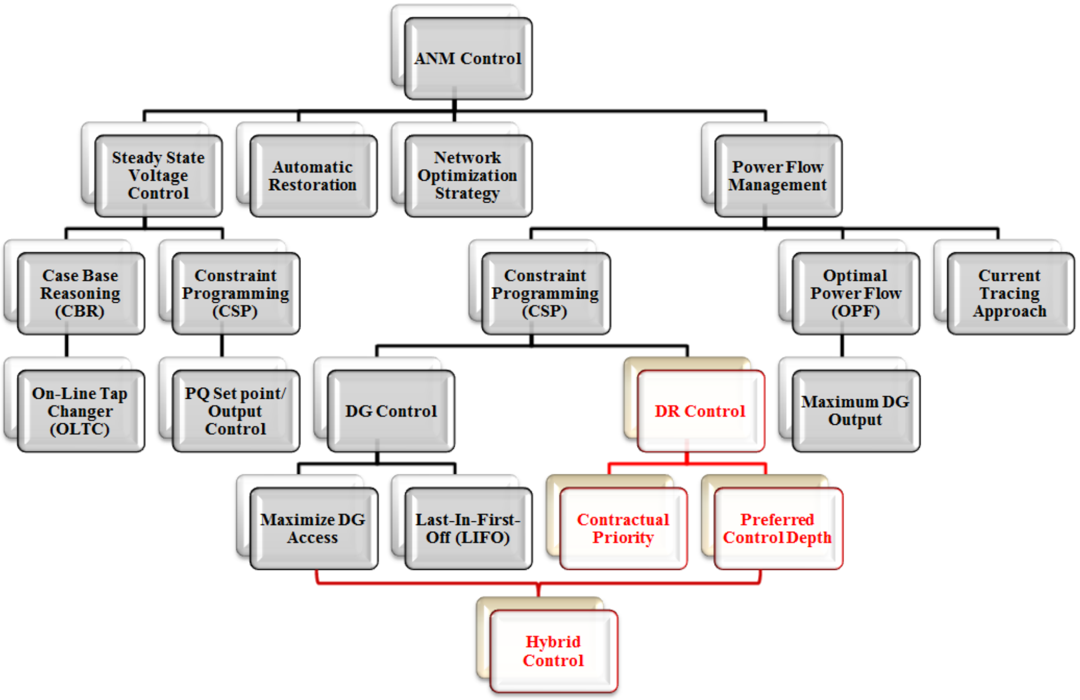


Figure 3-1: DR Control and Hybrid Control Integration in the ANM Control Platform

Since the network issue and the solution have been identified, a problem model is required to transfer a practical distribution network problem into a mathematical model that is operable to be solved under certain conditions. From the DNO's perspective, the thermal overload from the network should be relieved with the minimized control impact. Thus, the objective function of the on-line curtailment control solution is identified as the minimization of total curtailed real power from the controllable units. This includes all the DR units in a DR curtailment control action or all the DG and DR units in a hybrid curtailment control action. Meanwhile, besides the network thermal constraint, other constraints are also required to be concerned. One constraint is the financial incentive based contracts between the DNO and the controllable units, which clarifies the control priority list. Another constraint is the demand profile based preference in each controllable demand, which clarifies the maximum available real power that can be curtailed in a control action. Therefore a Constraint Satisfaction Problem (CSP) based model is adopted to compute solutions from these constraints. It is noted that financial incentive model and demand profile model are also important factors. However, this research only focuses on the feasibility and effectiveness of the DSM based on-line control performance. It is assumed that the DNO has a ranked financial incentive list which distinguishes the control order of each attendant. It is also assumed that the DNO has an agreement with each attendant to identify their preferred control depth. These two assumptions are based on the customer’s acceptance that is also required to be investigated in the future work.

3.3 Constraint Satisfaction Problem

Constraint Satisfaction Problem (CSP) is a problem model which transfers the factors of a problem in the real world into a certain mathematical format that facilitates the solution acquirement of the objective functions. It is applicable to solve multiple constraints in demand side control model such as network thermal rating constraint and demand response constraint. In comparison with other mathematical models, it takes advantages on easier problem reduction and faster computation response. The application of real problem solving by the CSP can be obtained in eight queens puzzles and graph coloring problem [1].

The CSP model is applied in ANM-PFM algorithms as an essential part of the solver to realize the thermal overload relief functions in network steady-state stability issues. It can be integrated in both DG units’ curtailment control function (generator dispatch approach) and DR units' curtailment control function (demand dispatch approach) and operates in combination with the load flow engine for solution calculation. In this thesis the CSP principle is applied in both the research of DR-PFM control approach and the further research of HC-PFM control approach.

3.3.1 Definition of Constraint Satisfaction Problem Parameters

A Constraint Satisfaction Problem (CSP) is defined as a mathematical problem to solve objective functions composed of "a finite set of variables, each of which is associated with a finite domain and a set of constraints that restricts the values the variables can simultaneously take" [1]. It is an objective function model that provides a different presentation of a problem in the real world, which facilitates the result obtaining process. Thus, variables, domains, and constraints are the critical participants in the CSP principle.

3.3.1.1 Variables

The variables are concerned as main aspects or stages of a real problem that may influence the process of the solution. The set of variables can be represented as:

$$V = \{v_1, v_2 \cdots v_n\} \tag{3.1}$$

Where v_n refers to the n^{th} variable in the variable set.

3.3.1.2 Domains

The domain of a variable can be identified as a set of optional values that can be assigned to the corresponding variable. The variables can be classified to numerical variables, Boolean variables, and symbolic variables according to the type of their domain components. Thus, the domain of a variable v can be represented as follows:

$$D_v = \{a, b, c \cdots\} \tag{3.2}$$

Where a, b, c refer to different values in the domain set D_v for the assignment of variable v.

And the domain set of the problem can be defined as the integration of all the domains of the variables in such problem:

$$D = \{D_1, D_2 \cdots D_n\} \tag{3.3}$$

Where D_n refers to the domain of the n^{th} variable. Additionally, the domain of the problem can also be represented in a form of $k * n$ matrix if all the domains of variables have the same dimension.

3.3.1.3 Labels and Compound Labels

During the variable assignment process, a variable-value pair is defined as a label, L, which represents the assignment of the value to the variable:

$$L = < v, d >, \qquad (d \in D_v) \tag{3.4}$$

Where v refers to a component in the variable set, d refers to a component of value in domain set, and D_v refers to the domain of variable v in Equation 3.2. And the label is only meaningful if the value d belongs to D_v, the domain of variable v. Assigning a value to a variable is also named as labeling a variable.

As for assigning values to a set of variables, however, the process in Equation 3.4 occurs in each variable separately. Therefore, the concept of a compound label is introduced which refers to a set of labels in the form of Equation 3.5 which denote the assignment of values to a set of variables simultaneously. The assignment of the domain values d_1, d_2… d_n, to the corresponding variables v_1, v_2… v_n can be represented in a compound label, L_c, as follows:

$$L_c = \{<v_1, d_1>, <v_2, d_2> \cdots <v_n, d_n>\} \tag{3.5}$$

Where $<v_n, d_n>$ refers to the label of the n^{th} variable-value pair. In addition, the above equation, Equation 3.5, also refers to an n-compound label with the assignment of n values to n variables simultaneously. Therefore, an assignment of multiple variables is defined as an n-compound label if the dimension of such variable-value pairs equals to n.

And the variables of an n-compound label are defined as the set of all variables that appears in such compound label. Thus the dimensions of both the variable set in Equation 3.1 and the n-compound label set in Equation 3.5 are the same:

$$V = \{v_1, v_2 \cdots v_n\} \equiv L_c = \{<v_1, d_1>, <v_2, d_2> \cdots <v_n, d_n>\} \tag{3.6}$$

3.3.1.4 Projection

As for the relationship between two compound labels, a further definition of projection is made to deal with the issue. A projection of an m-compound label M to an n-compound label N is defined if m and n are the integers such that $m \leqslant n$, and the labels in M all appears in N. Therefore M being a projection of N can be represented as follows:

$$P(M,N) \Leftrightarrow (M \subseteq N) \,\&\, (m \leq n) \tag{3.7}$$

Where:

$Dim(M) = m$ and $Dim(N) = n$

And M and N refer to two compound labels, in which m and n refer to their dimensions. The proposition $P(M, N)$ is true if and only if the conditions of M belonging to N and m being no larger than n are satisfied.

3.3.1.5 Constraints

The constraints is defined as a series of restrictions on the value assignment that can be concerned as a set of objective compound labels for problem solution. They can be represented as various mathematical approaches such as functions, inequalities, distributions, and matrices:

$$C = \{C_1, C_2 \cdots C_p\} \tag{3.8}$$

Where C_p refers to the P^{th} constraint of the problem. It is noted that C_p is a subset of C which contains several n-compound labels of all the variables in the problem.

And the variables of a constraint are defined as the set of all variables that relates to the constraint which can be represented as follows:

$$V = \{v_1, v_2 \cdots v_n\} \equiv C_p(v_1, v_2 \cdots v_n) \tag{3.9}$$

Where C_p is a subset of C in Equation 3.8 which relates to all the variables in the problem.

In addition, a constraint is defined as an n-constraint if the number compound labels in the set equals to n. Thus the dimensions of the variable set V in Equation 3.1, the domain set D in Equation 3.3, and the n-constraint subsets in Equation 3.8 are coherent in the objective problem with n variables.

3.3.1.6 Subsumed-By

As for the relationship between two constraints, a further definition of subsumed-by is made to deal with the issues. It is assumed that an m-constraint set C_M and an n-constraint set C_N with the integers m and n which fulfill the condition such that $m \leqslant n$. It is defined that C_M is subsumed-by C_N, represented as $S(C_M, C_N)$, if for any compound label L_{cM} in C_M there exists a compound label L_{cN} in C_N such that L_{cM} is a projection of L_{cN}. The equation of subsumed-by $S(C_M, C_N)$ is represented as follows:

$$S(C_M, C_N) \Leftrightarrow \forall L_{cM}, \exists L_{cN} : P(L_{cM}, L_{cN}) \,\&\, (m \leq n) \tag{3.10}$$

Where:

$L_{cM} \in C_M$ and $L_{cN} \in C_N$

$Dim(C_M) = m$ and $Dim(C_N) = n$

And C_M and C_N refer to two constraint sets, L_{cM} and L_{cN} refer to two compound labels, and m and n refer to the dimensions of C_M and C_N. The proposition $S(C_M, C_N)$ is true if and only if for any L_{cM} in constraint set C_M, there is a L_{cN} in constraint set C_N such that the following conditions are satisfied. The conditions are L_{cM} being a projection of L_{cN} and m being no larger than n.

3.3.1.7 Satisfiability

As another significant part of CSP sections, satisfiability is defined as a binary logical relationship between a label or a compound label and a constraint set. Satisfiability of s single constraint can be achieved between a compound label L_c and a constraint set C_p if and only if L_c is one of the subsets in C_p, and the variables of L_c are the same as the ones of the compound labels in C_p. Therefore, L_c satisfies C_p can be represented as follows:

$$Satisfies(L_c, C_p) \Leftrightarrow L_c \subseteq C_p \tag{3.11}$$

Where:

$$V = \{v_1, v_2 \cdots v_n\} \equiv L_c = \{<v_1, d_1>, <v_2, d_2> \cdots <v_n, d_n>\}$$

$$V = \{v_1, v_2 \cdots v_n\} \equiv C_p(v_1, v_2 \cdots v_n)$$

And L_c has the same dimension as C_p of variables that derive from Equation 3.6 and Equation 3.9. Thus, the equation, Equation 3.11, refers to satisfiability of a single constraint.

Then satisfiability of the problem with all constraints can be defined based on Equation 3.11. Satisfiability between a compound label L_c and a set C of all the constraints in the problem can be achieved if and only if the projection of L_c can represent any subset of the constraint set C and the variables of L_c are the same as the ones of all the compound labels in any C_p in constraint set C. Thus, the compound label L_c satisfies constraint C is represented as follows:

$$Satisfies(L_c, C) \Leftrightarrow \forall C_p \subseteq C : P(C_p, L_c) \tag{3.12}$$

Where:

$$V = \{v_1, v_2 \cdots v_n\} \equiv L_c = \{< v_1, d_1 >, < v_2, d_2 > \cdots < v_n, d_n >\}$$

$$V = \{v_1, v_2 \cdots v_n\} \equiv C_p(v_1, v_2 \cdots v_n)$$

$$C = \{C_1, C_2 \cdots C_p\}$$

And L_c has the same dimension as C_p of variables that derive from Equation 3.11. It is noted that as a subset of C, C_p contains compound labels as lower level of subsets.

3.3.2 Formal Definition of Constraint Satisfaction Problem

So far, definitions and explanations have been made to variables, domains, labels, compound labels, projection, variables of a compound label, constraints, variables of a constraint, subsumed-by, satisfiability of single constraint, and satisfiability of the problem, from Equation 3.1 to Equation 3.12 [1]. And a formal definition of CSP can be made based on the previous principles.

Formally, a CSP can be defined as a problem with triple factors [1]:

$$CSP(P) = (V, D, C) \tag{3.13}$$

Where V represents a finite set of variables that represent the problem:

$$V = \{v_1, v_2 \cdots v_n\}$$

D represents a finite set of objectives of any type that represents a function which maps every variable in *V* to a set of objects with arbitrary type. It is noted that D_{vn} represents the domain of variable v_n. And it contains all the possible values for the assignment of the variable v_n.

$$D = \{D_{v1}, D_{v2} \cdots D_{vn}\}$$

And C represents a finite set of constraints on an arbitrary subset of variables in *V*, which restricts the variables and compound labels to satisfiability. It is noted that *C* is a set of sets of compound labels.

$$C = \{C_1, C_2 \cdots C_p\}$$

Therefore, the objective of solving a CSP is to obtain all the compound labels that satisfy the constraints of the problem from the domains over the identified variables. To achieve such function, Constraint Programming (CP) solvers are developed for the application of various problems.

3.3.3 Constraint Programming

Constraint Programming (CP), as the essence part in a CSP based functions, is applied to deal with the domain specific problem with a finite set of relations, which “embodies such diverse areas as Linear Algebra, Global Optimization, Linear and Integer Programming, etc.” [2]. It is applied to solve complex planning and scheduling problems with logical constraints and discrete variables. A CP engine makes decisions on the compound label of variables and performs a series of logical inference to the remaining domain options for problem reduction until no better solution is obtained. In the case that more than one set of variable assignments are suitable when all constraints are met, the CP engine can be set to output "either a user-defined number of solutions in *best-first* manner or to exhaustively search for all possible solutions" [3].

3.4 Constraint Satisfaction Problem Based Demand Control Models

In this section, two CSP based demand control models are developed: Demand Response for Power Flow Management (DR-PFM) and Hybrid Control for Power Flow Management (HC-PFM).

3.4.1 Demand Response for Power Flow Management

Demand Response for Power Flow Management (DR-PFM) is defined as the implementation of DR control actions to deal with potential thermal overloads for PFM. It focuses on minimization of MW curtailed from the demand instead of operational cost optimization in constraint management. The novelty of this control approach is the integration of CSP principle to DR-PFM in the application of constraint management objective function. This also benefits the real life trials of demand response and may also contributes on some of the Low Carbon Network Funds (LCNF) projects [4].

In DR-PFM application environment, the CSP parameters of variables, domains, and constraints defined in Section 3.3 are redefined with their new practical meanings. The variables represented by a set of controllable devices refer to the performance of the contractual demand such as DR units or storage devices. The values of these variables are assigned via the satisfaction criteria of the pre-determined finite domains and constraints. The domains, also named as control bands, refer to the adoptable control actions performed to the controllable demand. They constitute the solution sets of the variables. The constraints refer to the requirements of the control task that have to be achieved simultaneously. They are the prerequisite of the variables' assignment.

The general CSP expression in DR-PFM application environment is derived from the formal CSP definition in Equation 3.13, which can be represented as follows:

$$CSP(P_{DR}) = (V_{DR}, D_{DR}, C_{DR}) \tag{3.14}$$

Where V_{DR} refers to the finite set of demand variables, D_{DR} refers to the domain solution sets of each variable, and C_{DR} refers to the constraints applied to determine limit variable assignments.

The variables of DR-PFM are defined in the form of a flexible demand set, which can be represented as follows:

$$V_{DR} = \{L_1, L_2, ...L_n\} \tag{3.15}$$

Where L_n refers to the n^{th} contractual DR unit in the control area. The contractual DR units in such variable set are assumed to be flexible demands which can be controlled directly in this DNO-DSM scheme.

The domain set of DR-PFM is defined as a matrix of values which represents the curtailment percentage of the real power consumption in the contractual demand variables:

$$D_{DR} = \{D_{L1}, D_{L2}, ...D_{Ln}\} \tag{3.16}$$

Where D_{Ln} represents the set of control bands which contains the available curtailment options of the n^{th} DR unit.

The subsets of domain for each variable can be represented with different control bands, which are represented as follows:

$$\begin{aligned} D_{L1} &= \{a_1, a_2, \ldots a_m\} \\ D_{L2} &= \{b_1, b_2, \ldots b_n\} \\ &\vdots \\ D_{Ln} &= \{v_1, v_2, \ldots v_x\} \end{aligned} \tag{3.17}$$

Where a_m, b_n, and v_x are the sorted numbers between 0 and 1, which represents the percentage of power consumption curtailed in a given control action. Such control bands are arranged differently according to the requirements of these demand profiles.

Thus, the potential control solutions can be represented in the form of n-compound labels with the definition of V_{DR} in Equation 3.15 and D_{DR} in Equation 3.16 and Equation 3.17:

$$L_c = \{< L_1, a_m >, < L_2, b_n > \cdots < L_n, v_x >\} \tag{3.18}$$

Where a_m, b_n… v_x refer to any values in the domain sets D_{L1}, D_{L2}… D_{Ln} on their variables L_1, L_2... L_n respectively. It means that any combination of such variables and the relevant domain values in the form of n-compound labels as shown in Equation 3.18 is concerned as one of the potential solutions. However, satisfiability of such CSP problem can be achieved by identifying its constraints.

In the DR-PFM model, three constraints are defined for decision making of the control action implementation which includes network constraint, preference constraint, and contractual constraint:

$$C_{DR} = \{C_n, C_p, C_c\} \tag{3.19}$$

Where C_n (network constraint), C_p (preference constraint), and C_c (contractual constraint) are aimed to be satisfied simultaneously to obtain the proper domain pattern for variable assignment.

The network constraint, also known as power flow constraint, refers to the maintaining of the seasonal thermal rating limits on each cable in the network. The contractual constraint refers to the priority list that enables DNO load control based on customer participation contracts. The preference constraint refers to the level of demand control in that for a given priority or contractual constraint the minimum level of demand will be curtailed to alleviate the thermal congestion. It contributes to the exploration of the preferred variable solution in domain options for minimum demand curtailment with the customer agreement. The above constraints identify the criteria of domain value selection from the pre-determined pool in Equation 3.17.

Therefore, the process of solving a CSP based DR-PFM control task can be achieved in the following steps. As for a DR-PFM problem presented in Equation 3.14, with variables of controllable demand defined in Equation 3.15, the CSP approach will be implemented to evaluate potential solutions of control action dispatch within the domains in Equation 3.16 and 3.17. Such control action dispatch is represented in the form of n-compound labels in Equation 3.18. Thus, satisfiability can be achieved by those compound labels, the projection of which can represent any subset of the constraints defined in Equation 3.19 simultaneously. And the output solution of the CSP solver is restricted to a single n-compound label by the three constraints, especially by the preference constraint of demand curtailment minimization, in DR-PFM application environment.

3.4.2 Hybrid Control for Power Flow Management

To extend the control function of the DR-PFM approach, a study of a new control pattern is investigated to achieve the same thermal constraint described in Chapter 4. The new control pattern includes a set of controllable DR units and a set of adjustable DG units. As discussed previously, the DR-PFM approach takes advantages on enables demand participation. However, the requirement of demand control is restricted by the profiles and environment. The control efficiency is relevantly low comparing with the generation dispatch control. Thus, this new control pattern has potential to provide a more efficient and economical way in the control performance. This control approach is called Hybrid Control for Power Flow Management (HC-PFM).

The CSP solver is also applied as the essential part of the algorithm. The CSP parameters, variables domains and constraints, are redefined in this new control environment. The variables, represented as a set of finite arrays, indicate the control participants including all the available controllable DR and DG units. Control variable values are assigned in solving process of the CSP in accordance with domains and constraints. The domains, represented as a set of discrete decimal fraction, identify the feasible control actions that can be implemented on each variable. The control intervals and control depth of each variable are pre-determined in the domain set. And the constraints refer to the control objectives that should be satisfied simultaneously for an appropriate value assignment of the variables. They are identified as allowable control actions via DNO contracts, supplier and customers' preferences, and network requirements such as inacceptable voltage fluctuation, power flow congestion, and unpredictable environmental limitation.

The general CSP expression in HC-PFM application environment is also derived from the formal CSP definition in Equation 3.13, which can be represented as follows:

$$CSP(P_{HC}) = (V_{HC}, D_{HC}, C_{HC}) \tag{3.20}$$

Where V_{HC} refers to the finite set of variables, D_{HC} refers to the finite set of domain integration, and C_{HC} refers to the constraints for control requirements. In this manner, the HC-PFM problem is described as a constraint function of variables in the domain set.

The solution of the problem returns to a series of control actions on the variable set of the DG and DR units. Such variable set can be defined in a double matrix form as follows:

$$V_{HC} = \begin{pmatrix} G_1 & G_2 & \cdots & G_m \\ L_1 & L_2 & \cdots & L_n \end{pmatrix} \tag{3.21}$$

Where G_m represents the m^{th} DG unit and L_n represents the n^{th} DR unit in the control area. It is noted that the dimension of the DG variable set, m, is not usually equals to the one of the DR variable set, n.

The domain set of HC-PFM is also defined as a double matrix of Boolean values which represents the curtailment percentage of real power output or consumption of the contractual DG or DR variables:

$$D_{HC} = \begin{pmatrix} D_G \\ D_L \end{pmatrix} \tag{3.22}$$

Where D_G refers to the domain set, or the control band set, of the DG variables and D_L refers to the ones of the DR variables. Such domain set constrains the available curtailment options of the DG or DR variables.

The expansion of the domain sets of both DG and DR variables are also defined in the matrix form respectively, which are represented as follows:

$$D_G = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1x} \\ a_{21} & a_{22} & \cdots & a_{2x} \\ \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mx} \end{pmatrix} \tag{3.23}$$

$$D_L = \begin{pmatrix} b_{11} & b_{12} & \cdots & b_{1y} \\ b_{21} & b_{22} & \cdots & b_{2y} \\ \vdots & \vdots & \ddots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{ny} \end{pmatrix} \tag{3.24}$$

Where a_{mx} and b_{ny} refer to the elements in the matrix are the sorted values between 0 and 1 which indicate the allowable control levels of the DG and DR variables. Such allowable control levels are arranged differently according to the requirements of the DG or DR profiles. For instance, a domain value of 0.7 indicates that the variable of the DG or DR unit is constrained to 70% of its real power output or consumption in a certain control action.

Thus, the potential control solutions can be represented in the form of double compound labels each of which comprises an m-compound label of DG variables and an n-compound label of DR variables. The expression of such double compound labels can be derived from the definition of V_{HC} in Equation 3.21 and D_{HC} in Equation 3.22, Equation 3.23, and Equation 3.24:

$$L_c = \{ \begin{matrix} < G_1, a_{1x} >, < G_2, a_{2x} > \cdots < G_m, a_{mx} > \\ < L_1, b_{1y} >, < L_2, b_{2y} > \cdots < L_n, b_{ny} > \end{matrix} \} \tag{3.25}$$

Where $<G_{m,} a_{mx}>$ refers to the variable-value assignment pair of the mth DG variable and $<L_{n,}\, b_{ny}>$ refers to the one of the n^{th} DR variable. A double compound label indicates one possible solution of control actions for all the variables. In order to screen the desirable solution from the double compound labels, however, satisfiability of the presented CSP problem can be achieved according to its predetermined constraints.

The constraints which performed as a solution filter in distributed control of PFM can be summarized as the logical conjunction of network constraint, contractual constraint, and preference constraint:

$$C = (C_n, C_p, C_c) \tag{3.26}$$

Where C_n C_p and C_c refer to the network constraint, the preference constraint, and the contractual constraint respectively. The CSP solver searches for the applicable double compound labels until satisfiability is achieved with the satisfaction of all these three constraints simultaneously.

The network constraint, known as power flow constraint, refers to the thermal limit of distribution circuits which is the main objective of the PFM. The contractual constraint refers to the prioritization of the DR and DG units based on customer participation contracts for the arrangement of curtailment order (also known as ‘principles of access’ [5]). And the preference constraint refers to the desired control level for all participants that is reflected in the minimization of power curtailment for a given set of network and contractual constraint as well as the prevailing network state.

The above definition identifies the application of CSP solver to the ANM-PFM distributed control problem. For a given HC-PFM problem presented in Equation 3.20, the control variables for both DR and DG units are identified in Equation 3.21.

The PFM control system keeps monitoring the system with the constraints in Equation 3.26. Once the network constraint is detected (according to measurements and thresholds levels), the CP algorithm will be activated to compute the optimal solution from the domains in Equation 3.22, Equation 3.23, and Equation 3.24 according to an iterative load flow engine. This load flow engine is driven by the CSP solver and performs load flow simulation in IPSA software. Then the optimal solution will be assigned to the variables in Equation 3.20 from the double compound labels in Equation 3.25 when satisfiability is achieved by the satisfaction of all the constraints in Equation 3.26. Afterwards, the CSP solver will be in standby status until next control action is required from the monitoring system.

3.4.3 CSP Search for Control Solutions

The active control solutions are computed by the CSP solver that integrates the identified variables, domains, and constraints. In an on-line control activity, the solver continuously operates to obtain the compatible variables' assignment labels from the domain sets limited by the constraints. It also generates an optimal solution to achieve the objective function. In the active demand control approaches, it is defined as the minimization of the total curtailed real power. However, the computation system within the CSP solver is still a black box. Thus, CSP solution search, computation complexity and problem reduction are presented in this subsection.

The main algorithm within the CSP solver is a chronological backtracking search loop, shown in Figure 3-2 [1]. For a given active demand control problem, the basic operation of the system is to label one variable at a time. It means to pick a variable from the variable sets and assign a value for it from the relevant domain set. The newly labelled variable should be accordantly with the existing variables in a compound label, which indicates that no repetition is allowed. Then the system examines the compatibility of the selected label to the constraint labels. If the selected label is compatible with the all the constraints, the system moves from the current state to the next state and continuously pick other variables. If the selected label violates certain constraints, an alternative value in the relevant domain set will be assigned to the variable for the next compatibility examination. However, if all the values are examined and failed in the compatibility examination, the system will operate in a backtracking loop. It will return to the previous state and revise the last picked label. This process carries on until a compatible label is found. The system will output a solution (or a compound label) if all the variables are labelled without any constraint violation. An optimal solution is obtained from the solution set according to the objective function of the main problem. In the case that all the combinations of labels have been examined and failed to backtrack to the previous state, a convergence problem occurs. The system will return with no solution and start to solve the next problem.

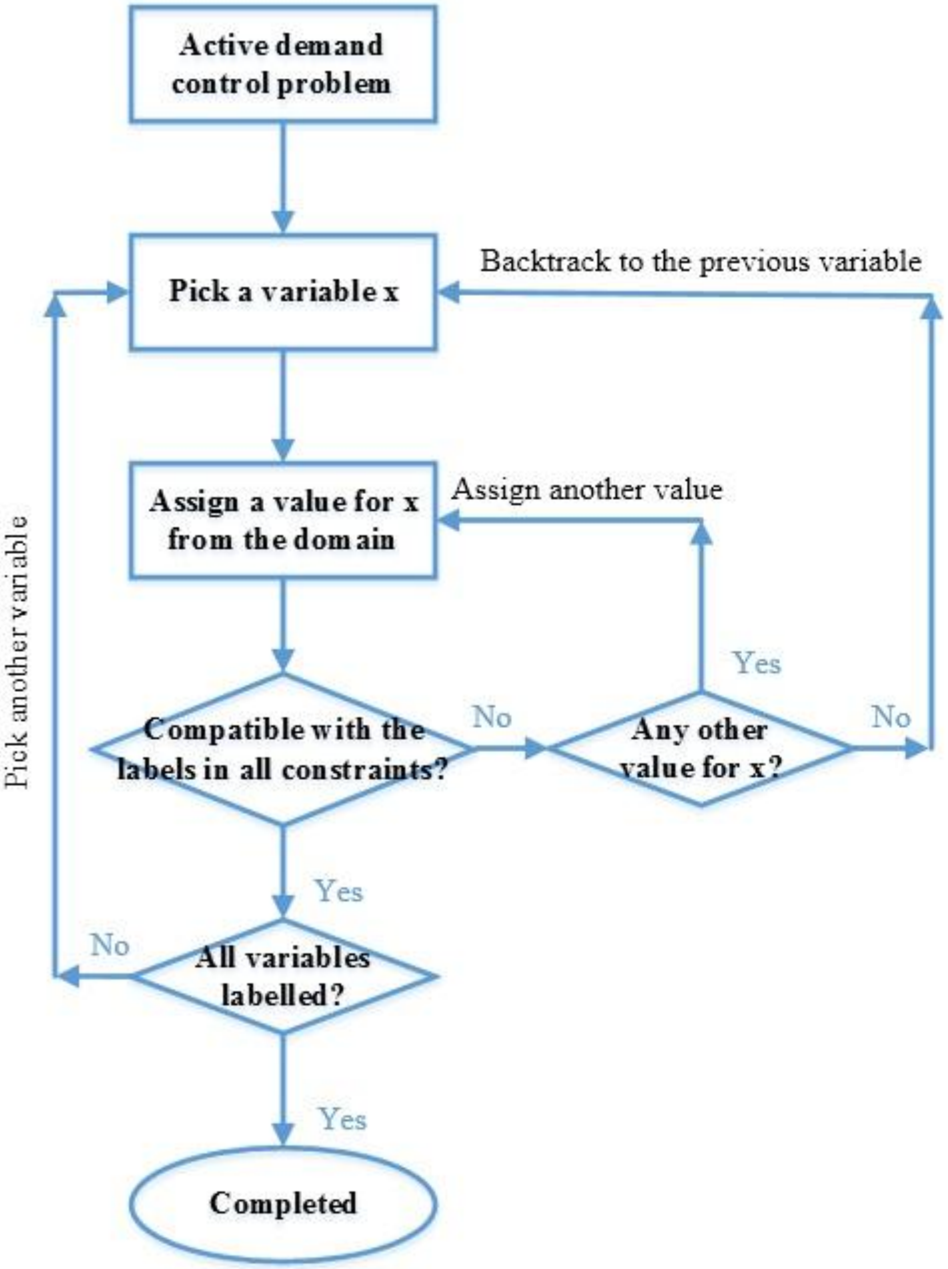


Figure 3-2: Chronological Backtracking Loop for Solution Search [1]

The computation time to obtain an optimal solution is influenced by the size of the search space that depends on the number of the variables and the relevant domain size. The search space is defined as the total number of the computation times in a problem solving process. The search process that includes both forward and backtracking actions is organized by following each branch of a large tree diagram. In the tree diagram, the variables and the domain values are located in adjacent levels. Thus, the total search space size can be calculated by the product of all the domain size. The tree diagram for the CSP search process is shown in Figure 3-3. It is noted that V_k represents the kth variable and D_{km} represents the mth value in the kth domain set. The kth domain is the domain of the kth variable. $|D_n|$ represents to the size of the nth domain.

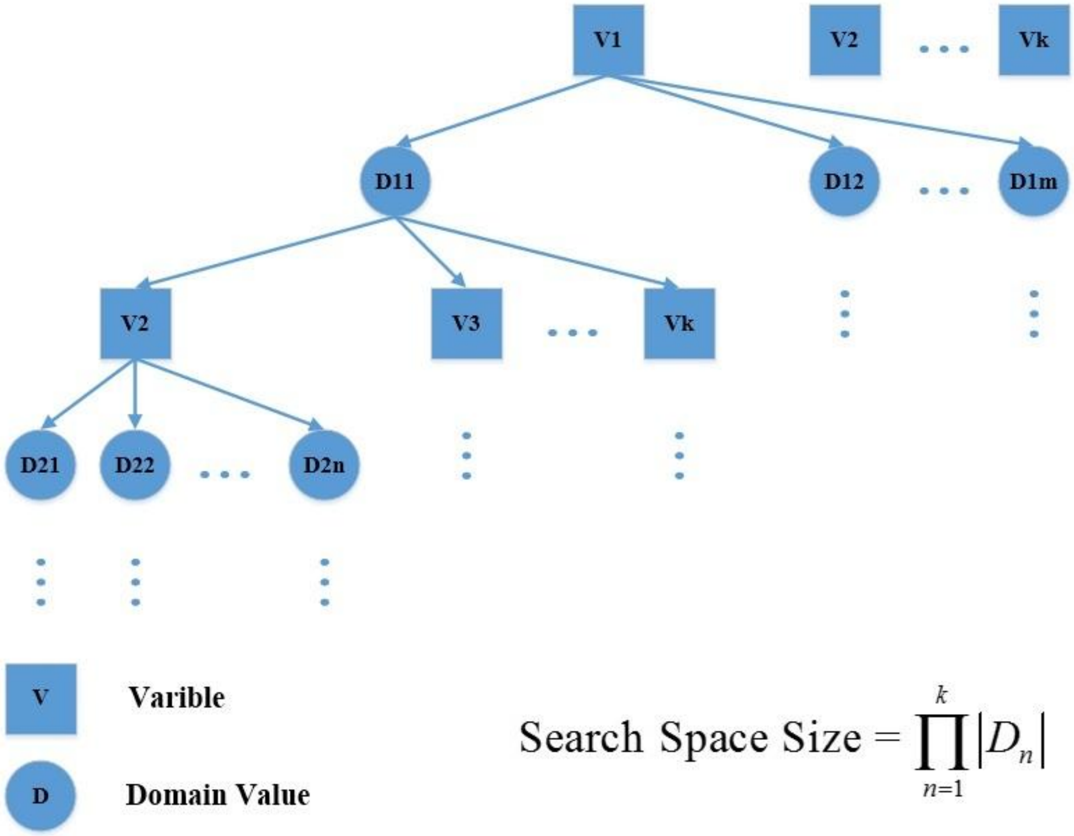


Figure 3-3: Tree Diagram for the CSP Search Process

The search process obeys a Depth-First Search (DFS) criterion which “starting from the rood node and selecting a child node to assign a domain value based upon meeting the problem constraints” [6]. The system will continuously search in a downward direction until all the possible paths are passed. Then the search moves to the adjacent child node for further operating. In Figure 3-3, the search follows the direction of V_1, D_{11}, V_2 and D_{21}. It moves from left to right until all the available options under V_1 is exhausted. Then the next variable V_2 will be examined.

Since the computation complexity is influenced by the search space size of the problem, the CSP solver may experience longer response time when dealing with a complex problem with more variables and domain values. Thus, computation reduction is required to reduce the search space, avoid repeatedly searching futile sub-trees, and detecting insoluble problems [1]. As for the active demand control problem, this can be achieved by the arrangement of the ordering variables under the DFS criterion. It means that a unit A with a higher priority will never be curtailed unless all the units with lower priorities are curtailed. In this case, no more solution is searched for all the units that possess higher priorities than the unit A. Although this approach never contributes to reducing the search space size, it effectively reduces the computation complexity by removing all the impermissible assignments.

3.5 Control Environment in a Distribution Network

ANM refers to the application of communication, automation, and control algorithms to manage the network constraints associated with the increasing number of DG access. The capacity reinforcement deferral and network constraint management are concerned as the main contribution on developing this novel ANM approach.

As one of the ANM control approaches, the active demand control algorithm is applied to a close-loop test environment based on an ABB COM6xx series substation automation controller which implements regional curtailment control actions via IEDs. The ABB COM600 box is a Windows XP embedded industrial computer workstation. It has been designed and acts as a gateway that can translate between different legacy master/intra and slave/inner substation protocols using IEC61850 servers as common data models and OPC technologies to provide an open, flexible and “plug-and-play” software environment. Thus, it is designed as a software interface to the existing protection, control and monitoring systems as well as existing communication protocols [7].

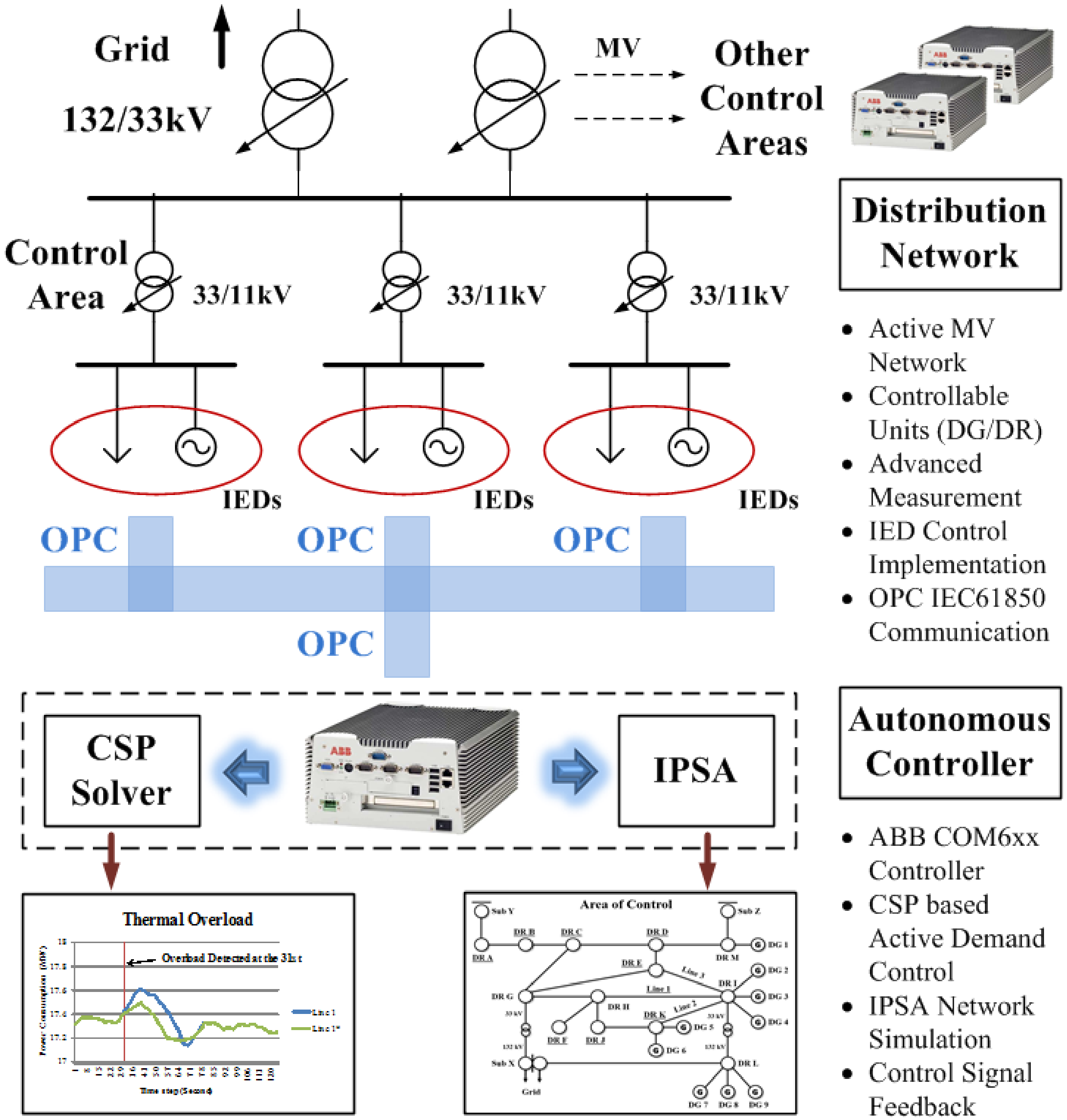


Figure 3-4: Active Demand Control Environment in Distribution Network

The architecture of active demand control environment in a MV distribution network is shown in Figure 3-4. The CSP based active demand control system is installed in a simplified MV distribution network with access of DG units and DR units. In the control area, the controllable units are flexibly or contractually designed with the ANM requirement that includes advanced measurement equipment, fast response communication system, and IED control system. Assumption has also been made that the network transparency is thoroughly achieved by the above technologies in this area. IEC61850 server based OPC communication system is applied to transmit network response to the control room while feeding the control signal back to each IED. The fast response communication system in reality can be achieved by IT networks such as WAN, FAN, LAN and HAN. In each control region, the ABB COM600 substation automation controller is installed to analyse the network response with a CSP solver and IPSA power flow software for control decision making. Then the solutions are returned as the output of control signals. The control signals are finally fed back to the control area for IED control action implementations. The control system will be continuously operating in this close-loop simulation for network unconstrained recovery and new constraint detection.

In addition, assumptions have been made to this control model in reality. First of all, all the attendants in the DSM scheme are prioritized by the financial incentives that are contracted with the DNO separately. Although there are other influence factors such as security levels and available schedules, the contract based prioritization is the only concern for the control order. Secondly, all the attendants in the DSM scheme are contracted with their curtailment preferences. The control depth that limits the maximum amount of real power curtailment from each units results from the negotiation between the DNO and each attendant. Furthermore, the control time schedule is also an outcome from the contract. Thirdly, the complexity of the control region influences the response time in the communication system. The internet delay is also required to be investigated in reality. However, the long distance communication delay is neglected in this model. Finally, it is also assumed that the distribution network is monitored under an ideal advance measurement system. The power flow information is available in each busbar.

3.6 Control Cycles for the Simulation Model

The CSP based active demand control approach is modeled for the implementation of load curtailment in an AC distribution system with an ABB COM600 substation automation controller and a PC simulator that emulates network response in real world. This model is established to evaluate the feasibility and effectiveness of the control performance in a HIL simulation.

The ABB COM600 substation automation controller processes the network response and solves the constraint problems, while the PC simulator emulates connected load and generation data and simulates the IED configurations which implement the control actions to the controllable devices. It is noted that the controller and the simulator are operated in synchronized time step for a better analysis of control time response. Therefore the communication delay in reality is ignored in this simulation. The CSP based active demand control simulation architecture is shown in Figure 3-5.

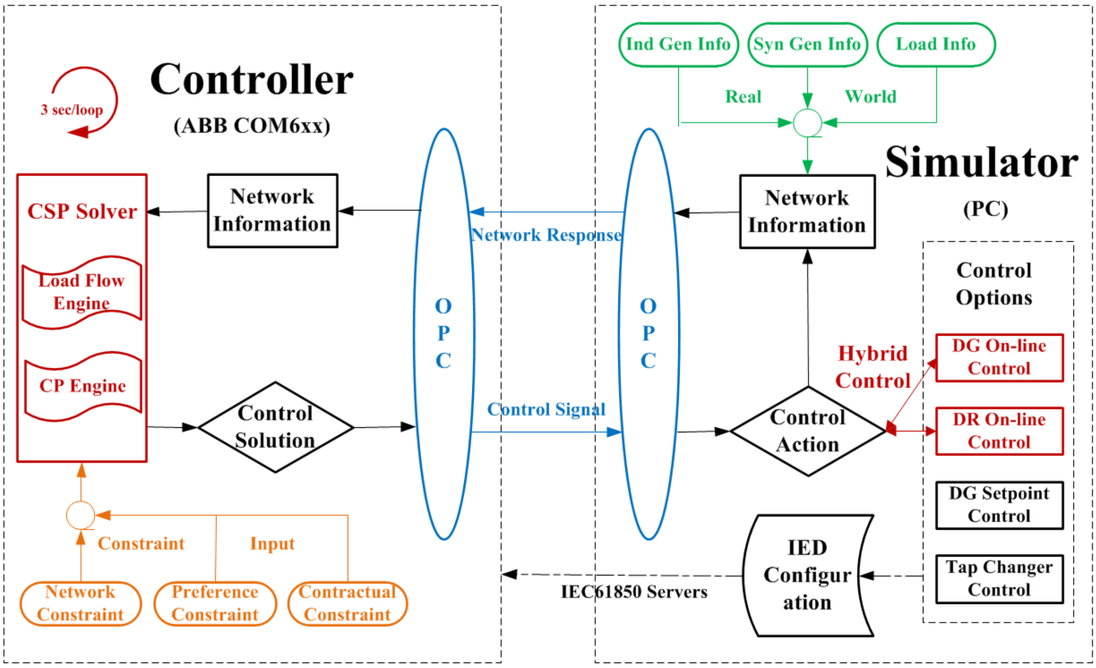


Figure 3-5: CSP-based Active Demand Control Simulation Model

In the simulation model, the COM600 substation automation controller is embedded with IPSA power flow software and Python programmed CSP solver. The network response from the PC simulator which includes the information from synchronous generators, induction machines, and local demands is communicated and updated to the IPSA load flow engine with the time interval of one second. Such information of the network response simulates the response in the real network which can be derived from the advanced measurement system in reality.

The load flow engine implements load flow simulation in IPSA software on a three seconds loop in this HIL simulation. The load flow simulation result is considered as the input of the network constraint for the CP engine. Meanwhile, the CP engine integrates the input constraints which include the network constraint (load flow result), the priority constraint, and the contractual constraint. These constraints are continuing updated in the CSP solver until the solution is obtained from the computation. The control actions acquired from the CSP solver are transmitted to the simulator to implement the desirable curtailment actions via the virtual IEDs.

In order to achieve flexibility and extensibility objective, all the ANM control algorithms are installed in the simulator for different types of control actions, such as DG trim control, DR trim control, DG set-point control, and tap change control. However, in the active demand control model, only DR on-line control and DG on-line control are applied. The DR on-line control is applied for the DR-PFM approach, while the combination of DG and DR on-line control is applied for the HC-PFM approach. Once the control actions are performed, the CSP solver (both load flow engine and CP engine) will continue running for the further overload detection and reaction until the thermal constraint is relieved.

In the case that the thermal overload is no longer detected, the CSP solver will focus on releasing the demand back to a less constrained or unconstrained operation. The control actions reinstate the DR units gradually while maintaining the priority order until the thermal constraint is totally removed. In this model, all the information of network response and control signals is communicated via OPC technology with IEC61850 standard servers.

3.7 Active Demand Response Realization

The application of ANM control platform requires new control concepts to deal with network issues from the demand side which also fulfills the development principle of smart grid on the requirement of reliability of power supply and affordability of customer participation. Thus, the integration of DSM control schemes to an ANM platform has been put on the agenda for the realization of DNO network objectives in future decentralized environment. The ANM-DSM functions can be realized in three sections: demand requirement, network realization, and DNO implementation.

3.7.1 Controllable Demand

One of the most import aspects of the DSM realization is customer acceptance from the demand side. The requirement of power quality differs from various demand profile and application environment. Thus, the requirements of DSM scheme selection are leveled differently in industrial demand, commercial demand, and domestic demand. In general, there are three types of demand requirements for ANM-DSM realization: energy efficiency, DR, and dynamic demand.

Energy efficiency refers to the application of advanced technologies and improvement of energy utilization habit in order to reduce the amount of energy consumption for the provision of certain products or services. It contributes to the network issues in ANM such as capacity reinforcement deferral, distribution loss reduction, increasing power supply security, enabling renewable integration and peak demand shift. The advanced technologies for increasing demand side energy efficiency include heat pump, micro-CHP, micro-generation, and economic appliances. And improvement of energy utilization habit can be achieved by customer awareness and adaptive smart appliances. Customer awareness can be cultivated by education, advertisement, financial incentives, and living environment. And adaptive smart appliance influences the consumption habit by occupancy based energy management and scheduled appliances.

DR refers to the application of all intentional or preventative modifications to the energy consumption pattern to reduce, flatten, or shift the park demand for consumers' preferences and lifestyles. It is concerned as a cost-effective alternative to maintain the power supply reliability instead of enlarge the generation capacities for the requirement of periodical peak press or occasional demand spike. DR can be influenced by DNO-DSM control schemes of indirect load control, direct load control, and direct appliance schedule which have already been introduced in Chapter 2. In current power network, DR is frequently related to load shedding strategy which is implemented to forcibly decrease the overall demand in a given region during the critical peak period. It can be realized either by constraining the controllable services and demands, or by sacrificing the supply voltage level, known as brownout, to protect the important equipment and services from damages of power outage disruption. However, the improvement of ANM-DSM control technologies will utilize the control potential of DR from Active Demand (AD) in next generation power grid. In this thesis, two novel control approaches are developed in the following chapters.

Dynamic demand refers to a semi-passive technology introduced by DNO or local control centers to perform dynamic control actions which provides significant stability and peak demand management in the power network. It contributes to carbon dioxide savings as well as facilitates large intermittent renewable energy penetration to the grid. Dynamic demand control system monitors the network parameter such as voltage rate, frequency, power flow, and power factor to control the loads of dynamic demand intermittently in optimal time durations to balance the mismatched supply and demand within desirable ranges. For instance, spinning reserves are frequently applied in droop speed control to deal with the frequency response issue in the grid which indicates the overall power imbalance results from large demand increase. And power curtailment control of flexible demand (either dynamic demand or DR) is applicable to deal with the power conjunction issues for ANM-DSM functions.

3.7.2 Communication Realization

Since the demand requirement has been identified in the previous subsection, the communication of ANM-DSM control signal should be considered as another aspect of control function realization. The main requirements of ANM-DSM control signal communication are small response delay, high accurate reliability, and strong network security. Thus, the existing communication networks are applicable to transmit control signals from DNO’s Distribution Control Centers (DCC) to the demand side. Such communication networks include Wide Area Network (WAN), Local Area Network (LAN), Field Area Network (FAN)/ Neighborhood Area Network (NAN), and Home Area Network (HAN). The ANM-DSM control signal communication architecture is shown in Figure 3-6.

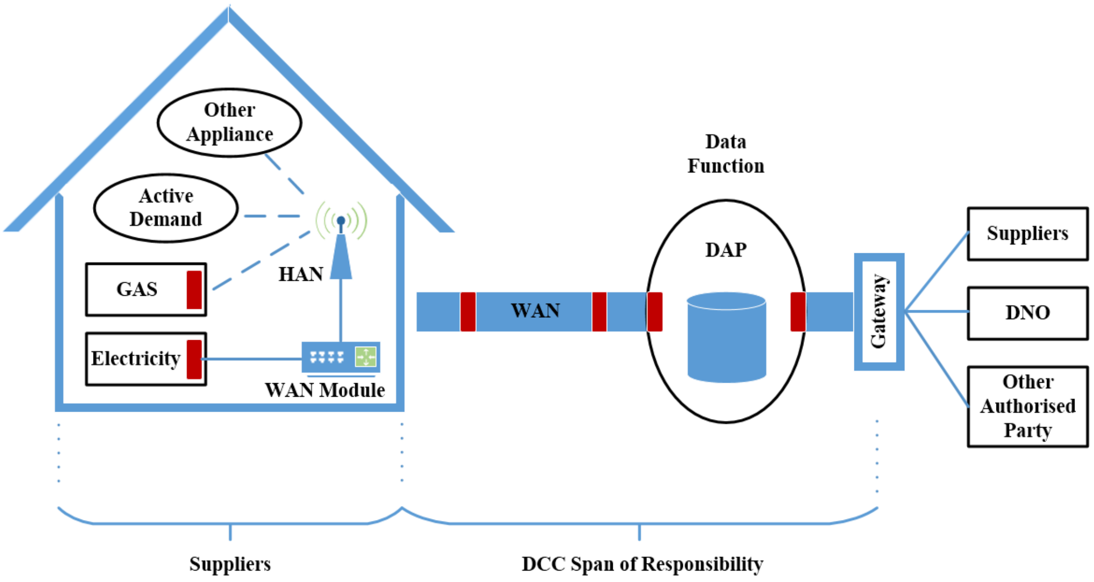


Figure 3-6: ANM-DSM Communication Realization to the End User

Information transparency is of significant importance in ANM-DSM communication model which enables bidirectional data share among the network participants. The information from suppliers, DNO and other authorized party is transmitted through WAN/ FAN gateway to the local substation which is regulated by DCC. Data Aggregator Points (DAP) located between WAN and LAN are applied to categorize the transmitted data by their functions and distribute them to FAN/HAN in demand side. DAP is an important data connection substation which applies WiMAX or LTE mobile technology to realize data communication function in different division of domestic areas. As for domestic area, the communication is realized by FAN/HAN which is connected to domestic demand by the WAN module and smart meter. Then the control signal is transmitted to the controllable appliances and scheduled devices, and the DR feedback is returned to DCC by the smart meter. The realization of the whole communication system can be achieved technically, however, the identification of the role of demand participation and the implementation issues of ANM-DSM schemes are still required for discussion.

3.7.3 Commercial Model

From the DNO perspective, the DSM implementation that includes indirect load control, direct load control, and direct appliance schedule contributes to capacity investment reduction, losses reduction, increasing energy efficiency, enabling low carbon transport, enabling low carbon heating, and enabling renewable generation, which has been introduced in Chapter 2. However, the DNO implementation issue in a market model which balances the relationship among the DNO, suppliers, and customers has not yet been discussed.

Market implementation of demand side alternatives relates to the specific DSM commercial implementation approaches such as direct customer contract and alternative energy rates which can be taken to increase consumer adoption of DSM programs. Such consumer adoption are required to be adaptable to new uses which either provide new services or improve the quality or desirability of a new service over conventional alternatives [8]. These products such as advanced heat pump, home automation, and electrification expend either the range of existing market or the functions to a brand new market. The ANM-DSM for PFM implementation in electricity market model is shown in Figure 3-7.

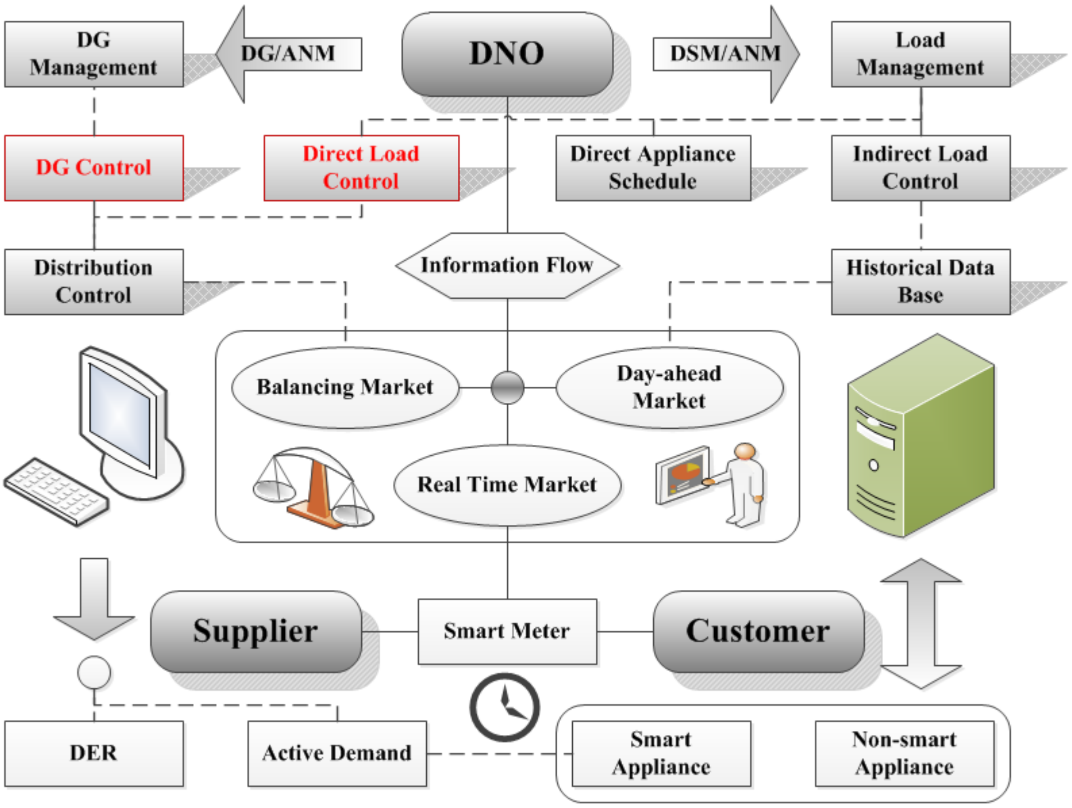


Figure 3-7: ANM-DSM for PFM Implementation in Electricity Market Model

The DNO implements ANM constraint management for PFM implementation by DG management and load management in this electricity market model. As for control approaches, direct load control is applied either solely or in a combination with DER control for PFM distribution control in balancing market which sets contract with utilities and customers for control access of DER and active demand. Direct appliance schedule of load management is applied by the direct DNO contract to customer that enables the adoption of smart schedulable appliances as one of their home automation plans. And indirect load control of load management is applied to the financial incentive based market planning strategies which influence customer energy consumption behaviors in a long application cycle. Smart meter in this model is applied to achieve information transparency and scheduled control of smart appliances while balancing the relationships between the DNO, suppliers, and customers in a real time market. In this thesis, novel ANM-PFM control approaches are developed for the DNO to implement both DER and direct load control in a CSP based control platform.

3.8 Summary

Future distribution network requires technical innovations to handle new challenges of network constraints. ANM control technologies are applied in decentralized distribution environment to achieve the DNO’s network objectives. The active demand control technologies are applicable to be integrated in the ANM control platform to provide support to the network thermal overload in a power flow management scheme. The CSP model is adopted to realize this function in two active demand control approaches: demand response for power flow management and hybrid control for power flow management. In the model, the distribution network problem is constrained by the factors of thermal overload from the network (network constraint), the preferred pattern from the DNO (preference constraint), and the contractual requirement from the demand (contractual constraint). The objective function of the control is to minimize the curtailed real power form the scheme attendants to satisfy the above constraints. The structure of control environment is presented with the assumptions that may limit the control actions in reality. Furthermore, the simulation model is designed for the HIL simulation which is applied to evaluate the feasibility and effectiveness of the control performance. Case studies and result analyses will be presented in Chapter 4 and Chapter 5.

3.9 Reference for Chapter 3

[1] E. Tsing, *Foundation of constraint Satisfaction* vol. 1. Department of Computer Science, University of Essex, Colchester, Essex, UK: Academic Press Limited, 1993-1995.

[2] K. R. Apt, *Principles of Constraint Programming* vol. 2. the Pitt Building, Trumpington Street, Cambridge, UK: Cambridge University Press, 2003.

[3] E. M. Davidson, M. J. Dolan, S. D. J. McArthur, and G. W. Ault, "The Use of Constraint Programming for the Autonomous Management of Power Flows," in *Intelligent System Applications to Power Systems, 2009. ISAP '09. 15th International Conference on*, 2009, pp. 1-7.

[4] J. Berry, "Integrating new technologies and power quality issues," in *Power Quality, IET Seminar on*, 2012, pp. 1-24.

[5] L. Kane, G. Ault, and S. Gill, "An assessment of principles of access for wind generation curtailment in active network management schemes," in *Electricity Distribution (CIRED 2013), 22nd International Conference and Exhibition on*, 2013, pp. 1-4.

[6] M. Dolan, "The Application and Assessment of Active Network Management Techniques for Distribution Network Power Flows," PhD, Electronic and Electrical Engineering, University of Strathclyde, Glasgow, UK, 2012.

[7] E. Davidson, S. McArthur, J. McDonald, and P. Taylor, "An architecture for flexible and autonomous network management systems," in *Electricity Distribution - Part 1, 2009. CIRED 2009. 20th International Conference and Exhibition on*, 2009, pp. 1-4.

[8] C. W. Gellings, K. E. Parmenter, and P. Hurtado, "Efficient Use and Conservation of Energy," in *Efficient Use and Conservation of Energy*. vol. 2, C. W. Gellings, Ed., ed: Eloss, 2008.

Chapter 4

Constraint Satisfaction Problem Based Demand Response for Power Flow Management

4.1 Overview of Chapter 4

This chapter performs the Hardware-In-the-Loop (HIL) simulation for the Demand Response for Power Flow Management (DR-PFM) control approach in a 33 KV interconnected distribution network. As a support of the ANM-PFM control functions, the presented approach aims to detect thermal overload issues, provide solutions from the CSP solver, relieve the thermal constraints, and recover the curtailed units for unconstrained networks. The curtailment control actions are implemented among 8 controllable loads. The objective function is to minimize the curtailed real power consumption while satisfying the network constraint, preference constraint, and contractual constraint. The on-line simulation is applied to 4 case study tasks which include 2 single load control cases and 2 multiple load control cases. Assumptions are clarified before each case. The control performance is evaluated by the parameters of control range, curtailment index, duration factor, and control efficiency. It is influenced by the location, control depth and contractual priority when relieving the same thermal constraint. Contrastive analysis is discussed at the end of this chapter.

4.2 Case Study for Demand Response Control

The CSP based DR-PFM HIL simulation case study is performed on an interconnected 33kV distribution network, shown in Figure 4-1. In the control area, the network locates across the distribution area from 132 kV to 33 kV.

The network participants are DG units (including synchronized generator and induction machine) and DR units. The DG units emulate the local wind farm and hydro generation which support the normal operation of demand units in this area. The synchronized generators are operated in the rating range from 2.5 MW to 25

MW, while the induction machines consume real power and generate reactive power to compensate the network. The DR units emulate the flexible loads that can be obtained from the combination of central heating, energy charging, and domestic appliances in the area. They are operated in the consumption from 3.6 MW to 9.6 MW. It is assumed in the simulation that all the DR units are available to perform DR curtailment control actions under the predetermined preference constraint. However, this study is based on the demand profile analysis in reality. Financial incentives and tariff contracts are the main issues to be concerned. From the DNO's perspective, cost-benefit analysis is required for different demand profiles.

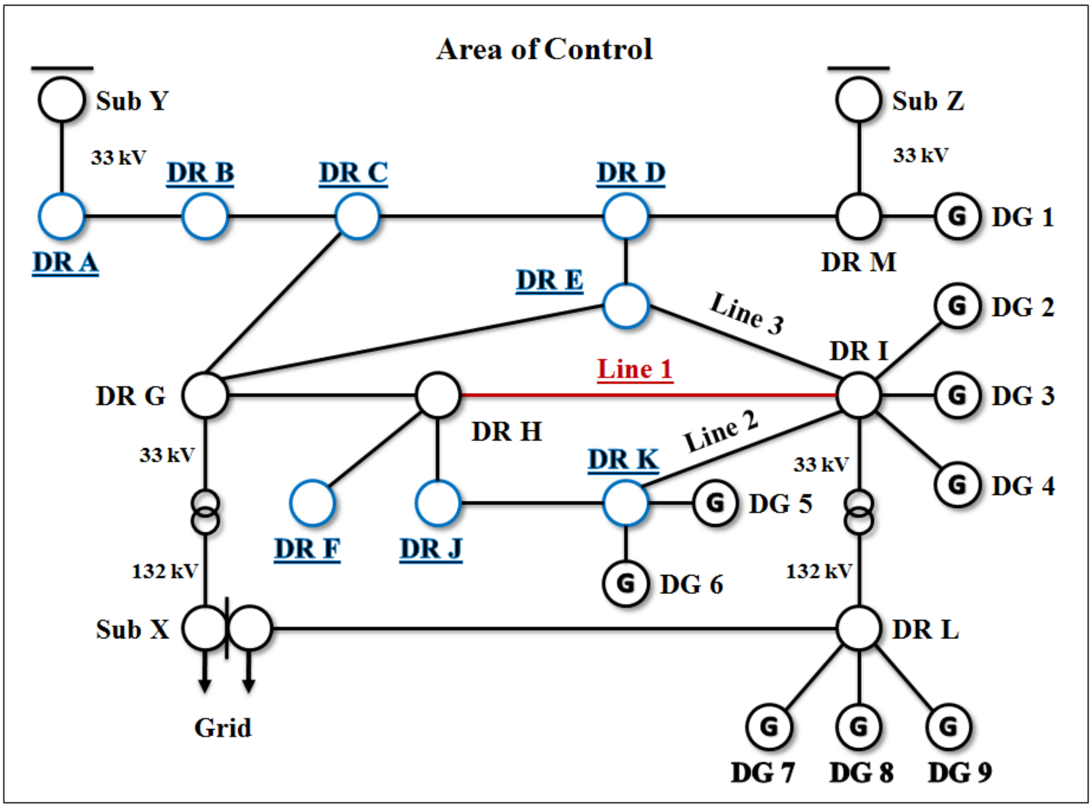


Figure 4-1: 33 kV Interconnected Test Network with Flexible DR Units

There are 9 fixed DG units and 8 controllable DR units (*DR A*, *DR B*, *DR C*, *DR D*, *DR E*, *DR F*, *DR J* and *DR K*) in this distribution network. These controllable loads are selected as the contractual demand to perform the CSP based DR-PFM control actions. They are also listed with control priorities from *Priority 1* to *Priority 8* in the contractual constraint. *Priority 1* means the DR unit holds the highest priority and is required to be controlled after all other DR units. *Priority 8* in the priority list means the DR unit holds the lowest priority and is required to be controlled first among all the DR units. It is assumed that all the DR units within this DR control scheme are contracted with financial incentive. The one with lower priority receives more incentive to provide an earlier control support, while the one with higher incentive receives less incentive to stay longer with network connection.

All the DG units are operated within their rated values to satisfy the regional demand requirement and to feed power back to the grid via two 33kV/132kV transformers and the bus of *Sub X*. Two terminal buses, *Sub Y* and *Sub Z*, both in 33 kV voltage level, are disconnected with the demands located beyond this area which operate in lower voltage level for the HIL simulation convenience.

A load flow simulation in a testing case indicates that the main power flows from the DG units, *DG 2*, *DG 3*, *DG 4*, *DG 7*, *DG 8*, and *DG 9*, is transmitted to the demand area via the transmission lines, *Line 1*, *Line 2*, and *Line 3*, located from *DR I* to *DR E*, *DR H*, and *DR K* respectively. In this model, the distribution line, Line 1, has the lowest thermal rating which is slightly higher than the peak flow under the base case. This means that small demand increase on local energy consumption may cause the thermal overload violation on this transmission line. In this scenario, the substation automation controller activates the CSP based DR-PFM control for solution investigation of the constraint relief. And such thermal overload relief on Line 1 is concerned as the network constraint in the CSP definition. Furthermore, the flexible demand buses are prioritized to a control order list according to their pre-identified contractual requirements which are concerned as the contractual constraint in the CSP definition. In addition, the control actions are performed to achieve the objective function of curtailment minimization while satisfying the network constraint, the preference constraint, and the contractual constraint in the CSP definition.

In this simulation, a sharp increase of demand energy consumption, which lasts for approximate 30 seconds (for the purpose of simulation), is imposed on *DR F* as a temporary disturbance of DR impact. The disturbance will result in larger real power transmission in *Line1* which exceeds the rating limit of the season. Thus, CSP based DR-PFM tests are implemented to deal with this thermal overload problem with difference contractual constraints and demand requirements. 4 tests will be presented with evaluations and discussions in next section.

4.3 Simulation and Result Analysis

The CSP based DR-PFM simulation results are presented in this section which includes two parts: control performance evaluation and case study analysis. Control performance evaluation identifies the evaluation parameters of control performance while case study analysis presents, compares, and discusses the control performance via these parameters.

4.3.1 Control Performance Evaluation

In the CSP based DR-PFM simulation, the DR units are designed to be curtailed successively in the priority order until the overload is no longer detected. A series of two minute tests are implemented and evaluated by the following parameters: feasibility, control response delay, control range, curtailment index, duration factor, control efficiency, and CSP response.

The feasibility is defined as the PFM problem solving ability and the network impact that results from the control actions. It indicates the fact if the control actions successfully relieve the thermal overload and recover the curtailed DR units in the unconstrained condition. It can be identified by comparing the real power curves of the constrained line in both controlled and uncontrolled cases. It is noted that all the tests result in positive feasibility in this chapter. However, this parameter is still important in practical tests which may encounters failure by convergence and control interaction issues.

The response delay is defined as the total control action time delay to the thermal overload detection. It indicates the ability of fast demand response to the network. In reality, the time duration for the on-line response delay can be influenced by the communication time and the first CSP calculation time. Since all the tests in this chapter are based on a small HIL simulation model, the response delay is much smaller than the one with long distance communication. The tests only provide a brief concept of response delay factors. Practical demonstration is required to identify this problem.

The control range indicates the instantaneous real power curtailed from the rated level as a function of time during the control period. It indicates the control impact range represented by the real power during the whole control period.

The maximum control range is defined as the value of the control range in the worst case in which the largest quantity of thermal overload is occurred with the deepest power curtailment. It is an important intermediate value to obtain the other parameters as well as involving in the evaluation directly. In addition, the worst case is defined as the critical time period in which the network encounters the largest control impact.

The curtailment index is defined as the value of total energy curtailed by the control actions during the whole control period. It indicates the energy loss of the DR control scheme which relates to cost-benefit analysis of potential financial incentives and contracted DR units in practical network planning. It is also an important parameter to evaluate the control efficiency and the network impact.

The duration factor is defined as the ratio of total energy loss to maximum real power curtailed which is expressed in time unit. It indicates the effectiveness of the average energy curtailment relating to the real power loss in the worst case. This parameter is of great importance to distinguish the sensitivity of the control pattern related to the thermal overloaded line. It measures the average contribution of all the controlled units to the total curtailed energy.

The control efficiency is defined as the relative quantity of energy curtailed in comparison with the overload energy which is calculated from the energy content of the increased demand (*DR F* in this set of tests). It indicates the effectiveness of the whole control actions relating to the total curtailed energy. It is a crucial parameter which reflects the merit rating of the whole performance in the evaluation and discussion aspect. It is noted that the control efficiency is lower for the DR control scheme comparing with the one with the DG dispatch scheme in an interconnected network. However, the tests in this chapter aim to provide another autonomous control approach from the demand side and demonstrate its performance. Future work is still required on the efficiency improvement.

The CSP response is defined as the calculation time of the CSP solver from overload detection to solution provision. It indicates the problem solving ability of the CSP solver in dealing with complex constraint management problems. The complexity of the control pattern is the major factor that influences the time duration of the CSP response. The highlight of the evaluation parameters is shown in Table 4-1.

Evaluation Parameters	**Comments (DR-PFM)**
Feasibility	If the control actions successfully relieve the thermal overload and recover the curtailed units in the unconstrained condition
Control Range	The total instantaneous real power curtailed from the rated level of demand as a function of time during the control period
Max Control Range	The value of the control range in the worst case in which the largest quantity of thermal overload is occurred with the deepest power curtailment from the demand units
Curtailment Index	The value of total energy curtailed by the control actions during the whole control period
Duration Factor	The ratio of total energy loss to maximum real power curtailed which is expressed in time unit
Overloaded Energy	The energy content of the increased demand (*DR F* in this set of tests)
Control Efficiency	The relative quantity of energy curtailed in comparison with the overload energy
Response Delay	The total control action time delay to the thermal overload detection
CSP Response	The calculation time of the CSP solver from overload detection to solution provision

Table 4-1: Highlight of the Evaluation Parameters (DR-PFM)

In addition, the simulation only focuses on the curtailment of real power consumption instead of reactive power compensation. However, the latter is also an important research direction in the future work. It can be applied to the reactive demand market which is still in the planning process.

Mathematical models are defined for the evaluation parameters of the control range, the maximum control range, the curtailment index, the duration factor and the control efficiency:

- The control range is calculated by the sum of the instantaneous real power curtailed from each demand under control action. It can be represented in a total real power function of time, which can be obtained as follows:

$$P_{Range}(t) = \sum_{i=1}^{n}[P_{i-Output}(t) - P_{i-Setpoint}(t)] \tag{4.1}$$

Where $P_{i\text{-}Output}(t)$ represents the actual instantaneous power consumption of the i^{th} DR unit without constraints; and $P_{i\text{-}Setpoint}(t)$ represents the controlled instantaneous power consumption of the i^{th} DR unit under the constraints.

- The maximum control range is calculated by the sum of the real power curtailed from each demand in the worst case. It can be represented as follows:

$$P_{MAX} = Max[P_{Range}(t)] \tag{4.2}$$

Where $\mathrm{P_{Range}(t)}$ refers to the control range obtained from Equation 4.1.

- The curtailment index is calculated by the integration of the control range along the control period *T*. It is represented in terms of energy curtailed during the control period which can be obtained as follows:

$$E_{Curtailed} = \int_{T} P_{Range}(t)dt \tag{4.3}$$

Where $P_{Range}(t)$ refers to the control range function which can be obtained from Equation 4.1. It is one of the critical parameters to evaluate the DR impact among different control performances.

- The duration factor is calculated by the ratio of the curtailment index and the maximum control range to evaluate the energy loss for certain peak clipping requirement. It can be represented as follows:

$$F = \frac{E_{Curtailed}}{P_{MAX}} = \frac{\int_T P_{Range}(t)dt}{Max[P_{Range}(t)]} \tag{4.4}$$

Where $E_{Curtailed}$ refers to the curtailment index obtained from Equation 4.3; and P_{MAX} refers to the maximum control range obtained from Equation 4.2. The curtailment factor indicates the control performance effectiveness in a certain control action united by kWh/MW.

- The control efficiency is calculated by the ratio of the expected total overloaded energy on the critical line, *Line 1*, to the total curtailed energy from the demand during the control period. It can be represented as follows:

$$f = \frac{E_{Overloaded}}{E_{Curtailed}} = \frac{\int_T P_{Overloaded}(t)dt}{\int_T P_{Range}(t)dt} \tag{4.5}$$

Where $E_{Overloaded}(t)$ refers to the total overloaded energy on *Line 1* which can be expressed to the integration of the real power exceeded to the thermal rate on *DR F* along the control period. And $E_{Curtailed}(t)$ refers to the curtailment index which can be obtained in Equation 4.3. It is noted that $E_{Overload}$ is the expected thermal overload which is supposed to occur in the environment without control actions. This parameter aims to evaluate the control performance among different DR units. Thus, in these tests, it is represented by the additional energy increase beyond the time step of overload detection on *DR F*.

In addition, the control system is assumed to operate with a trim/ramp rate of 0.05 p.u./sec, which means that the real power of demand won’t be curtailed in a sharp rate. This assumption is arranged for all the controllable units with the same trim/ramp rate in these tests. It contributes to better contrastive analyses. However, this figure defers from various demand profiles in the real network. In this HIL simulation, the transient state is neglected according to this setting.

In next subsection, 4 case study tests will be presented with this novel CSP based DR-PFM approach which are compared and evaluated by the above parameters. *Test 1* and *Test 2* simulate the situation where only one load is required to alleviate the thermal overload. Whilst *Test 3* and *Test 4* simulates a case where multiple loads are required to be controlled.

4.3.2 Case Study Analysis

Four case study tests are presented in this subsection which are Test 1: single load control 1; Test 2: single load control 2; Test 3: multiple load control 1; and Test 4: multiple load control 2. Comparisons and evaluations of the control performances will be made in the following discussion part.

4.3.2.1 Test 1: Single Load Control for DR-PFM

Test 1 performs a single demand curtailment control for DR-PFM issues of thermal overload relief. In this test, the objective function of the CSP solver is to minimize the total real power curtailed from the DR units for each control actions which aims to relieve the thermal overload. The variables are defined as the 8 DR units. The domain is set to be {0, 0.5, 0.7, 0.8, 0.9, 1} in each DR units. The domain sets identify the control details of each variable. In this test, all the DR units are controlled with the same domain arrangement.

The network constraint is derived from the result of thermal overload detection. The contractual constraint identifies the priority of the variables. In this test, *DR B* is operated with the lowest priority (priority 8), which should be curtailed first in the case of thermal overload detection. Since this test is only for single load control, only

DR B is curtailed during the control period. The preference constraint aims to limit the control depth for each DR unit. In this test, the control depth of the preference constraint is assumed to be 0.5. It means that each DR unit is limited to remain at least 50% of its rated consumption for their own preference.

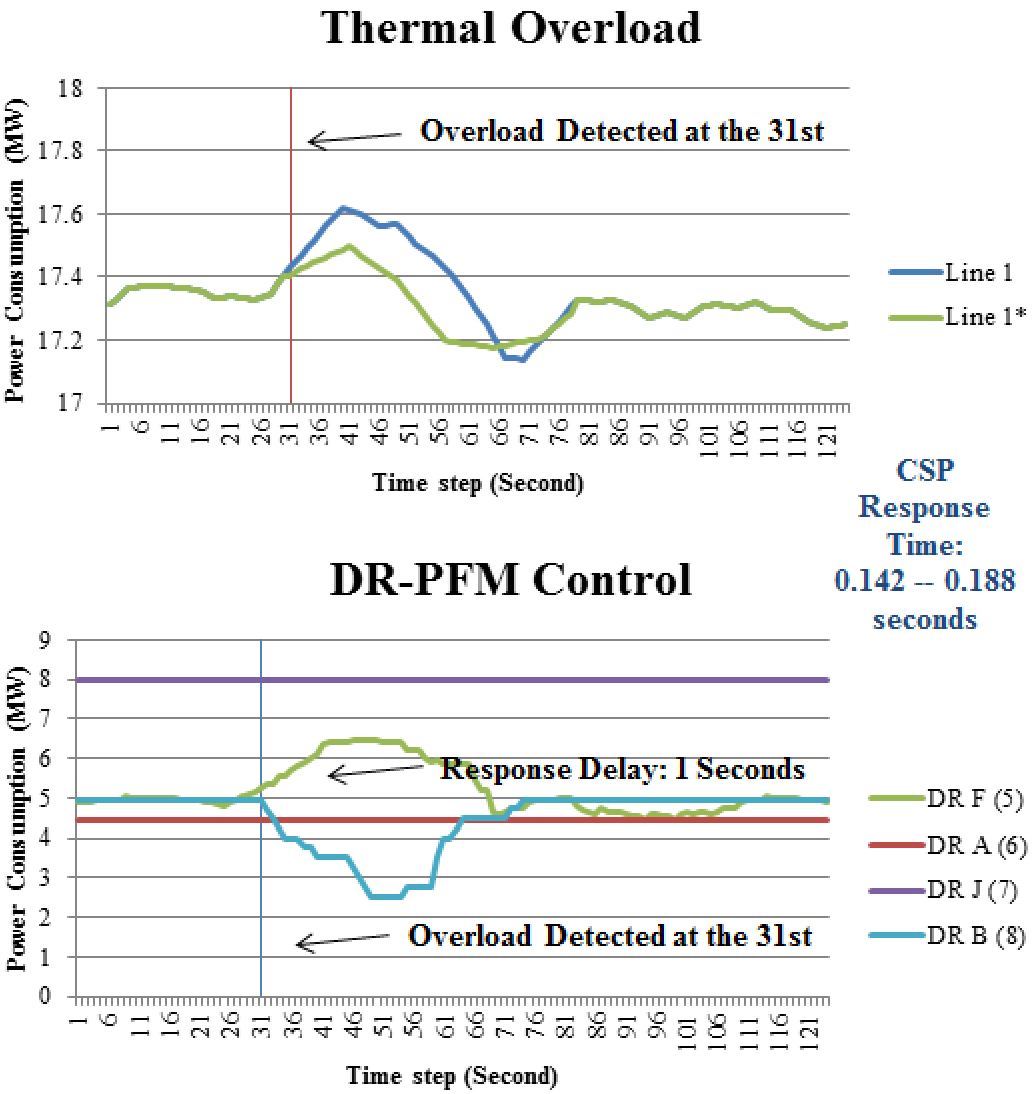


Figure 4-2: DR-PFM Single Load Control Test 1

The result of DR-PFM single load control Test 1 is shown in Figure 4-4. It is noted that the curve of Line 1 indicates the real power of Line 1 without control. The one of Line 1* indicates the real power of Line 1 with control. The thermal rating of Line 1 is 17.4 MW. The CSP response time of these control actions lies within the range from *t* = 0.412s to *t* = 0.188s. It is noted that the detail of control cycle within the ABB COM600 controller and computer simulator is presented in the previous chapter.

In order to investigate the exact control performance for calculation convenience, the details of control actions are collected and shown in Table 4-2.

CSP-Based DR-PFM Control Actions									
DR Units		*DR A*	*DR B*	*DR C*	*DR D*	*DR E*	*DR F*	*DR J*	*DR K*
Priority		6	8	2	3	4	5	7	1
Rated MW Output		-4.4	-5.0	-4.1	-3.6	-9.6	-4.9	-8.0	-3.6
Time Log of Control Signal	31	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	32	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	38	1.0	0.7	1.0	1.0	1.0	1.0	1.0	1.0
	46	1.0	0.5	1.0	1.0	1.0	1.0	1.0	1.0
	55	1.0	0.7	1.0	1.0	1.0	1.0	1.0	1.0
	60	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	63	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0
	72	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 4-2: Control Details of DR-PFM Single Load Control Test 1

According to Figure 4-2, the real power performances of 4 DR units, *DR F* (5), *DR A* (6), *DR J* (7), and *DR B* (8), are traced with their priorities marked in the brackets. The result shown in Figure 4-2 and Table 4-2 indicates that the simulated thermal overload occurs at the *t* = 31s resulting from the sharply increased demand in *DR F*. The control system activates at *t* = 32s and trims the load with the lowest priority, *DR B*, step by step until the overload is no longer detected. The worst case occurs between *t* = 46s and *t* = 55s with the single load of *DR B* trimmed to 50% of its rated consumption. After t = 55s, the overload situation on *Line 1* is relieved since the real power flowed through *Line 1* starts to reduce and the thermal constraint is removed from the current system. In this circumstance, the CSP solver re-evaluates the network situation and recovers the curtailed demand on DR B gradually at *t* = 55s, *t* = 60s, *t* = 63s, and *t* = 72s to its normal condition. The whole control action ends at *t* = 72s and the system is reinstated to its normal operation. The response delay which lasts from thermal overload detection to first control action activation is 1 seconds in this test result.

The result indicates that the DR-PFM control actions in *DR B* with rated real power consumption of 5.0 MW lasts from *t* = 32s to *t* = 72s which successfully relieves the thermal overload with single load curtailment of 50% in the worst case. The maximum control range of *DR B* can be obtained from Equation 4.2, which equals to 2.5 MW. The curtailment index indicates the total curtailed area between the rated power curve (P = 5 MW) and the DR curve of *DR B* according to Equation 4.3, which equals to 14.86 kWh. Therefore, the curtailment factor can be calculated by the ratio of curtailment index and maximum control range shown in Equation 4.4, which is 5.944 kWh/MW. And the control efficiency can be calculated by the ratio of the total overloaded energy in *DR F*, 7.95 kWh, and the total curtailed energy in *DR B*, 14.86 kWh, defined in Equation 4.5, which in percentage form is 53.50%. The analysis details of Test 1 are collected in Table 4-3.

Test Result Analysis Details					
Test Label	**Control Type**	**Controlled Items**	**Control Percentage**	**Feasibility**	**Response Delay**
Test 1	Single DR	*DR B*	0.5	Yes	1s
Max Control Range	**Curtailment Index**	**Duration Factor**	**Overloaded Energy**	**Control Efficiency**	**CSP Response**
2.50 MW	14.86 kWh	5.944 kWh/MW	7.95 kWh	53.50%	0.142s-0.188s

Table 4-3: Analysis Details of DR-PFM Single Load Control Test 1

To summarize, this test demonstrates the feasibility of DR-PFM single load control performance. The control response delay lasts for 1 second. The control range reaches 50% of the controlled item. The DR unit control curtails 14.86 kWh energy in total from the demand side to relieve 7.95 kWh thermal overload from the critical line with control frequency of 53.50% which may be improved with a different contractual constraint that curtails demand from a different DR unit. Thus, another DR-PFM single load control test, Test 2, is designed in the same environment to investigate this issue.

4.3.2.2 Test 2: Single Load Control for DR-PFM

Test 2 is also designed for the simulation of a single demand curtailment control for DR-PFM thermal overload relief issues to contrast with Test 1. Thus, in this test, the variables, the domains and the network constraint remain the same as the ones in Test 1. The control depth of the preference constraint is also assumed to be 0.5.

However, in order to investigate the location influence in different demand control, the priority list in the contractual constraint is changed to a different control order. In this case, the DR unit with the lowest priority, *Priority 8*, is reset to be *DR J* instead of *DR B*. Since Test 2 is also for single load control, only *DR J* is curtailed during the control period. From the network topology in Figure 4-1, *DR J* is located adjacently to the thermal overloaded line, *Line 1*, whilst *DR B* is located remotely to it. Therefore, the result comparison of Test 1 and Test 2 indicates the influence of location factor to the maximum control range, curtailment index, and control efficiency. The result of DR-PFM single load control Test 2 is shown in Figure 4-3. The real time computation period of these control actions lies within the range from t = 0.181s to t = 0.197s.

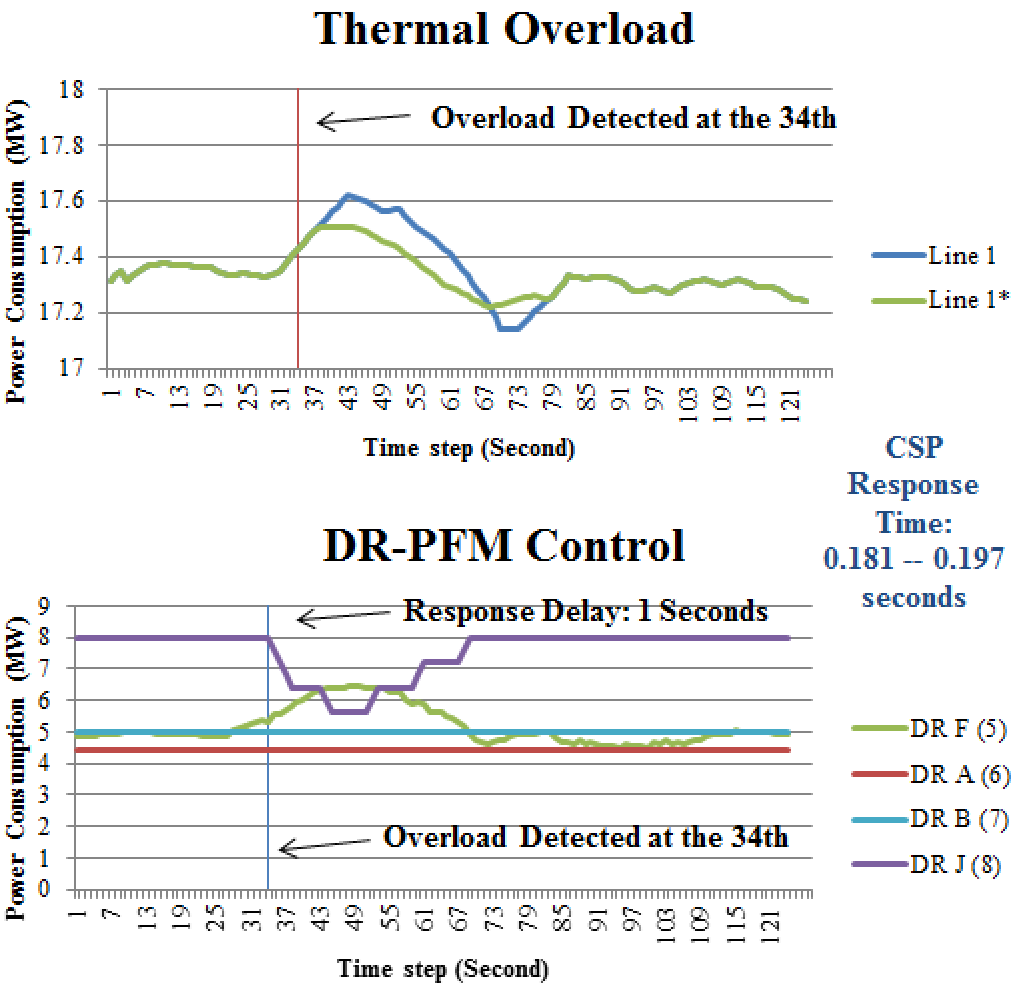


Figure 4-3: DR-PFM Single Load Control Test 2

The details of control actions are shown in Table 4-4 for analysis convenience.

According to Figure 4-3, the real power performances of 4 DR units, *DR F* (5), *DR A* (6), *DR B* (7), and *DR J* (8), are traced with their priorities in the bracket. The result shown in Figure 4-3 and Table 4-4 indicates that the simulated thermal overload occurs at the t = 34s resulting from the sharply increased demand in *DR F*. The control system activates at t = 35s and trims the load with the lowest priority, *DR J*, step by step until the overload is no longer detected. The worst case occurs between t = 44s and t = 52s with the single load of *DR B* trimmed to 70% of its rated consumption. It indicates that the curtailment percentage is smaller than the one in

Test 1. After t = 52s, the overload situation on *Line 1* is relieved since the demand at *DR F* starts to reduce and the thermal constraint is removed from the current system. In this circumstance, the CSP solver re-evaluated the network situation and recovers the curtailed demand on DR B gradually at *t* = 52s, *t* = 60s, and *t* = 68s to its normal condition. The whole control action ends at *t* = 68s and the system is reinstated to its normal operation. The response delay which lasts from thermal overload detection to first control action activation is 1 seconds in this test result.

DR Units		*DR A*	*DR B*	*DR C*	*DR D*	*DR E*	*DR F*	*DR J*	*DR K*
Priority		6	7	2	3	4	5	8	1
Rated MW Output		-4.4	-5.0	-4.1	-3.6	-9.6	-4.9	-8.0	-3.6
Time Log of Control Signal	34	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	35	1.0	1.0	1.0	1.0	1.0	1.0	0.8	1.0
	44	1.0	1.0	1.0	1.0	1.0	1.0	0.7	1.0
	52	1.0	1.0	1.0	1.0	1.0	1.0	0.8	1.0
	60	1.0	1.0	1.0	1.0	1.0	1.0	0.9	1.0
	68	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 4-4: Control Details for DR-PFM Single Load Control Test 2

The result indicates that the DR-PFM control actions in *DR J* with rated real power consumption of 8.0 MW lasts from *t* = 35s to *t* = 68s which also successfully relieves the thermal overload with single load curtailment of 70% in the worst case. The maximum control range of *DR J* can be obtained from Equation 4.2, which equals to 2.4 MW. The curtailment index indicates the total curtailed area between the rated power curve (P = 5 MW) and the DR curve of *DR J* according to Equation 4.3, which equals to 14.22 kWh. Therefore, the curtailment factor can be calculated by the ratio of curtailment index and maximum control range shown in Equation 4.4, which is 5.925 kWh/MW. And the control efficiency can be calculated by the ratio of the total overloaded energy in *DR F*, 7.95 kWh, and the total curtailed energy in *DR J*, 14.22 kWh, defined in Equation 4.5, which in percentage form is 55.91%. The analysis details of Test 2 are collected in Table 4-5.

Test Result Analysis Details					
Test Label	**Control Type**	**Controlled Items**	**Control Percentage**	**Feasibility**	**Response Delay**
Test 2	Single DR	*DR J*	0.7	Yes	1s
Max Control Range	**Curtailment Index**	**Duration Factor**	**Overloaded Energy**	**Control Efficiency**	**CSP Response**
2.40 MW	14.22 kWh	5.925 kWh/MW	7.95 kWh	55.91%	0.181s-0.197s

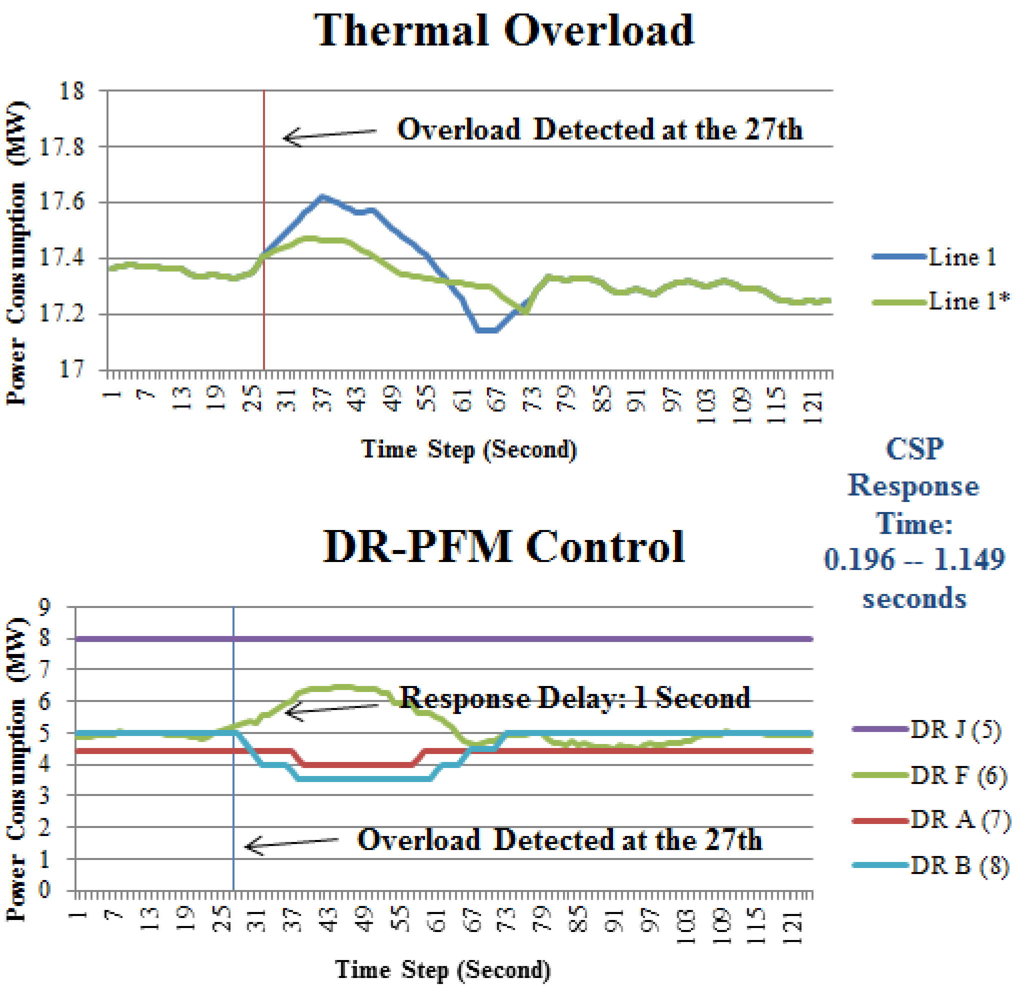
Table 4-5: Analysis Details of DR-PFM Single Load Control Test 2

The comparing result indicates that the rated consumption and location of demand influence the performance of DR-PFM. The adjacent DR unit results in a better performance of control range and curtailment factor. And the DR unit with higher rated consumption also results in a better performance of percentage curtailment from the operator perspective. The control action for *DR J* in the worst case (rated consumption of 8.0 MW) is 70% which is larger than the one of 50% for *DR B* (rated consumption of 5.0 MW) in Test 1. And the curtailment index, duration factor, and control efficiency also indicate a better performance of Test 2 in comparison with Test 1. In addition, Test 2 also results in a smaller CSP response range which also indicates a better performance in computation duration. The further result comparison will be analyzed to the detail in the following tests.

4.3.2.3 Test 3: Multiple Load Control for DR-PFM

The previous tests have demonstrated the feasibility and influence factors of DR-PFM single load control. However, in reality, most of the DR units connected to a single substation are not suitable for the large range of real power curtailment operation. Therefore, the DR-PFM multiple load control algorithm is developed. Test

3 performs a multiple demand curtailment control for DR-PFM issues of thermal overload relief. The new algorithm is able to deal with the customers at dispersed locations who have signed up to participate in such a control scheme.



CSP Response Time: 0.196 -- 1.149 seconds

Figure 4-4: DR-PFM Multiple Loads Control Test 3

In this test, the variables, the domain and the network constraint remain the same as the previous tests. However, the control depth of the preference constraint is changed to 0.7. It means that the maximum real power curtailment percentage of each DR unit is constrained to 30% of its rated value. The contractual constraint has also been changed with the lowest priority, *Priority 8*, in *DR B*. Since the control result of Test 1 indicates that the maximum control range of *DR B* results in 0.5 of its rated value, it will be insufficient to relieve the same thermal overload totally with the setting of 0.7 control depth. Therefore, the DR unit, *DR A*, with the second lowest priority, *Priority 7*, will be curtailed in further control actions when *DR B* reaches its control depth. The result of DR-PFM multiple load control Test 3 is shown in Figure 4-4. It is noted that the control algorithm has been improved to a faster response loop which is flexible to multiple load control decision making and decrease the computation response of the CSP solver. The real time computation period of these control actions lies within the range from t = 0.196s to t = 1.149s.

The control details are shown in Table 4-6 for analysis convenience.

CSP-Based DR-PFM Control Actions									
DR Units		*DR A*	*DR B*	*DR C*	*DR D*	*DR E*	*DR F*	*DR J*	*DR K*
Priority		7	8	2	3	4	6	5	1
Rated MW Output		-4.4	-5.0	-4.1	-3.6	-9.6	-4.9	-8.0	-3.6
Time Log of Control Signal	27	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	28	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	37	0.9	0.7	1.0	1.0	1.0	1.0	1.0	1.0
	57	1.0	0.7	1.0	1.0	1.0	1.0	1.0	1.0
	60	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	65	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0
	71	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 4-6: Control Details for DR-PFM Multiple Loads Control Test 3

According to Figure 4-4, the real power performances of 4 DR units, *DR J* (5), *DR F* (6), *DR A* (7), and *DR B* (8), are traced with their priorities in the bracket. The result shown in Figure 4-4 and Table 4-6 indicates that the simulated thermal overload occurs at the t = 27s resulting from the same amount of increased demand in *DR F*. The control system activates at t = 28s with the response delay of 1s and trims the load with the lowest priority, *DR B*, step by step until the curtailment amount reaches its control depth. *DR A* with the second lowest priority is curtailed to 0.9 of its rated value after *DR B* is fully controlled at *t* = 37s. The worst case occurs between *t* = 37s and *t* = 57s with the two loads controlled which trims *DR B* to 70% of its rated consumption and *DR A* to 90% of its rated consumption. After t = 57s, the overload situation on *Line 1* is relieved since the demand at *DR F* starts to reduce and the thermal constraint is removed from the current system. In this circumstance, the CSP solver re-evaluated the network situation and recovers the curtailed demand on *DR B* and *DR A* gradually at *t* = 57s, *t* = 60s, *t* = 65s, and *t* = 71s to its normal condition. It is noted that the recovery process is in the opposite order of the way that the DR units are curtailed. The whole control action ends at *t* = 71s and the system is reinstated to its normal operation. The response delay which lasts from thermal overload detection to first control action activation is 1s. The CSP response time is larger than the previous single load tests. This results from the increased complexity of control pattern in the worst case.

The result indicates that the DR-PFM control actions in *DR B* and *DR A* with rated real power consumption of 5.0 MW and 4.4 MW respectively lasts from *t* = 28s to *t* = 71s. It also successfully relieves the thermal overload with multiple load curtailment of 70% and 90% in the worst case. In this case, the maximum control range of the two DR units is equal to the sum of each real power reduction according to Equation 4.2, which equals to 1.94 MW. And the total curtailment index equals to the sum of energy lost during the control action according to Equation 4.3, which is 16.44 kWh. Therefore, the curtailment factor equals to the ratio of curtailment index and maximum control range which equals to 8.474 kWh/MW according to Equation 4.4. And the control efficiency can be calculated by the ratio of the total overloaded energy in *DR F*, 7.95 kWh, and the curtailment index, 16.44 kWh, which in percentage form is 48.36% according to Equation 4.5. The analysis details of Test 3 are collected in Table 4-7.

Test Result Analysis Details					
Test Label	**Control Type**	**Controlled Items**	**Control Percentage**	**Feasibility**	**Response Delay**
Test 3	Multiple DR	*DR B, DR A*	0.7	Yes	1s
Max Control Range	**Curtailment Index**	**Duration Factor**	**Overloaded Energy**	**Control Efficiency**	**CSP Response**
1.94 MW	16.44 kWh	8.474 kWh/MW	7.95 kWh	48.36%	0.196s-1.149s

Table 4-7: Analysis Details of DR-PFM Multiple Load Control Test 3

To compare with the single load control, the maximum control range in this multiple load control is smaller because of the finer subdivision of control interval, maximum 0.5 MW for *DR A* and *DR B* (10% domain interval of 5 MW rated power). In reality, this subdivision will be complicated to satisfy various contracts for the participation of customers with different profiles. Furthermore, the curtailment index is larger than the one in previous tests which results from the coordination of multiple load control. The curtailment index in this test is larger than the ones in the previous tests, which indicates the increasing energy curtailed in required peak clipping control. As a result, the control efficiency is a little lower than the ones in previous test with the same thermal overload condition because of the larger curtailment index value. Therefore, the DR-PFM multiple load control contributes on customer participation issues, but increases the complexity which results in more energy curtailed and lower control efficiency. In addition, the CSP response time is larger than the one in the single load control tests for the increasing complexity and computation.

4.3.2.4 Test 4: Multiple Load Control for DR-PFM

Test 4 is also designed for the simulation of a multiple demand curtailment control for DR-PFM thermal overload relief issues to contrast with Test 3. In this test, the variables, the domains, the network constraint and the contractual constraint remain the same as the ones in Test 3.

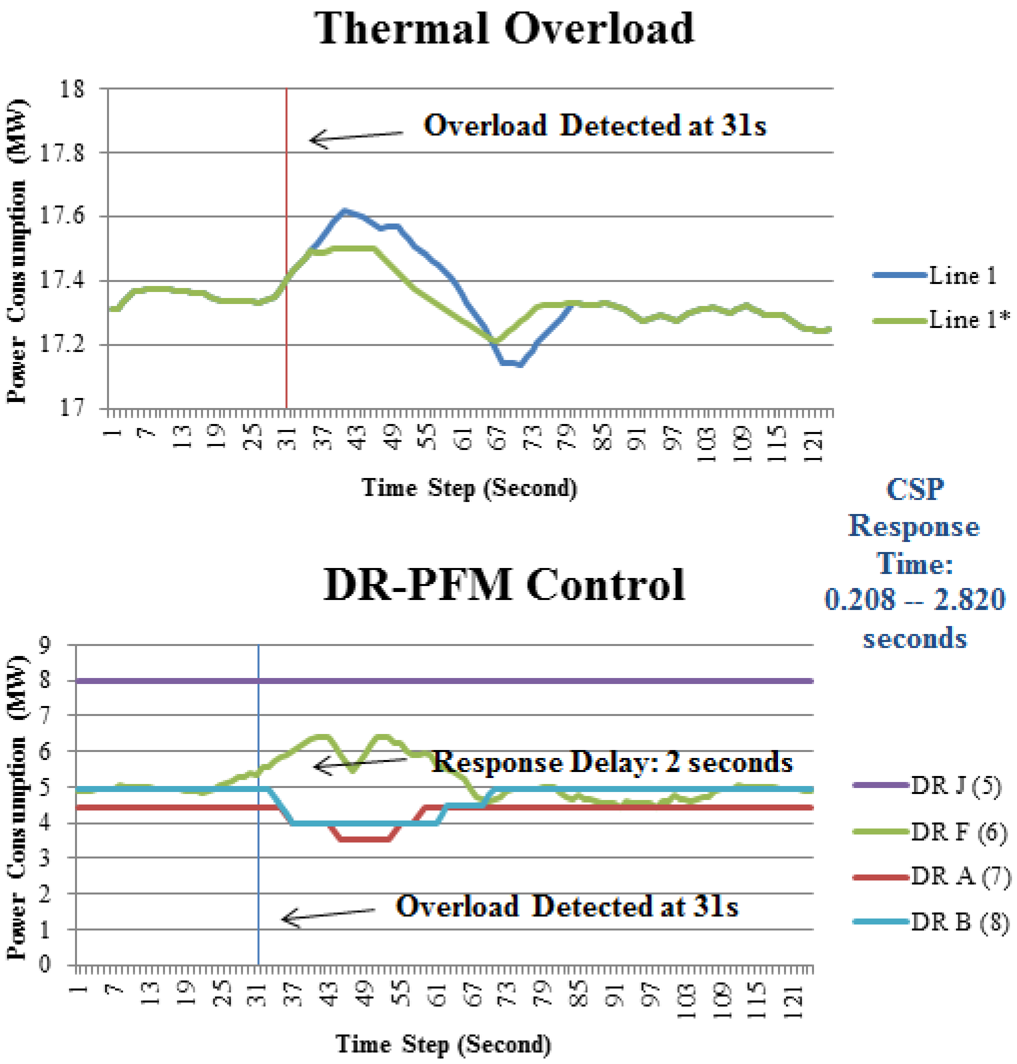


Figure 4-5: DR-PFM Multiple Loads Control Test 4

However, the control depth of the contractual constraint is further limited to 0.8. It means that the maximum real power curtailment percentage of each DR unit is constrained to 20% of its rated value. It is designed for the investigation of DR-PFM multiple load control feasibility in those demands with higher security requirements. Since the available real power in each DR unit decreased, it will be insufficient to relieve the same thermal overload as the one in Test 3 with only two DR units curtailed. Thus, more DR units will be involved in the control actions according to the contractual constraint when first two DR units are fully utilized. The result of DR-PFM multiple load control Test 3 is shown in Figure 4-5. It is noted that the improved control algorithm is still operating in this test. The real time computation period of these control actions lies within the range from *t* = 0.208s to *t* = 2.820s.

The control details are shown in Table 4-8 for analysis convenience.

CSP-Based DR-PFM Control Actions									
DR Units		*DR A*	*DR B*	*DR C*	*DR D*	*DR E*	*DR F*	*DR J*	*DR K*
Priority		7	8	2	3	4	6	5	1
Rated MW Output		-4.4	-5.0	-4.1	-3.6	-9.6	-4.9	-8.0	-3.6
Time Log of Control Signal	31	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	33	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	35	0.9	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	43	0.8	0.8	1.0	1.0	1.0	0.9	1.0	1.0
	48	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	53	0.9	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	57	1.0	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	61	1.0	0.9	1.0	1.0	1.0	1.0	1.0	1.0
	69	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 4-8: Control Details for DR-PFM Multiple Loads Control Test 4

According to Figure 4-5, the real power performances of 4 DR units, *DR J* (5), *DR F* (6), *DR A* (7), and *DR B* (8), are traced with their priorities in the bracket, which are the same as the ones in Test 3. The result shown in Figure 4-5 and Table 4-8 indicates that the simulated thermal overload occurs at the *t* = 31s resulting from the same interference of *DR F*. The control system activates at *t* = 33s with the response delay of 2s and starts to trim the load in the order that identified by the contractual constraint. Both *DR B* and *DR A* are curtailed to 0.8 and 0.9 of their rated consumption respectively at *t* = 35s. The worst case occurs between *t* = 43s and *t* = 48s with three DR units controlled as follows: *DR B* to 0.8 of its rated consumption, *DR A* to 0.8 of its rated consumption, and *DR F* to 0.9 of its rated consumption. After t = 48s, the overload situation on *Line 1* is relieved since the demand at *DR F* starts to reduce and the thermal constraint is removed from the current system. In this circumstance, the CSP solver re-evaluated the network situation and recovers the curtailed demand on the controlled DR units gradually at *t* = 48s, *t* = 53s, *t* = 57s, *t* = 61s, and *t* = 69s to its normal condition in the same order that is presented in Test 3. The whole control action ends at *t* = 69s and the system is reinstated to its normal operation. The response delay which lasts from thermal overload detection to first control action activation is 2s in this test result which is a little larger than the one in Test 3. The reason consists in the control complexity of the control process which curtails 3 DR units in this test in comparison with the one of 2 DR units in Test 3.

Test Result Analysis Details					
Test Label	**Control Type**	**Controlled Items**	**Control Percentage**	**Feasibility**	**Response Delay**
Test 4	Multiple DR	*DR B, DR A, DR F*	0.8	Yes	2s
Max Control Range	**Curtailment Index**	**Duration Factor**	**Overloaded Energy**	**Control Efficiency**	**CSP Response**
2.86 MW	13.26 kWh	4.636 kWh/MW	7.95 kWh	59.95%	0.208s-2.820s

Table 4-9: Analysis Details of DR-PFM Multiple Load Control Test 4

The result indicates that the DR-PFM control actions in *DR B*, *DR A* and *DR F* with rated real power consumption of 5.0 MW, 4.4 MW, and 4.9 MW respectively lasts from *t* = 28s to *t* = 71s. It also successfully relieves the thermal overload with multiple load curtailment of 80%, 80%, and 90% in the worst case. In this case, the maximum control range of the three DR units is equal to the sum of each real power reduction according to Equation 4.2, which equals to 2.86 MW. And the total curtailment index equals to the sum of energy lost during the control action according to Equation 4.3, which is 13.26 kWh. Therefore, the curtailment factor equals to the ratio of curtailment index and maximum control range which equals to 4.636 kWh/MW according to Equation 4.4. And the control efficiency can be calculated by the ratio of the total overloaded energy in *DR F*, 7.95 kWh, and the curtailment index, 13.26 kWh, which in percentage form is 59.95% according to Equation 4.5. The analysis details of Test 4 are collected in Table 4-9.

To compare with the result in Test 3, the maximum control range in this test is much larger than the one in Test 3. Although the subdivisions of control interval are the same in *DR B* and *DR A* in both tests (10% domain interval of 5 MW rated power), the further curtailment of consumption in *DR F* (from 6.40 MW to 5.42 MW in the worst case) results in more real power curtailed in the worst case in this test. It is noted that *DR F* which leads to the thermal overload in *Line 1* is also curtailed as the DR unit with third lowest priority. The arrangement of such contractual constraint aims to prevent the critical demand from extremely sharp increase which cannot be totally relieved by the curtailment of other DR units. In addition, the curtailment index in this test is smaller than the one in Test 3 because of the direct control of the critical demand, *DR F*, in the worst case, which is connected to the bus exactly located at the downstream of the power flow to the overloaded line, *Line 1*. Thus, the location of the controlled DR units is also an important factor which influences the control performance in the multiple load control. As a result, the duration factor is also smaller than the one in Test 3. Furthermore, the control efficiency in this test is higher than the one in Test 3 also because of the direct constraining of the critical demand. It is noted that both the control response delay and the CSP calculation response are longer than the ones in Test 3 which are resulted from the complexity of controlled DR units that is 3 DR units in this test in comparison with 2 DR units in Test 3.

4.4 Discussions

The above 4 tests have demonstrated the feasibility and contribution of CSP based DR-PFM on relieving the network thermal overload constraint. The control action successfully relieves the network constraint with the satisfaction of the preference constraint and the contractual constraint in acceptable control response delays and suitably fast computation timescales in the HIL simulation. All the control response delays are within 2 seconds and all the CSP calculation response in the tests last within 3 seconds, which has potential to contribute to the thermal problem in reality. Discussions are posed based on the impact of the constraints on control performance evaluated by the parameters of these tests which are list in the comparison analysis table, Table 4-10.

The comparison of Test 1 and Test 2 indicates that the rated consumption and location of the controlled demand influence the DR-PFM control performance in difference contractual constraint condition. It means that the control actions for the same thermal overload which are imposed on the DR units with different power consumption rate result in different control percentage. It also means that the prioritization of the controllable DR units in the contractual constraint list which locates differently to the thermal overloaded line is of significant importance in the control performances. The comparison result indicates that Test 2 has a better control performance than the one in Test 1. The evaluation parameters such as maximum control range, curtailment index and control efficiency are location sensitive to the control actions performed. Thus, the control of DR unit located adjacently to the downstream of power flow direction to the critical line, such as the case in Test 2, is more effective than the control of the one located remotely to it, such as the case in Test 1, in most DR-PFM cases. In addition, the control response delay and the CSP calculation response in Test 1 and Test 2 are almost the same. However, the communication delay in reality is also another factor which results in an extra delay for the control actions to the remote DR units.

Result Comparison Analysis for DR-PFM Control				
Test Label	Test 1	Test 2	Test 3	Test 4
Control Type	Single DR	Single DR	Multiple DR	Multiple DR
Controlled Items	*DR B*	*DR J*	*DR B, DR A*	*DR B, DR A, DR F*
Control Percentage	0.5	0.7	0.7	0.8
Feasibility	Yes	Yes	Yes	Yes
Response Delay (s)	6	5	1	2
Max Control Range (MW)	2.5	2.4	1.94	2.86
Curtailment Index (kWh)	14.86	14.22	16.44	13.26
Duration Factor (kWh/MW)	5.944	5.925	8.474	4.636
Overloaded Energy (kWh)	7.95	7.95	7.95	7.95
Control Efficiency	53.50%	55.91%	48.36%	59.95%
CSP Response (s)	0.142-0.188	0.181-0.197	0.196-1.149	0.208-2.820

Table 4-10: Comparison Analysis Details for 4 DR-PFM Control Tests

The comparison of Test 1 and Test 3 indicates that the multiple load control contributes on more customer participation in the DR-PFM control actions with less consumption curtailment for each demand. Since the DR units in Test 3 are located at the same branch of power flow as the one in Test 1, the impact of location factor in contractual constraint is reasonable small which can be neglected in this analysis. However, the flexible of control options are realized at the cost of worse control performance comparing with the one in single load control for the same quantity of thermal overload issue. It can be represented as the larger curtailment index and duration factor and lower control efficiency in Test 3 in comparison with the relevant parameters in Test 1. The complexity of control actions results in an extra curtailed energy in total demand to satisfy the same quantity of overload energy in the critical line. Although the other evaluation parameters indicate a worse control performance in Test 3, the maximum control range in it is smaller than the one in Test 1. The reason consists in another important influence factor, the subdivision of control interval in the domains. The domain of the single load control in Test 1 with the control depth of 0.5 can be represented as {0.5, 0.7, 0.8, 0.9, 1} while the one of the multiple control in Test 3 with control depth of 0.7 can be represented as {0.7, 0.8, 0.9, 1}. The subdivision of the former includes a 20% control interval between 0.5 and 0.7 which may result in redundant power cut from the demand. In addition, the increasing complexity of the control pattern in Test 3 results in longer CSP response time comparing with the one in Test 1

The comparison of Test 3 and Test 4 indicates that Test 4 involves in more complex control actions with power consumption of 3 DR units instead of 2 DR units in Test 3 under the pre-identified control depth of 0.8 for the same thermal overload. It is noted that the demand which leads to the thermal overload in the critical line is also involved in the control actions in Test 4 after the available power consumption is totally curtailed from the previous DR units. The design of such contractual constraint aims to prevent the critical demand from extremely sharp increase which cannot be totally relieved by the curtailment of other DR units. This design can be applied to constrain unpredictably sharp demand increase in the peak period which may threaten the reliability of distribution power supply. With such arrangement, Test 4 has a better control performance on curtailment index, duration factor, and control efficiency which results from the direct control of the overload-led-demand that has the largest effectiveness in comparison with the other DR units. However, the maximum control range in Test 4 are much larger than the one in Test 3 because of the large power consumption curtailment on the overloaded-led-demand in the worst case which is much greater than the one on the other DR units in Test 3. In addition, the complex control actions in Test 4 also result in longer control response delay and CSP calculation responses in comparison with the ones in Test 3.

Furthermore, the arrangement of the control depth in each DR unit, also concerned as the preference constraint, is another crucial factor in DR-PFM for multiple customer participation. The control range is determined by both the contractual constraint and the rated power consumption, which influences the control complexity. The control complexity is evaluated by the number of active DR units that are curtailed during the control action. Therefore, small control depth of domain results in large control range and complexity for relevantly large peak clipping requirement, which leads to higher level of operational energy loss. However, the control depth of each demand is strictly constrained by load profile and its own characteristics in reality. In this scenario, customers sign up contract with DNO for certain DSM schemes and obtain tariff incentives. Therefore, it is inadmissible to implement deep demand curtailment for maintaining its own functionality.

Finally, some problems have to be clarified after the above discussions. This chapter focuses on the HIL simulation of a novel CSP based DR-PFM approach in real time instead of implementing thermal model analysis. The operational cost of control actions is another aspect in OPF based management approaches which may also contributes on the relief of thermal overload. The comparison of this approach to CSP based DR-PFM approach is a new direction in the future research. In addition, the application of DSM is still an alternative in network control options. The construction of information communication and advanced measurement system is also a future work to satisfy the assumptions in this chapter.

4.5 Summary

This chapter has presented a case study for the CSP based DR-PFM approach. The active demand control approach successfully relieves the on-line thermal constraint. The performance of the control actions is evaluated in terms of feasibility, control range, curtailment index, duration factor, control efficiency, response delay, and CSP response. The multiple load control facilitates customer participation within the contractual order and preference limits. Discussions of the four tests indicate that the pre-defined domain setting and constraints influence the control performance and flexibility. The increasing complexity of control actions can be achieved at the cost of much energy loss and lower frequency. However, further research is still required on the investigation of the contractual constraint prioritization, commercial analysis and network transparency. In addition, further investigation in hybrid control of both DG and DR is another option for a more flexible and extensible smart distribution network control approach. This approach will be presented in the next chapter.

Chapter 5

Constraint Satisfaction Problem Based Hybrid Control for Power Flow Management

5.1 Overview of Chapter 5

The previous chapter has presented a novel CSP based DR-PFM control approach for ANM control platform in distribution network application. The simulation results for single and multiple load control actions successfully demonstrated that the control approach effectively solved the network thermal overload problem in an acceptable time response range. However, the control opportunity from the demand side varies in different environment and time period which influence the control efficiency of DR units with specific preference and contractual constraints.

In this chapter, further research has been developed on a novel CSP based Hybrid Control for Power Flow Management (HC-PFM) to deal with large thermal overload in ANM distributed control platform. The HC-PFM implements on-line real power curtailment control actions from both DR and DG units. In this case, the objective function of the CSP solver is adaptively changed to minimize the total curtailed real power from both DR and DG units while relieving the thermal constraint during a temporary peak overload. The control objective remains the same as the one in Chapter 4 that aims to obtain the desirable solution with preferred control depth in a contractual prioritization. Case studies are simulated for the comparison of optimal control scheme in two tests of DG control supported by DR, two tests of DR control supported by DG, and a test of DG only control. The control performance will be evaluated in the same parameters of feasibility, control range, curtailment index, duration factor, control efficiency, response delay, and CSP response. The key findings will be discussed at the end of this chapter.

5.2 Case Study for Hybrid Control

The CSP-based HC-PFM HIL simulation case study is tested on a 33 kV distribution network, shown in Figure 5-3. The test network is interconnected between the MV wide grid in *Sub X* and the LV distribution area in *Sub Y* and *Sub Z*. The whole network contains 13 main loads supported by 9 renewable DG units. The case study network is the same as the one in Chapter 4 for the HIL simulation convenience except for the predetermined controllable DG and DR units.

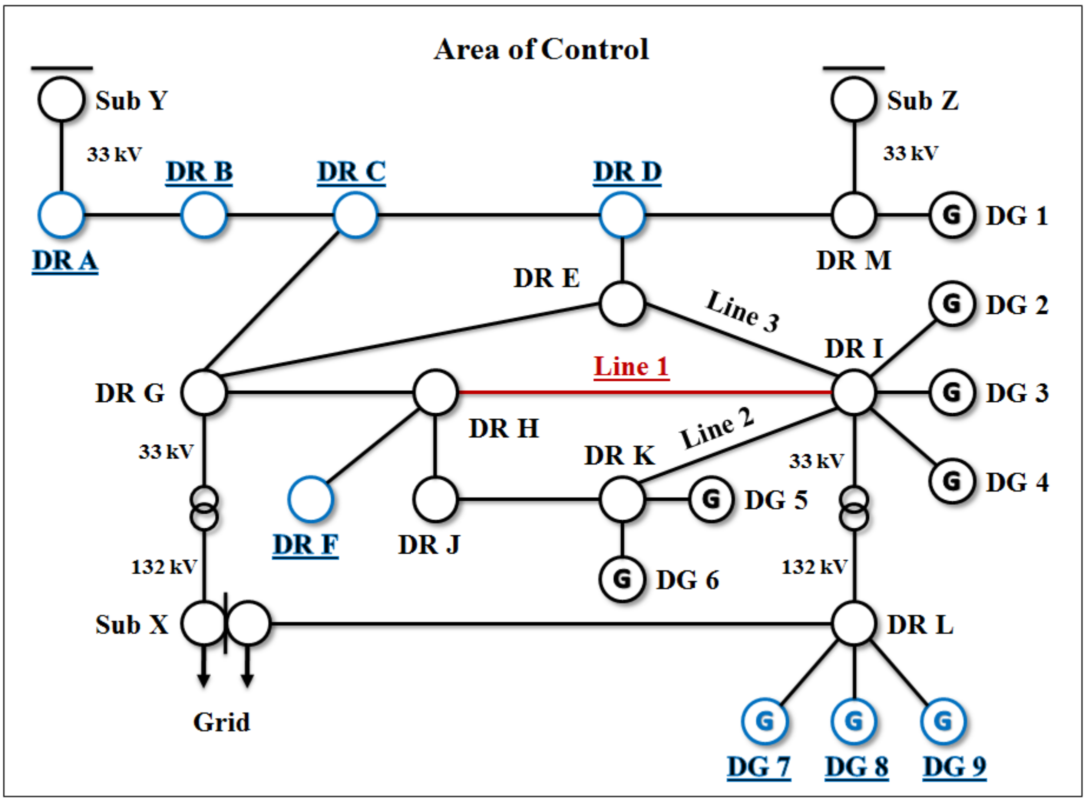


Figure 5-1: 33 kV Interconnected Test Network with Flexible DG and DR Units

In the control scheme, 3 DG units and 5 DR units (synchronized generators) are assigned to implement the HC-PFM control actions, which are *DR A*, *DR B*, *DR C*, *DR D*, *DR F*, *DG 7*, *DG 8*, and *DG 9*. The DG units emulate wind farms which can be curtailed and totally tripped. The other DG units are assumed to be important local generators that are not applicable to be controlled. The DR units emulate flexible demand that can be obtained from the combination of central heating, energy charging, and domestic appliances in the area. Financial incentives are also the assumption for priority arrangement from *Priority 1* to *Priority 8*. The DG units are operated in the rating range from 12.5 MW to 25 MW while the DR units are operated in the consumption from 3.6 MW to 9.6 MW.

However, the target objective is changed to a more severe thermal overload problem. The CSP-based HC-PFM control is implemented to relieve a short term thermal overload in *Line 1* which is caused by a sharp increase of demand at *DR F* that lasts for approximate 80 seconds during a 124 seconds' test. The thermal overload quantity and duration are both larger than the corresponding parameters of the HIL simulation in Chapter 4 to obtain a better comparison result of both DG and DR units control. Five case study tests are implemented within the same thermal overload conditions, but different contractual constraints, to examine this novel HC-PFM control approach. The thermal issues in this HIL simulation are not concerned as the critical one in such short time scales for the thermal constants of most distribution equipment are frequently in minutes or hours. However, these onerous tests are deliberately designed to present the speed and responsiveness of the novel approach. The results are presented and discussed in the following sections.

5.3 Simulation and Result Analysis

In this section, the evaluation adopts the same parameters of control performance as previous tests in Chapter 4. They are highlighted in Section 5.3.1. The HC-PFM approach is demonstrated in 5 case study tests. The tests include 2 sets of DG control supported by DR tests, 2 sets of DR control supported by DG, and 1 DG only control as a reference test for comparison.

5.3.1 Control Performance Evaluation

The CSP-based PFM distributed control cases are also evaluated by the same parameters as the ones in Chapter 4, which are presented as follows: feasibility, response delay, control range, curtailment index, duration factor, control efficiency, and CSP response. The objective function of the CSP solver in HC-PFM is to minimize the total curtailed real power from both DG and DR units to achieve the thermal overload relief objective. The control evaluation parameters are highlighted in Table 5-1.

Evaluation Parameters	**Comments (HC-PFM)**
Feasibility	If the control actions successfully relieve the thermal overload and recover the curtailed units in the unconstrained condition
Control Range	The total instantaneous real power curtailed from the rated level of controllable units as a function of time during the control period
Max Control Range	The value of the control range in the worst case in which the largest quantity of thermal overload is occurred with the deepest power curtailment from the controllable units
Curtailment Index	The value of total energy curtailed from both DG and DR units by the control actions during the whole control period
Duration Factor	The ratio of total energy loss to maximum real power curtailed which is expressed in time unit
Overloaded Energy	The energy content of the increased demand (*DR F* in this set of tests)
Control Efficiency	The relative quantity of energy curtailed in comparison with the overload energy
Response Delay	The total control action time delay to the thermal overload detection
CSP Response	The calculation time of the CSP solver from overload detection to solution provision

Table 5-1: Highlight of the Evaluation Parameters (HC-PFM)

The assumption has been made on the financial incentives that the DNO provides to both DG and DR units for the attendance of the control scheme. Although the controllable units hold different profiles, this assumption ensures that the case study tests are implemented in an ideal environment. The research only focuses on the control performance analysis based on a simplified control model with contractual priority arrangement and preferred control depth of DR.

Mathematical models are redefined from Chapter 4 for the evaluation parameters of the control range, the maximum control range, the curtailment index, the duration factor and the control efficiency:

- The control range is redefined as follows:

$$P_{Range}(t) = \sum_{i=1}^{n}[P_{i-Output}(t) - P_{i-Setpoint}(t)] \tag{5.1}$$

Where $P_{i\text{-}Output}(t)$ refers to the actual instantaneous power consumption of the i^{th} controllable unit (DR or DG) without constraints; while $P_{i\text{-}setpoint}(t)$ refers to the controlled instantaneous power consumption of the i^{th} controllable unit under constraints.

- The maximum control range is redefined as follows:

$$P_{MAX} = Max[P_{Range}(t)] \tag{5.2}$$

Where $P_{Range}(t)$ refers to the control range obtained from Equation 5.1.

- The curtailment index is redefined as follows:

$$E_{Curtailed} = \int_T P_{Range}(t)dt \tag{5.3}$$

Where $P_{Range}(t)$ represents the *control range* that is obtained from Equation 5.1. And the integral is limited within in the control period *T*.

- The duration factor is redefined as follows:

$$F = \frac{E_{Curtailed}}{P_{Curtailed}} = \frac{\int_T P_{Range}(t)dt}{Max[P_{Range}(t)]} \tag{5.4}$$

Where $E_{Curtailed}$ refers to the curtailment index obtained from Equation 5.3; and $P_{Curtailed}$ refers to the maximum value of the control range in Equation 5.2 during the control period.

- And the control efficiency is redefined as follows:

$$f = \frac{E_{Overloaded}}{E_{Curtailed}} = \frac{\int_T P_{Overloaded}(t)dt}{\int_T P_{Range}(t)dt} \tag{5.5}$$

Where $E_{Overloaded}(t)$, so-called overloaded energy, refers to the amount of transient increased energy from the fluctuated demand that results in thermal overload (*DR F* in this simulation); and $E_{Curtailed}(t)$ refers to the curtailment index obtained from Equation 5.3.

It is noted that the application of this approach in reality is based on complex cost-benefit analyses on both DG and DR profiles. In addition, the sensitivity factor that evaluates the contribution relationship between controllable units and thermal overloaded lines is another important aspect. However, the purpose of these tests is to demonstrated the feasibility of the hybrid control and do comparison analysis for the result. The economic factor and the sensitivity factor based analyses are taken into the future work.

5.3.2 Case Study Analysis

Five case study tests are presented in this subsection which are Test 1: PFM DG control supported by DR (0.8/0 control depth); Test 2: PFM DG control supported by DR (0.7/0 control depth); Test 3: PFM DR control supported by DG (0.8/0 control depth); Test 4: PFM DR supported by DG (0.7/0 control depth); and Test 5: PFM DG only control. Further comparisons and evaluations of the control performances will be made in the following discussion part.

5.3.2.1 Test 1: PFM DG Control Supported by DR

Test 1 presents a PFM DG curtailment control supported by DR for temporary large thermal overload relief in certain distribution line. In this test, the variables are marked with underline in Figure 5-1 which comprise 3 DG units which are *DG 7*, *DG 8*, and *DG 9*, and 5 DR units which are *DR A*, *DR B*, *DR C*, *DR D*, and *DR F*. The domain is set to be {0, 0.5, 0.8, 1} for the DG units and {0, 0.5, 0.7, 0.8, 0.9, 1} for the DR units. The objective function is to minimize the curtailed real power from both DG and DR units.

The network constraint is derived from the IPSA simulation model in a rate of 3 seconds per cycle. The contractual constraint identifies the priority of control actions performed on the distributed control units, which is {*DG 9*, *DR A*, *DR B*, *DG 7*, *DG 8*, *DR C*, *DR D*, *DR F*} incrementally. The controllable unit located in the left of the priority list, DG 9, has the lowest priority which will be curtailed first during the thermal overload period. And the preference constraint is assumed to be 0.8 for all the DR units and 0 for all the DG units. It indicates that the deepest control action performed on any DR unit is 20% curtailment, while the DG unit can be tripped unrestrictedly. The result of PFM DG control supported by DR (0.8/0 control depth) is shown in Figure 5-2. It is noted that the horizontal-axis represents simulation time in seconds, and the vertical-axis represents the real power output in MW in the figure.

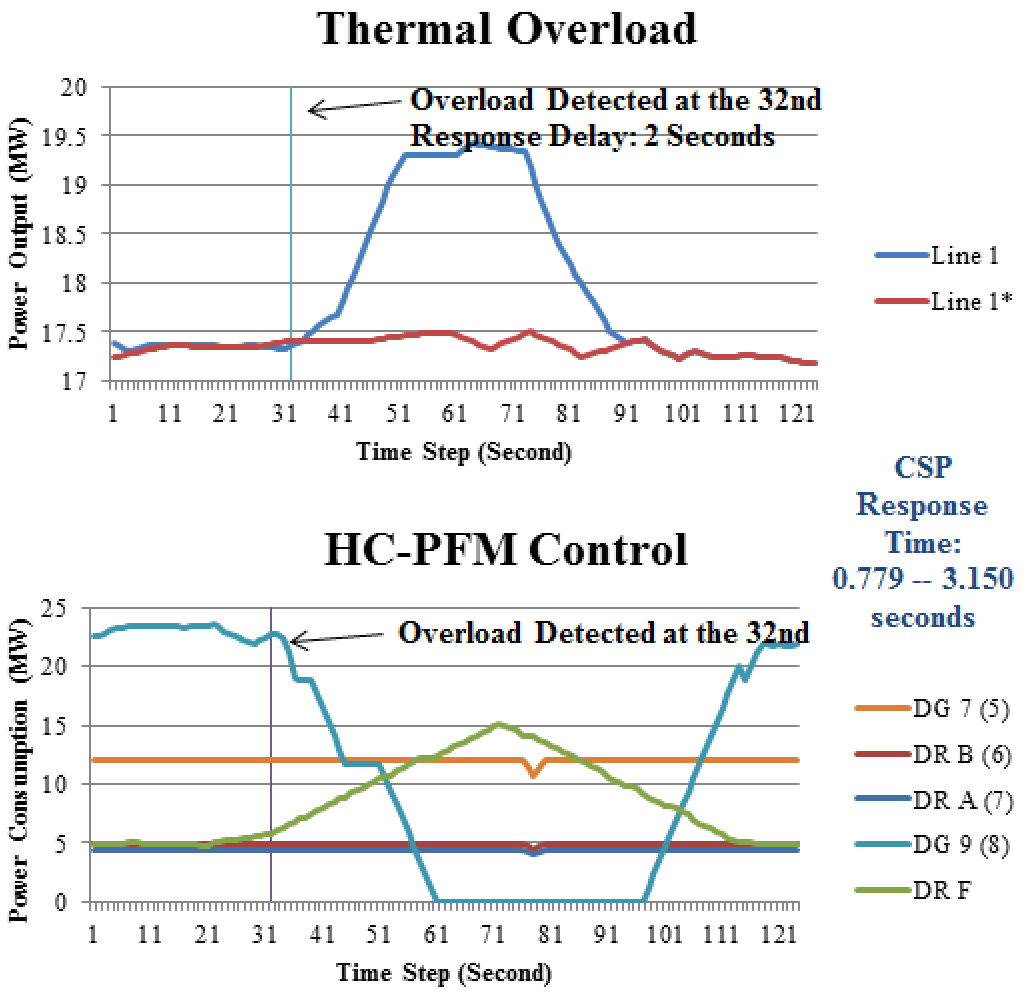


Figure 5-2: PFM Distribution Control Result for Test 1 – DG Control Supported by DR (0.8/0 control depth)

In order to investigate the exact control performance for calculation convenience, the details of control actions are collected and shown in Table 5-2.

CSP-Based PFM Distributed Control Actions									
DR Units		DR A	DR B	DR C	DR D	DR F	DG 7	DG 8	DG 9
Priority		7	6	3	2	1	5	4	8
Rated MW Output		-4.4	-5.0	-4.1	-3.6	-4.9	12.0	23.5	23.5
Time Log of Control Signal	32	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	34	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8
	39	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5
	51	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
	75	0.8	0.8	1.0	1.0	1.0	0.8	1.0	0.0
	79	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
	96	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5
	106	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8
	114	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 5-2: Control Details for PFM Distribution Control Test 1

The control actions are performed on 4 controllable items, *DG 9* (8), *DG 7* (7), *DR A* (6), and *DR B* (5), the real power of which are recorded in Figure 5-2 with their priorities marked in the brackets. The result shown in Figure 5-2 and Table 5-2 indicates a successful relief of thermal overload caused by the sharply increased demand in DR F during the period from *t* = 32s to *t* = 114s. The thermal overload is detected at *t* = 32s resulting from the sharply increased demand in *DR F*. The control action from the CSP solver is activated at *t* = 34s and starts to trim the controllable items gradually according to the contractual constraint until the thermal overload is completely removed. At first, DG 7 is controlled first and curtailed to 80% at *t* = 34s, 50% at *t* = 39s, and tripped at *t* = 51s. However, the real power curtailed is insufficient to remove the thermal overload totally on *Line 1*. Thus, further control actions are developed on *DR A*, *DR B*, and *DG 9* simultaneously in the worst case with 20% curtailment of their rate real power respectively at *t* = 75s. The worst case lasts 4 seconds and the thermal overload is no longer detected at t = 79s, after which the CSP solver will be involved in recovering the whole system to the unconstrained status gradually in the opposite order of the contractual prioritization. The thermal constraint is totally removed at the t = 114s, and the controllable items are all operated in unconstrained condition at t = 116s. It is noted that the response delay of this test is 2s which is acceptable in a distribution PFM control. And the real time response of the CSP solve for each control action lies within the range from 0.779s to 3.150s.

The result indicates that the CSP based HC-PFM control performance lasts 84 seconds and reaches the compound label for the controlled variables of {<*DG 9*, 0>, <*DR A*, 80%>, <*DR B*, 80%>, <*DG 7*, 80%>} at the worst case. The maximum control range of these controlled variables can be obtained from Equation 5.2, which equals to 27.78 MW. The curtailment index indicates the total curtailed area between the rated real power curve and the actual real power curve of all these variables according to Equation 5.3, which equals to 371.11 kWh. Therefore, the duration factor can be calculated by the ratio of curtailment index and maximum control range shown in Equation 5.4, which is 13.36 kWh/MW. And the control efficiency can be calculated by the ratio of the total overloaded energy in *DR F*, 106.16 kWh, and the curtailment index, 371.11 kWh, which in percentage form is 28.61%. The analysis details of Test 1 are collected in Table 5-3.

Test Result Analysis Details					
Test Label	**Control Type**	**Controlled Items**	**Control Percentage**	**Feasibility**	**Response Delay**
Test 1	DG/DR	*DG 9, DR A, DR B, DG 7*	0/0.8	Yes	2s
Max Control Range	**Curtailment Index**	**Duration Factor**	**Overloaded Energy**	**Control Efficiency**	**CSP Response**
27.78 MW	371.11 kWh	13.36 kWh/MW	106.16 kWh	28.61 %	0.779s-3.150s

Table 5-3: Analysis Details of HC-PFM DG Control Supported by DR (80%)

The above evaluation parameters demonstrate the feasibility of the HC-PFM DG control supported by DR. The control response delay lasts within 2s and the CSP calculation response lasts within 3.15s which are acceptable in distribution control activities in comparison with the ones in Chapter 4. The maximum control range reaches 27.78 MW which covers 4 controlled items to solve the thermal overload resulted from sharp demand increase of 10.116 MW at *DR F* in the worst case. During the 80s control period, the total energy loss, 371.11 kWh, from both DG and DR units is performed to relieve the overloaded energy of 106.16 kWh from the line with the overall control efficiency of 28.61%. The control efficiency is approximately at 50% of the one in the single load control. Thus, the increased control complexity of controlled items contributes to the ANM flexibility and extensibility objectives at the cost of much lower control efficiency. However, such control performance may be improved with different domain settings or contractual constraints. It will be demonstrated in the following tests.

5.3.2.2 Test 2: PFM DG Control Supported by DR

Test 2 also presents a PFM DG curtailment control supported by DR for the same thermal overload relief objective to contrast with Test 1. Thus, in this test, the variables, the domain, the network constraint and the contractual constraint remain the same as the ones in Test 1. However, the contractual constraint for each DR unit is changed to 0.7, which means the control depth of each DR variable decreases to 0.7 of its rated value in comparison with the one of 0.8 in Test 1. And the domain sets for all the DG units remain the same as the one in Test 1. This arrangement is made to investigate the control depth influence to the whole control performance according to the comparing analysis of the evaluation parameters. The result of PFM DG curtailment control supported by DR (0.7/0 control depth) is shown in Figure 5-3.

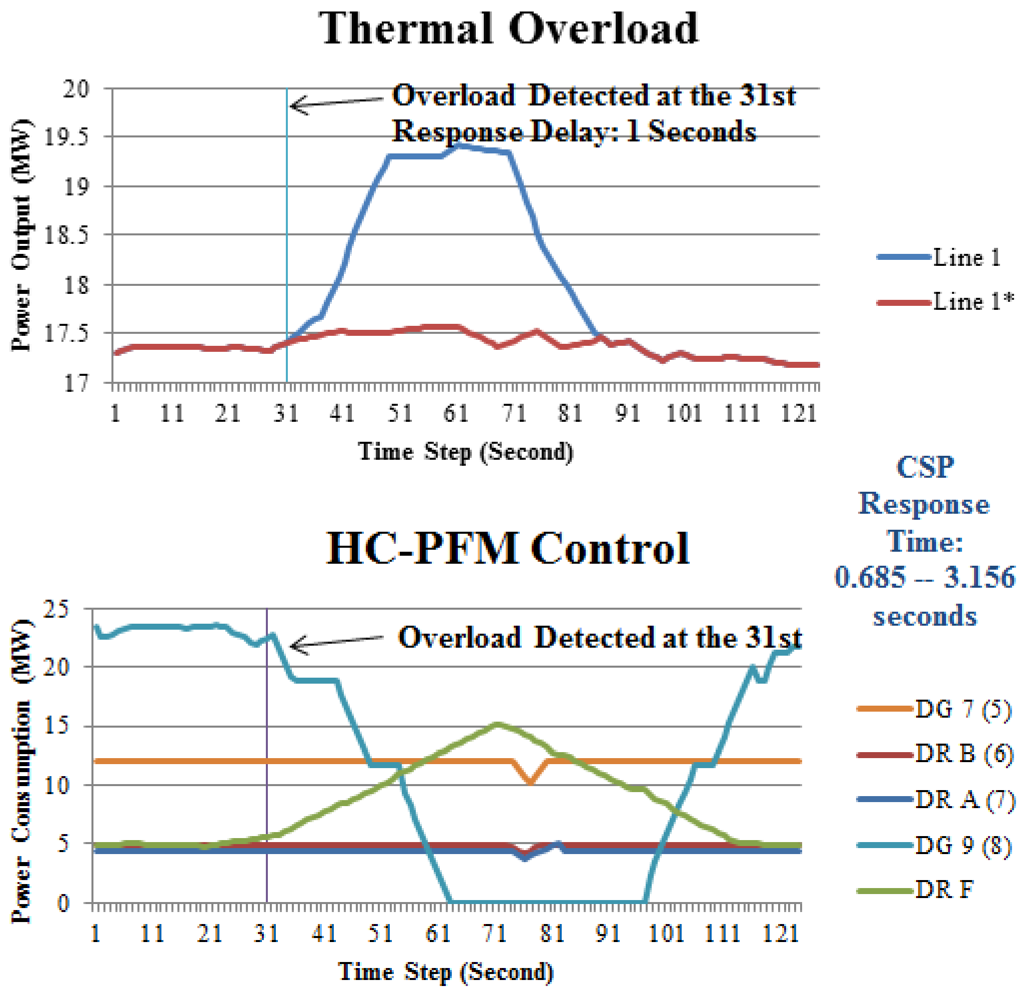


Figure 5-3: PFM Distribution Control Result for Test 1 – DG Control Supported by DR (0.7/0 control depth)

The details of control actions are shown in Table 5-4 for analysis convenience.

CSP-Based PFM Distributed Control Actions									
DR Units		DR A	DR B	DR C	DR D	DR F	DG 7	DG 8	DG 9
Priority		7	6	3	2	1	5	4	8
Rated MW Output		-4.4	-5.0	-4.1	-3.6	-4.9	12.0	23.5	23.5
Time Log of Control Signal	31	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	32	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8
	42	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5
	53	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
	72	0.7	0.7	1.0	1.0	1.0	0.8	1.0	0.0
	74	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
	96	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5
	108	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8
	117	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 5-4: Control Details for PFM Distribution Control Test 2

According to Figure 5-3, the control actions are performed on the same variables which are *DG 9* (8), *DG 7* (7), *DR A* (6), and *DR B* (5), the real power of which are traced and recorded with their priorities marked in the brackets. The result shown in Figure 5-3 and Tables 5-4 indicates a successful relief of thermal overload caused by the same quantity of demand increase in *DR F* during the period from t = 31s to t = 117s. The thermal overload is detected at t = 31s, and the first solution comes out of the CSP solver at t = 32s. Then the variable with the lowest priority, *DG 7*, is curtailed to 80% at t = 32s, 50% at t = 42s, and tripped at t = 53s. However, the insufficient real power curtailment requires further control actions for the increasing thermal overload. Thus, control actions are imposed to *DR A*, *DR B*, and *DG 9* with 30%, 30%, and 20% curtailment quantity respectively in the worst case which occurs from t = 72s to t = 74s. The worst case lasts 2 seconds and the thermal overload is no longer detected at t = 74s, after which the whole system starts to recover to the unconstraint status in the same procedure as Test 1. The thermal overload is totally removed at t = 117s and the whole system is recovered at t = 119s. It is noted that the control response delay of this test is 1s and the CSP calculation response for each control action lies within the range from 0.685s to 3.156s in which the longest duration occurs in the worst case.

The result indicates that the control actions of this test lasts 89 seconds and the compound label for the controlled variables at the worst case is {<*DG 9*, 0>, <*DR A*, 70%>, <*DR B*, 70%>, <*DG 7*, 80%>}. The maximum control range of these controlled variables equals to 28.72 MW. The curtailment index indicates the total curtailed area between the rated real power curve and the actual real power curve of all these variables, which equals to 363.24 kWh. Therefore, the duration factor can be calculated by the ratio of curtailment index and maximum control range, which is 12.65 kWh/MW. And the control efficiency can be calculated by the ratio of the total overloaded energy in *DR F*, 106.16 kWh, and the curtailment index, 363.24 kWh, which in percentage form is 29.22%. The analysis details of Test 2 are collected in Table 5-5.

Test Result Analysis Details					
Test Label	**Control Type**	**Controlled Items**	**Control Percentage**	**Feasibility**	**Response Delay**
Test 2	DG/DR	*DG 9, DR A, DR B, DG 7*	0/0.7	Yes	1s
Max Control Range	**Curtailment Index**	**Duration Factor**	**Overloaded Energy**	**Control Efficiency**	**CSP Response**
28.72 MW	363.24 kWh	12.65 kWh/MW	106.16 kWh	29.22 %	0.685s-3.156s

Table 5-5: Analysis Details of HC-PFM DG Control Supported by DR (70%)

The HC-PFM DG control supported by DR Test 2 is also demonstrated to be feasible of thermal overload control performance. The control response delay lasts within 1s which is a little smaller than the one in Test 1. And the CSP calculation response lasts within 3.15s which is almost the same as the one in Test 1. The maximum control range reaches 28.72 MW in the worst case which also covers the same 4 controlled items to the same amount of 10.116 MW thermal overload resulted from temporary sharp demand increase in *DR F*. It is larger than the one in Test 1 because of the deeper range of the control actions in DR variables which is 70% in control depth instead of 80%. The curtailment index in this test is 363.24 MW which is slightly smaller than the one of 371.11 MW in Test 1. The reason consists in the shorter time period of the worst case which is 2s in comparison with the one of 4s in Test 1. Thus, the deeper control depth of domain contributes to the faster thermal constraint relief in the worst case. The duration factor of 12.65 kWh/MW in this test is also smaller than the one in Test I which indicates a shorter control period and a smaller impact. And as a result, the overall control efficiency of 29.22% I this test is higher than the one of 28.61% in Test 1. Therefore, such improvement of duration factor and control efficiency is achieved in this test at the cost of larger maximum control range which relates to wider curtailment impact from the controllable items.

5.3.2.3 Test 3: PFM DR Control Supported by DG

Test 3 presents a PFM DR curtailment control supported by DG for the same thermal overload relief task to make a comparison analysis with Test 1. Thus, in this test, the variables, the domains, the network constraint, and the preference constraint remain the same as the ones in Test 1. However, the contractual constraint is rearranged to shift *DR A*, and *DR B* to the front of the priority list, which is {*DR A*, *DR B*, *DG 9*, *DG 7*, *DG 8*, *DR C*, *DR D*, *DR F*} in priority order. This rearrangement is designed to implement a contrastive analysis of control performance in difference contractual constraints. The measured power flow also remains unchanged to ensure a same thermal overload environment for analysis convenience. The result of PFM DR curtailment control supported by DG Test 3 is shown in Figure 5-4.

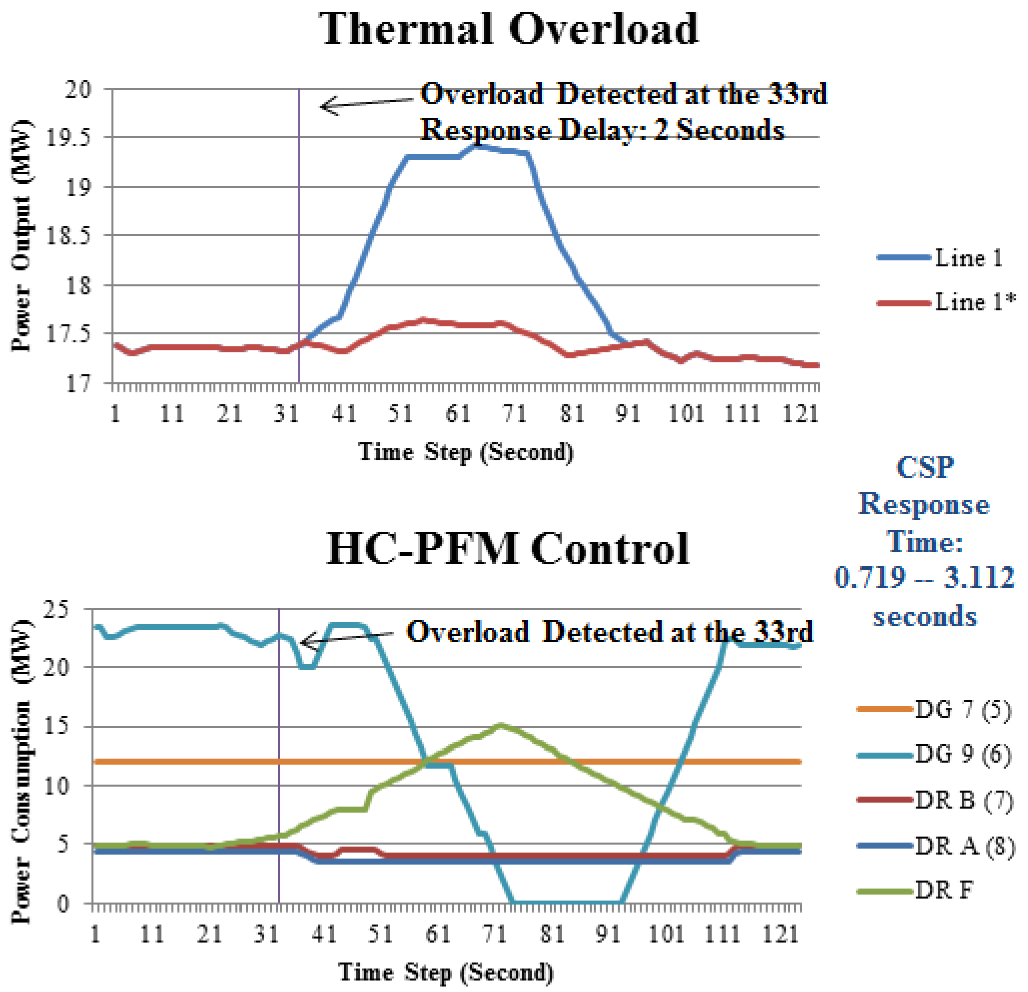


Figure 5-4: PFM Distribution Control Result for Test 3 – DR Control Supported by DG (0.8/0 control depth)

The details of control actions are shown in Table 5-6 for analysis convenience.

CSP-Based PFM Distributed Control Actions									
DR Units		DR A	DR B	DR C	DR D	DR F	DG 7	DG 8	DG 9
Priority		8	7	3	2	1	5	4	6
Rated MW Output		-4.4	-5.0	-4.1	-3.6	-4.9	12.0	23.5	23.5
Time Log of Control Signal	33	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	35	0.8	0.8	1.0	1.0	1.0	1.0	1.0	0.8
	37	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	41	0.8	0.9	1.0	1.0	1.0	1.0	1.0	1.0
	50	0.8	0.8	1.0	1.0	1.0	1.0	1.0	0.5
	62	0.8	0.8	1.0	1.0	1.0	1.0	1.0	0.0
	92	0.8	0.8	1.0	1.0	1.0	1.0	1.0	0.5
	100	0.8	0.8	1.0	1.0	1.0	1.0	1.0	0.8
	108	0.8	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	110	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	111	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 5-6: Control Details for PFM Distribution Control Test 3

According to Figure 5-4, the control actions are performed on 3 variables which are *DR A* (8), *DR B* (7), and *DG 9* (6), the real power of which are traced and recorded with their priorities marked in the brackets. In this test, *DG 7* (5) remains unconstrained since the amount of curtailment on the other three DG units is sufficient to satisfy the requirement of thermal constraint relief. The result shown in Figure 5-4 and Table 5-6 also indicates a successful control performance on these three variables during the control period between t = 33s and t = 113s. The thermal overload is detected at t = 33s and the CSP solver is activated at t = 35s. In this case, DR A, DR B, and DG 9 are controlled simultaneously to 80% in the first control action. The system recovered shortly at t = 37s and t = 41s for a transient constraint relief. The thermal overload is continuously increased since the time step of t = 50s and culminates in the worst case from t = 62s to t = 92s. In the worst case, the operation condition of these controllable items is: *DR A* 80%, *DR B* 80%, and *DG 9* tripped. The thermal overload is on longer detected at t = 92s, after which the CSP solver will be involved in recovering the whole system to the unconstrained status gradually in the opposite order of the contractual prioritization that is {*DG 9* (6), *DR B* (7), *DR A* (8)}. The thermal constraint is totally removed at t = 111s, and the system is operated in unconstrained condition at t = 113s. It is noted that the response delay of this test is 2s and the real time response of the CSP solver for each control action lies within the range from 0.719s to 3.112s.

The result indicates that the control actions of this test lasts 79 seconds and the compound label for the controlled variables at the worst case is {<*DR A*, 80%>, <*DR B*, 80%>, <*DG 9*, 0>}. The maximum control range of these controlled variables equals to 25.38 MW. The curtailment index indicates the total curtailed area between the rated real power curve and the actual real power curve of all these variables which equals to 259.07 kWh. Therefore, the duration factor can be calculated by the ratio of curtailment index and maximum control range, which is 11.63 kWh/MW. And the control efficiency can be calculated by the ratio of the total overloaded energy in *DR F*, 106.16 kWh, and the curtailment index, 295.07 kWh, which in percentage form is 35.98%. The analysis details of Test 3 are collected in Table 5-7.

Test Result Analysis Details					
Test Label	**Control Type**	**Controlled Items**	**Control Percentage**	**Feasibility**	**Response Delay**
Test 3	DR/DG	*DR A, DR B, DG 9*	0.8/0	Yes	2s
Max Control Range	**Curtailment Index**	**Duration Factor**	**Overloaded Energy**	**Control Efficiency**	**CSP Response**
25.38 MW	295.07 kWh	11.63 kWh/MW	106.16 kWh	35.98 %	0.719s-3.112s

Table 5-7: Analysis Details of HC-PFM DR Control (80%) Supported by DG

The HC-PFM DR control supported by DG Test 3 is also demonstrated to be feasible of thermal overload control performance. To compare with Test 1, the control response delay and the range of CSP calculation response remain the same. However, the maximum control range of 25.38 MW in this test is smaller than the one of 27.78 MW in Test 1 with less control complexity of 3 controlled variables instead of 4. The curtailment index of 295.07 kWh is also smaller than the one of 371.11 kWh in Test 1 which indicates a smaller impact of real power loss. In addition, the duration factor of 11.63 kWh/MW is also smaller than the one of 13.36 kWh/MW in Test 1 which indicates shorter control duration for the same thermal overload problem. Furthermore, the control efficiency of 35.98% in this test is much higher than the one of 28.61% in Test 1 which indicates a better performance and smaller impact in this type of PFM control. The comparison of result between Test 3 and Test 1 demonstrates a better HC-PFM type of DR control supported by DG in control performance.

5.3.2.4 Test 4: PFM DR Control Supported by DG

Test 4 presents another PFM DR curtailment control supported by DG for the same thermal overload relief task to make a comparison analysis with Test 3. Thus, in this test, the variables, the domain, the network constraints and the contractual constraint remain the same as the ones in Test 3. However, the preference constraint of each DR unit is changed to 0.7, which means the control depth of each DR variable decreases to 0.7 in comparison with the one of 0.8 in Test 3. The objective of DR control depth change from Test 3 to Test 4 is similar to the one occurs from Test 1 to Test 2 which aims to investigate the influence from the control depth in different control environment. The result of PFM DR curtailment control supported by DG Test 4 is shown in Figure 5-5.

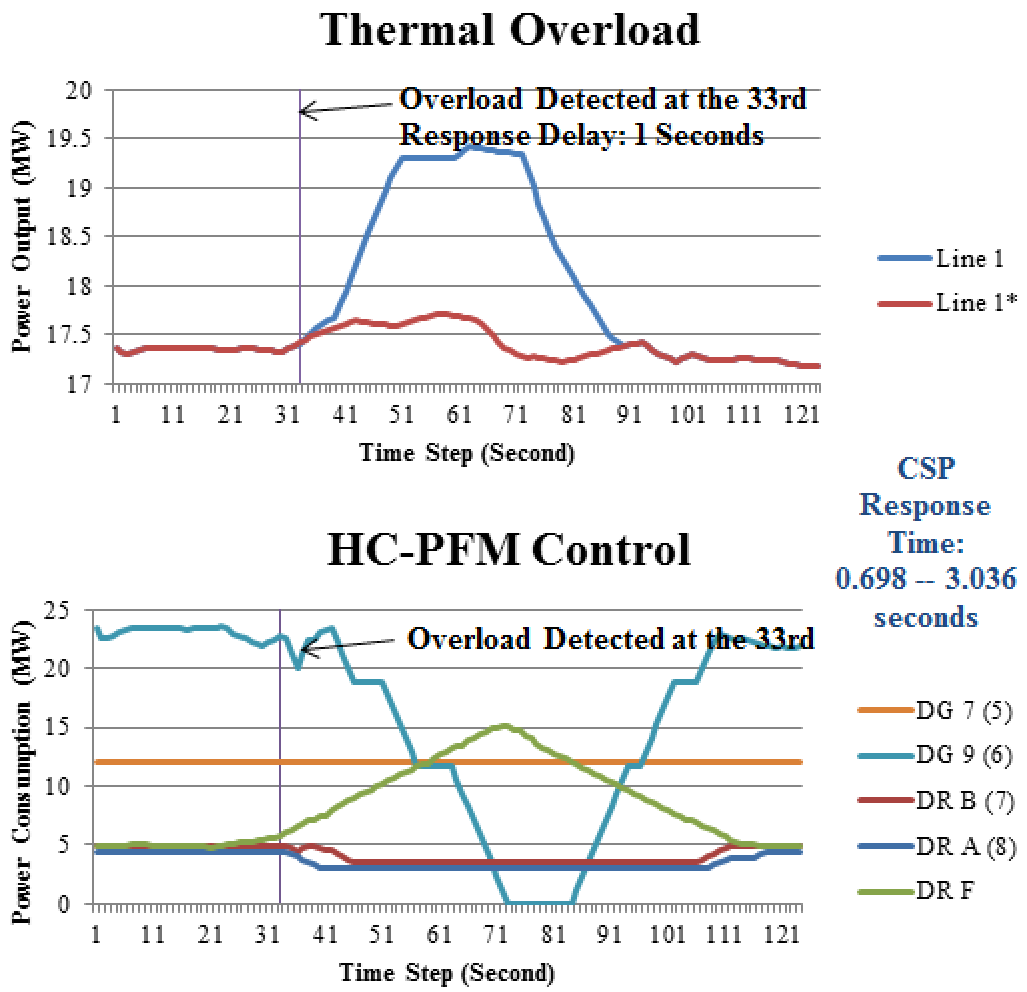


Figure 5-5: PFM Distribution Control Result for Test 3 – DR Control Supported by DG (0.7/0 control depth)

The details of control actions are shown in Table 5-8 for analysis convenience.

CSP-Based PFM Distributed Control Actions									
DR Units		DR A	DR B	DR C	DR D	DR F	DG 7	DG 8	DG 9
Priority		8	7	3	2	1	5	4	6
Rated MW Output		-4.4	-5.0	-4.1	-3.6	-4.9	12.0	23.5	23.5
Time Log of Control Signal	33	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	34	0.7	0.7	1.0	1.0	1.0	1.0	1.0	1.0
	35	0.7	0.7	1.0	1.0	1.0	1.0	1.0	0.8
	36	0.7	0.7	1.0	1.0	1.0	1.0	1.0	1.0
	39	0.7	0.9	1.0	1.0	1.0	1.0	1.0	1.0
	42	0.7	0.7	1.0	1.0	1.0	1.0	1.0	0.8
	51	0.7	0.7	1.0	1.0	1.0	1.0	1.0	0.5
	63	0.7	0.7	1.0	1.0	1.0	1.0	1.0	0.0
	84	0.7	0.7	1.0	1.0	1.0	1.0	1.0	0.5
	96	0.7	0.7	1.0	1.0	1.0	1.0	1.0	0.8
	106	0.7	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	108	0.9	0.8	1.0	1.0	1.0	1.0	1.0	1.0
	109	0.9	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	115	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 5-8: Control Details for PFM Distribution Control Test 4

According to Figure 5-5, the control actions are also performed on the same variables of *DR A* (8), *DR B* (7), and *DG 9* (6) with their priorities marked in the brackets. *DG 7* (5) still remains unconstrained since the control depth of the DR variables is reset with more control margin comparing with Test 3. The result shown in Figure 5-5 and Table 5-8 also indicates a successful control performance on the same three variables during the control period between *t* = 33s and *t* = 115s. The thermal overload is detected at *t* = 33s and the CSP solver is activated at *t* = 34s. In this case, DR A, DR B, and DG 9 are curtailed to 70%, 70%, and 80% at *t* = 35s to deal with the first detection of thermal overload. And the system recovered shortly at *t* = 36s and *t* = 39s for a transient constraint relief. The thermal overload is continuously increased since the time step of *t* = 42s and the variables are curtailed gradually from *t* = 51 to *t* = 63. Such quantity of thermal overload culminates in the worst case from *t* = 63s to *t* = 84s. In the worst case, the operation condition of these controllable items is: *DR A* 70%, *DR B* 70%, and *DG 9* tripped. And then the thermal overload is no longer detected since t = 84s, after which the system is recovered in the same order as the one in Test 3, {*DG 9* (6), *DR B* (7), *DR A* (8)}, at t = 96s, t = 106s, t = 108s, and t = 109s. The thermal constraint is totally removed at *t* = 115s, and the system is operated in unconstrained condition at *t* = 117s. It is noted that the response delay of this test is 1s and the real time response of the CSP solver for each control action lies within the range from 0.698s to 3.036s.

The result indicates that the control actions of this test lasts 83 seconds and the compound label for the controlled variables at the worst case is {<*DR A*, 70%>, <*DR B*, 70%>, <*DG 9*, 0>}. The maximum control range of these controlled variables equals to 26.32 MW. The curtailment index can be calculated from the total curtailed area between the rated real power curve and the actual real power curve of all these variables, which equals to 280.58 kWh. Therefore, the duration factor can be calculated by the ratio of curtailment index and maximum control range, which is 10.66 kWh/MW. And the control efficiency can be calculated by the ratio of the total overloaded energy in *DR F*, 106.16 kWh, and the curtailment index, 280.58 kWh, which is 37.84% in percentage form. The analysis details of Test 4 are collected in Table 5-9.

Test Result Analysis Details					
Test Label	**Control Type**	**Controlled Items**	**Control Percentage**	**Feasibility**	**Response Delay**
Test 4	DR/DG	*DR A, DR B, DG 9*	0.7/0	Yes	1s
Max Control Range	**Curtailment Index**	**Duration Factor**	**Overloaded Energy**	**Control Efficiency**	**CSP Response**
26.32 MW	280.58 kWh	10.66 kWh/MW	106.16 kWh	37.84 %	0.698s-3.036s

Table 5-9: Analysis Details of HC-PFM DR Control (70%) Supported by DG

The HC-PFM DR control supported by DG Test 4 is also demonstrated to be feasible in realization of ANM objective. To compare with Test 1, the control response delay and the range of CSP calculation response are shorter than the ones in Test 3. The maximum control range of 26.32 MW in this test is larger than the one of 25.38 MW in Test 3 because of deeper control depth in the domain of the DR variables which is 70% comparing with 80%. However, the curtailment index of 280.58 kWh in this test is smaller than the one of 295.07 kWh in Test 3 owing to the same reason of deeper control depth as the comparison between Test1 and Test 2. The duration factor of 10.66 kWh/MW in this test is smaller than the one of 11.63 kWh/MW in Test 3 which relates to a shorter control period. It is noted that the shorter control period resulted from deeper control depth contributes to the smaller curtailment index which also results in higher control efficiency of 37.84% comparing with the one of 35.98% in Test 3. Therefore, the comparison result between Test 4 and Test 3 also demonstrates that the improvement of duration factor and control efficiency is achieved at the cost of deeper control depth and larger maximum control range which results in wider impact of the variables.

5.3.2.5 Test 5: PFM DG Only Control

Test 5 is designed to investigate the performance of DG dispatch control approach developed in the parallel project of ANM control platform [1] comparing with the presented HC-PFM control approach in the previous 4 tests. In this test, a PFM DG curtailment control is presented to deal with the problem of the same temporary large thermal overload for performance comparison. Thus, the condition of this test which includes the variables, the domain set of DG variables, the network constraint, and the preference constraint remains the same as the previous tests except for another rearrangement of the contractual constraint. In this case, two DG units, *DG 9* and *DG 7*, are shifted to the front of the priority list, which is {*DG 9*, *DG 7*, *DR A*, *DR B*, *DG 8*, *DR C*, *DR D*, and *DR F*} in priority order. This rearrangement is designed to implement a new control pattern sample for the contrastive analysis. The result of PFM DG only control Test 5 is shown in Figure 5-6.

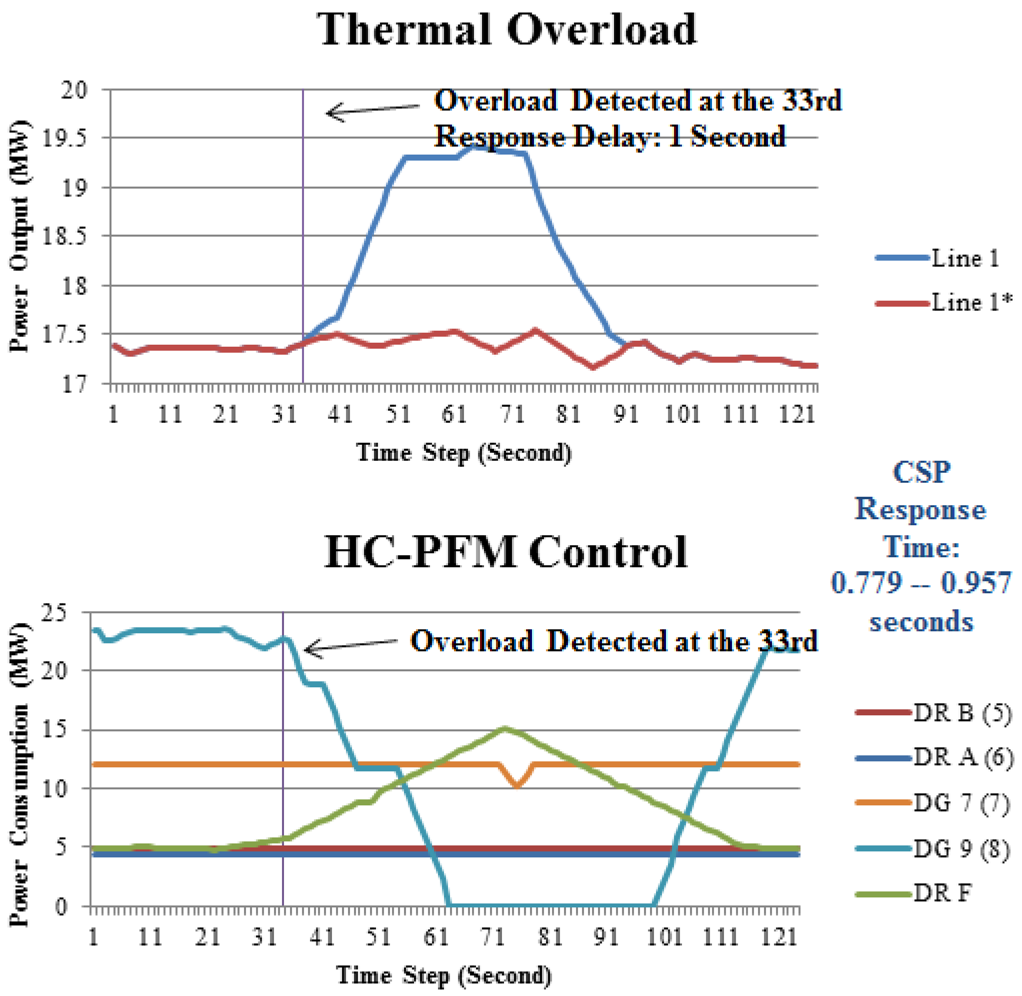


Figure 5-6: PFM Distribution Control Result for Test 3 – DG Only Control

The details of control actions are shown in Table 5-10 for analysis convenience.

CSP-Based PFM Distributed Control Actions									
DR Units		DR A	DR B	DR C	DR D	DR F	DG 7	DG 8	DG 9
Priority		6	5	3	2	1	7	4	8
Rated MW Output		-4.4	-5.0	-4.1	-3.6	-4.9	12.0	23.5	23.5
Time Log of Control Signal	34	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	35	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8
	40	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5
	53	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
	72	1.0	1.0	1.0	1.0	1.0	0.8	1.0	0.0
	75	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.0
	98	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.5
	109	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8
	115	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 5-10: Control Details for PFM Distribution Control Test 5

According to Figure 5-6, the control actions are only performed on 2 DG variables which are *DR 9* (8) and *DG 7* (7), the real power of which are traced and recorded with their priorities marked in the brackets. In this test, the DR variables are remain unconstrained since the amount of real power curtailment from the 2 DG variables are sufficient to implement PFM control actions for the existing thermal overload. The result shown in Figure 5-6 and Table 5-10 indicates that the DG dispatch control is successfully implemented to deal with the same amount of thermal overload during the control period between t = 34s and t = 109s. The thermal overload is detected at t = 34s and the CSP solver is activated at t = 35s. Then the control actions are imposed to the variable with the lowest priority, DG 9, which are 80% at t = 35s, 50% at t = 40s, and tripped at t = 53s. The worst case lasts from t = 72s to t = 75s, in which the variables of *DR 9* and *DG 7* are curtailed to 0 and 80% of its rated power output respectively. The thermal overload is no longer detected at t = 75s, after which the variables are recovered to their normal operation status one by one. Thus, *DG 7* is operated without constraint at t = 75s and *DG 9* is controlled to 50% at t = 98s and totally recovered at t = 115s. And the whole system is recovered at t = 117s. It is noted that the control response delay of this test is 1s and the CSP calculation response for each control action lies within the range from 0.779s to 0.957s.

The result indicates that the control actions of this test lasts 82 seconds and the compound label for the controlled variables at the worst case is {<*DG 9*, 0>, <*DG 7*, 80%>}. The maximum control range of these DG units equals to 25.90 MW. The curtailment index can be calculated from the total curtailed area between the rated real power curve and the actual real power curve of all these variables, which equals to 368.42 kWh. Therefore, the duration factor can be calculated by the ratio of curtailment index and maximum control range, which is 14.22 kWh/MW. And the control efficiency can be calculated by the ratio of the total overloaded energy in *DR F*, 106.16 kWh, and the curtailment index, 368.42 kWh, which in percentage form is 28.81%. The analysis details of Test 5 are collected in Table 5-11.

Test Result Analysis Details					
Test Label	**Control Type**	**Controlled Items**	**Control Percentage**	**Feasibility**	**Response Delay**
Test 5	DG	*DG 9, DG 7*	0	Yes	1s
Max Control Range	**Curtailment Index**	**Duration Factor**	**Overloaded Energy**	**Control Efficiency**	**CSP Response**
25.90 MW	368.42 kWh	14.22 kWh/MW	106.16 kWh	28.81 %	0.779s-0.957s

Table 5-11: Analysis Details of HC-PFM DG Only Control

The PFM DG only control is successfully performed to implement DG dispatch control actions in this control environment with large thermal overload relieved. Comparing with the previous HC-PFM control tests, the parameters of maximum control range, curtailment index, duration factor, and control efficiency are all categorized into the worse performance level. However, the control response delay and the CSP calculation response in this test are shorter than the previous test. The duration of CSP calculation response depends on the complexity of the controlled variables. Thus, the advantage of the HC-PFM control approach consists in the smaller demand impact, high control efficiency, and more flexible demand participation. The contrastive analysis will be discussed to the detail in next section.

5.4 Discussions

The above 5 tests have demonstrated the feasibility of the CSP-based PFM distributed control actions on the same thermal overload problem with different domains and contractual constraints. In the simulation tests, the control actions successfully relieve the network constraint with the satisfaction of the preference constraint and the contractual constraint in the control response delays within 2 seconds and suitably fast computation timescales within 3.2 seconds. The control performances of the HIL simulation results are compared according to the evaluation parameters of response delay, maximum control range, curtailment index, duration factor, control efficiency, and CSP response. The contrastive analysis of the results will be presented and discussed in the following 3 subsections.

5.4.1 Discussion for Contrastive Analysis 1

In this subsection, the HIL simulation results of Test 1, Test 2, Test 3, and Test 4 are discussed to the detail. The above tests are all designed to deal with the same amount of the thermal overload occurred in the same critical transmission line. The discussion aims to investigate the impact from different domains and contractual constraints in the HC-PFM control actions. The control performances of the above 4 tests are list in Table 5-12.

Contrastive Analysis of the Results for HC-PFM Control 1				
Test Label	Test 1	Test 2	Test 3	Test 4
Control Type	DG/DR	DG/DR	DR/DG	DR/DG
Controlled Items	*DG 9*, *DR A*, *DR B*, *DG 7*	*DG 9*, *DR A*, *DR B*, *DG 7*	*DR A*, *DR B*, *DG 9*	*DR A*, *DR B*, *DG 9*
Control Percentage	0/0.8	0/0.7	0.8/0	0.7/0
Feasibility	Yes	Yes	Yes	Yes
Response Delay (s)	2	1	2	1
Max Control Range (MW)	27.78	28.72	25.38	26.32
Curtailment Index (kWh)	371.11	363.24	295.07	280.58
Duration Factor (kWh/MW)	13.36	12.65	11.63	10.66
Overloaded Energy (kWh)	106.16	106.16	106.16	106.16
Control Efficiency	28.61 %	29.22 %	35.98 %	37.84 %
CSP Response (s)	0.779-3.150	0.685-3.156	0.719-3.112	0.698-3.036
Test Evaluation	Less Effective	More Effective	Less Effective	More Effective

Table 5-12: Details of Contrastive Analysis 1 for HC-PFM Control Tests

First of all, the contrastive analysis is carried out between Test 1 and Test 2. Both tests are designed to implement the HC-PFM DG control supported by DR control actions. The involved variables of both tests are 4 controllable items with the same contractual constraint which are *DG 9* (8), *DG 7* (7), *DR A* (6), and *DR B* (5). The difference between Test 1 and Test 2 consists in the domain setting of the DR variables which influences the control depth of the consumption in each DR units. The domain setting of the DR variables in Test 1 is {0.8, 0.9, 1}, while the one in Test 2 is extended to {0.7, 0.8, 0.9, 1}. Thus, such extension of the DR domains in

Test 2 increases the maximum control range comparing with the one in Test 1 in the worst case, which indicates a larger impact of the instantaneous real power cut from the variables.

However, the DG units, each of which feeds larger amount of real power to the network comparing with the consumption of any single DR unit, have been demonstrated to contribute with larger sensitivity to the PFM curtailment control performance. Thus, the curtailment of the extra 10% real power consumption on the two DR variables in Test 2 defers the control actions that imposed on the next DG variable in the worst case. Besides, such arrangement of Test 2 also shortens the duration of the worst case which contributes to the reduction of DG output losses that improves the whole control performance. Therefore, the curtailment index and the duration factor in Test 2 are smaller than the ones in Test 1 which indicates a smaller energy loss impact and shorter average control duration. As a result, the control efficiency in Test 2 is higher than the one in Test 1. Therefore, the control performance of Test 2 is better than the one of Test 1 except for the wider control range impact in the DR variables during the period of the worst case.

Secondly, the contrastive analysis is carried out between Test 3 and Test 4. Both tests are designed to implement the HC-PFM DR control supported by DG control actions. The involved variables of both tests are 4 controllable items with the same contractual constraint, which are *DR A* (8), *DR B* (7), and *DG 9* (6). The difference between Test 3 and Test 4 also consists in the same domain change of the DR variable control depth from 80% in Test 3 to 70% in Test 4. The comparison of the evaluation parameters of maximum control range, curtailment index, duration factor, and control efficiency also demonstrates the conclusion derived from the above discussion. In summary, the control performance of Test 4 is better than the one of Test 3 which is achieved at the cost of the wider control range impact in the DR variables during the period of the worst case.

Finally, the contrastive analysis is carried out between the two groups of control actions that include the one of DG curtailment control supported by DR: Test 1 and Test 2, and the one of DR curtailment control supported by DG: Test 3 and Test 4. The former is implemented with 4 controlled variables: *DG 9* (8), *DG 7* (7), *DR A* (6), and *DR B* (5) while the latter is implemented with 3 of them: *DR A* (8), *DR B* (7), and *DG 9* (6). It is obvious that the maximum control range parameters of Test 3 and Test 4 are both smaller than the ones of Test 1 and Test 2, which indicates smaller impacts of the instantaneous real power cut from the variables. In addition, the curtailment index parameters of the former are both smaller than the ones of the latter, which indicates smaller energy losses from the variables during the control period. Furthermore, the duration factor parameters of the former are also both smaller than the ones of the latter, which indicates shorter average engaged periods of each variable. They can also be concerned as the smaller control impacts from the time period. And as a result, the control efficiency parameters of the former are much higher than the ones of the latter, which indicates a more efficient control performance in dealing with the same amount of thermal overload.

Therefore, the above discussions can be concluded as follows:

- Deeper control depth of the DR variables results in more economic control performance expect for the larger instantaneous real power cut in the worst case

- DR curtailment control supported by DG gains more effective control performance than the one of DG curtailment control supported by DR

5.4.2 Discussion for Contrastive Analysis 2

In this subsection, the HIL simulation results of Test 1, Test 2, and Test 5 are discussed to the detail. The discussion aims to investigate the difference of control actions between the DG curtailment control supported by DR and the DG only curtailment control. It also investigates the impact of the control performance when adding 2 DR variables to the middle of 2 controlled DG variables. The control performances of the involved 3 tests are list in Table 5-13.

Contrastive Analysis of the Results for HC-PFM Control 2			
Test Label	Test 1	Test 2	Test 5
Control Type	DG/DR	DG/DR	DG Only
Controlled Items	*DG 9, DR A, DR B, DG 7*	*DG 9, DR A, DR B, DG 7*	*DG 9, DG 7*
Control Percentage	0/0.8	0/0.7	0
Feasibility	Yes	Yes	Yes
Response Delay (s)	2	1	1
Max Control Range (MW)	27.78	28.72	25.90
Curtailment Index (kWh)	371.11	363.24	368.42
Duration Factor (kWh/MW)	13.36	12.65	14.22
Overloaded Energy (kWh)	106.16	106.16	106.16
Control Efficiency	28.61 %	29.22 %	28.81 %
CSP Response (s)	0.779-3.150	0.685-3.156	0.779-0.957
Test Evaluation	Less Effective	More Effective	Standard

Table 5-13: Details of Contrastive Analysis 2 for HC-PFM Control Tests

The contrastive analysis from the previous subsection has demonstrated that the control performance of Test 2 is better than the one of Test 1 owing to the deeper control depth in the domain setting. However, comparing with the DG only curtailment control in Test 5, the performances of Test 1 and Test 2 are further evaluated with new conclusions. Test 5 is designed as a sample of DG curtailment control in the evaluation with only 2 involved controllable items which are {*DR 9* (8), *DG 7* (7)}. It means that the complexity of the controlled variables in Test 5 is smaller than the one in any of the HC-PFM tests. Some assumptions of these tests have to be clarified at the moment. Firstly, it is assumed that the DG units that can be totally tripped for control requirements are more flexible than the DR units during the PFM control period. Secondly, the assumption also includes larger contribution of the DG variables to the PFM control actions comparing with the DR variables, which is also mentioned in the previous discussion.

The maximum control range of Test 5 is much smaller than the ones of Test 1 and Test 2 because of the smaller complexity of controlled variables and the first assumption of flexible DG variables in the control actions. The larger control complexity resulted from the inflexible DR variables causes more instantaneous real power cut in the worst case. In addition, the curtailment index of Test 5 lies between the ones of Test 1 and Test 2, which indicates that the total energy loss of Test 1 or Test 2 is various according to different domain settings. Furthermore, the duration factor of Test 5 is larger than the ones of Test 1 and Test 2, which indicates a longer average control duration of each variable resulted from smaller control complexity of 2 involved variables. And the control efficiency of Test 5 also ranked between the ones of Test 1 and Test 2, which also indicates a medium control performance comparing with the above tests. Finally, both the control response delay and the CSP calculation response of Test 5 indicate a faster problem solving ability which is also contributed by the smaller complexity of the controlled variables.

Therefore, the above discussions can be concluded as follows:

- The impact of instantaneous real power cut in the worst case will be increased when the DR curtailment control is involved in the whole system

- The control performance of the DG curtailment control supported by DR can be less or more economic depending on the arrangement of domain settings

- The complexity of the controlled variables is another important factor which influence the control response delay and the CSP calculation response

5.4.3 Discussion for Contrastive Analysis 3

In this subsection, the HIL simulation results of Test 2, Test 4, and Test 5 are discussed to the detail. The discussion aims to investigate the difference of control actions among the 3 different types of control arrangement: the DG curtailment control supported by DR, the DR curtailment control supported by DG, and the DG only curtailment control. The control performances of the involved 3 tests are list in Table 5-14.

Contrastive Analysis of the Results for HC-PFM Control 3			
Test Label	Test 2	Test 4	Test 5
Control Type	DG/DR	DR/DG	DG Only
Controlled Items	*DG 9, DR A, DR B, DG 7*	*DR A, DR B, DG 9*	*DG 9, DG 7*
Control Percentage	0/0.7	0.7/0	0
Feasibility	Yes	Yes	Yes
Response Delay (s)	1	1	1
Max Control Range (MW)	28.72	26.32	25.90
Curtailment Index (kWh)	363.24	280.58	368.42
Duration Factor (kWh/MW)	12.65	10.66	14.22
Overloaded Energy (kWh)	106.16	106.16	106.16
Control Efficiency	29.22 %	37.84 %	28.81 %
CSP Response (s)	0.685-3.156	0.698-3.036	0.779-0.957
Test Evaluation	More Effective	Most Effective	Standard

Table 5-14: Details of Contrastive Analysis 3 for HC-PFM Control Tests

The contrastive analysis from the previous subsection has demonstrated that Test 2 and Test 4 have more economic control performance comparing with the one of Test 1 and Test 3 respectively in each different control type. Thus, the contrastive analysis of Test 2, Test 4, and Test 5 are developed to identify the one with the most economic performance. The controlled variables in Test 2, Test 4, and Test 5 are {*DG 9* (8), *DR A* (7), *DR B* (6), *DG 7* (5)}, {*DR A* (8), *DR B* (7), *DG 9* (6)}, and {*DG 9* (8), *DG 7* (7)} respectively, which indicates a decreased order of the control complexity. The domain sets of both the DG and DG units remain the same in the above tests which are {0, 0.5, 0.8, 1} for all the DG variables and {0.7, 0.8, 0.9, 1} for all the DR variables. The constraints of the above tests also remain the same except for the contractual constraint. The same assumptions of DG units' performance are also required in this contrastive analysis.

The maximum control range is influenced by the complexity of the controlled variables which is a complicated phenomenon determined by both the control depth of domain and the contractual constraint in the prerequisite condition of the same network constraint. Thus, the maximum control range of Test 5 is larger than the one in the other two tests, which indicates the smaller cut of instantaneous real power in the worst case. The curtailment index in Test 4 has the smallest value among the 3 tests, which is also determined by both the control depth and the contractual constraint. In this scenario, however, the DR curtailment control supported by DG which is determined only by the contractual constraint has the advantages in the smaller impact of the total energy loss. The duration factor of Test 4 is also the smallest among the tests, which indicates a relatively shorter average control period of the variables with a medium control complexity. And the control efficiency of Test 4 also appears to be the highest of the tests, which indicates that Test 4 has the best control performance with smaller energy loss impact and smaller control duration impact. In addition, the control response delay values of the 3 tests are the same. But the CSP calculation response of Test 5 is also the shortest with the smallest control complexity.

Therefore, the new conclusions can be drawn as follows:

- The impact of instantaneous real power cut in the worst case is influenced by the complexity of the controlled variables

- The control performance of the DR curtailment control supported by DG is demonstrated to be the best among the PFM HIL simulation tests.

5.5 Summary

This chapter has presented a case study for the CSP based HC-PFM approach. In the HIL simulation case study, five simulation tests are successfully performed to relieve one large thermal overload in this active demand control model. The control performance is evaluated by the same parameters. The contrastive analysis of the result indicates that the control performance is influenced by the control depth, average control duration, the control complexity, and the control efficiency which are determined by the domain setting and the contractual constraint. Discussion on the 5 tests indicates that the control performance is influenced by the contractual arrangement of the control pattern. However, the overall practicality of this approach requires high reliability on smart grid technologies such as advanced measurement system, communication support, and flexible active demand. Further research is also required on the other influential factors of control performance such as the marketing impacts and the operation costs.

5.6 Reference for Chapter 5

[1] E. M. Davidson, M. J. Dolan, S. D. J. McArthur, and G. W. Ault, "The Use of Constraint Programming for the Autonomous Management of Power Flows," in *Intelligent System Applications to Power Systems, 2009. ISAP '09. 15th International Conference on*, 2009, pp. 1-7.

Chapter 6

Conclusion and Future Work

6.1 Conclusions

The research of the novel CSP based decentralized distribution control approaches and DSM application opportunities in various demand profiles are concluded in this section. The thesis structure and the contributions are presented in the following subsections.

6.1.1 Thesis Structure

The principle of this thesis is based on the structure of DNO advance distribution control platform, shown in Figure 6-1. The author's contribution focuses on a specific portion of the control platform, marked in red.

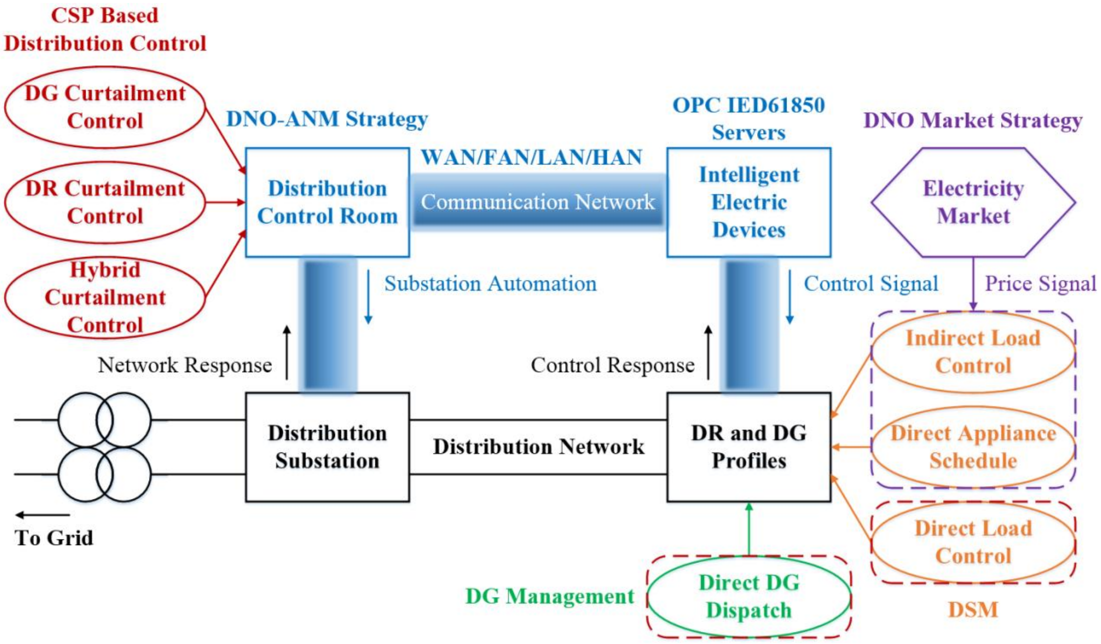


Figure 6-1: DNO Advanced Distribution Control Structure (with author/thesis contribution areas highlighted in red)

The figure illustrates that the DNO-ANM strategy is implemented in the distribution control platform to perform the CSP based distribution control approaches such as

DG curtailment control, DR curtailment control, and hybrid curtailment control. The control signals are communicated to the IEDs in the demand side through the internet topologies of WAN, FAN, LAN, and HAN. Thus, such DSM applications are categorized as the DNO direct load control application. The DNO market strategy is implemented in the reformed electricity market to perform the incentive based tariff schemes according to the suppliers. Thus, the DSM applications are categorized as the DNO indirect load control or direct appliance schedule application.

In addition, all the chapters in this thesis can be integrated in Figure 6-1 which shows the structure of the whole principle. Chapter 1 provides the introduction of the world energy outlook that includes the environmental issues, the renewable development, the policy support, and the future tendency of DSM based ANM application. It is concerned as the main background of the future highly decentralized distribution network marked in black in the figure. Chapter 2 introduces the DSM principle and its application environment of the future EMS that includes DMS, MMS, and the relevant services. Such contents cover the DNO market strategy and the DSM application approaches which are market in purple and yellow respectively in the figure. Chapter 3 presents the main platform of DNO-ANM strategies including the ANM control functions, ANM-DSM realization, and DR control potential. It is concerned as the methodology of the whole advanced distribution control platform which is marked in blue in the figure. And Chapter 4 and Chapter 5 develop novel CSP based distribution control approaches to achieve the PFM objective of network thermal overload alleviation. They are the essential control model design and simulation parts of the whole thesis which are marked in red in the figure. The involved control application approaches in the demand side, direct DG dispatch and direct load control, are also marked with red dot rectangles.

6.1.2 Contribution

This thesis has developed new CSP based active demand control technologies to deal with the DNO specified network thermal overloads in on-line condition. The main objective of this research can be concluded into 3 main points: identification of DNO’s network issues that can be achieved by DNM schemes, development of a DSM based on-line control model, and demonstration of the control performance in HIL simulation environment. The research is developed with the argument of “what the DNO’s network problem is”; “why DSM control is applied”; “how the control approaches work”; and “what’s the result of the control performance”. All the objectives are achieved in this thesis. The author’s contribution can be concluded into the following 3 aspects.

First of all, a literature review has been presented to identify the DSM principles and its application issues from the DNO’s perspective such as capacity reinforcement deferral, distribution loss reduction, active customer participation, and network constraint management. The novelty consists in the construction of a DNO-DSM commercial model which integrates the principles of DSM such as DSM objectives, demand side alternatives, DNO perspectives, and DNO-DSM control methods. It contributes to clarify the DNO’s concern on network issues and provide models for potential demand side alternatives.

Secondly, a new active demand control function has been developed and integrated into an existing ANM control platform for DNO’s direct load control application. The development of this novel DSM based ANM control platform includes the control objective definition, control function integration, control algorithm design, control solver deployment, control signal communication, control action simulation, and control performance evaluation. In the mathematical computation model, a

Constraint Programming (CP) control solver is applied with its remarkable advantage of handling multiple constraints in a relatively short time response. Another novelty is the re-definition of the parameters in the CSP solver with new meanings in the application environment of advanced distribution control approaches. It contributes to build a new mathematical model for DNO’s direct load control and recruitment of DR participants.

Finally, two novel CSP based advanced distribution control approaches, Demand Response for Power Flow Management (DR-PFM) and Hybrid Control for Power Flow Management (HC-PFM), are developed to realize the previously described network thermal rating constraint. The construction of their practical control environment and Hardware-In-Loop (HIL) simulation model is the main novel contribution to integrate the DSM controller, the CSP solver, and the real network together in a realistic test environment. In addition, simulation of the above two advance distribution control approaches demonstrates their feasibility and control performance by newly developed evaluation parameters of response delay, control range, curtailment index, duration factor, and CSP response time. It is concluded that demand location, control depth, and control pattern are important factors that will influence the performance of DR curtailment and generation dispatch. This contributes to a better realization of DSM functions from the DNO perspective.

6.2 Future Work

The previous sections have concluded the main principles, novelty contributions, and simulation discussions of this thesis. Such contributions are highlighted with their design principles which include flexibility, extensibility, and robustness Thus, the further research developments are suggested in this section which are presented as follows:

- As for the CSP based DR-PFM and HC-PFM control actions, besides the constraints identified in this thesis, other influence factors are required to be evaluated for the algorithm refinement such as the commercial factors based on DG connection fees, energy losses, CML, and operating costs. The commercial factors will directly influence the contractual prioritization and the minimum energy curtailed preference in real time. And the contrastive analyses are also suggested to be implemented between the CSP base PFM approaches and the OPF based PFM approaches.

- Additionally, the effectiveness of the PFM distribution control performance depends on the recruitment of DR participants and network topology. The contractual constraint is another important factor. However, the quality of variable contributions to the unity thermal overload in different transmission lines are required to be investigated as another influence factor of such control performance. The sensitivity factor which can be represented in a deviation matrix between variables and lines are suggested to be expended to both DG and DR domain in the future development [1].

- Furthermore, the curtailment accuracy analysis of the above CSP based PFM distribution control actions is another evaluation aspect which contributes to eliminate the unnecessary redundant curtailment that may result in larger financial revenues. From the DNO perspective, the obligation consists in the provision of reliable energy supply and affordable energy tariff while facilitating large renewable and demand accesses and benefiting the lifecycle of the network assets for security and business reasons. Thus, the accuracy of measurement sensors, the reliability of the communication network, and the quality of the network model in ANM are of crucial importance in balancing the relationship between demand and supply [2].

- The investigation of communication systems mentioned in the previous point is another important aspect in ANM realization process. In this thesis, the research project covers the DSM control models for substation automation from the network side and the DSM control opportunities in different demand profiles from the demand side. However, the control signal transmitting in a bidirectional communication system is still required to be demonstrated in the experiments of pilot programs. The evaluation analyses are suggested to be emphasized in the control response delay and communication reliability which may influence by the internet congestion problem and intermittent failure.

- As for the realization problem mentioned above, the distribution state estimation is another import aspect to identify the CSP parameters with the defective information of network response. The power flow transparency in current distribution network is limited by the existing measurement systems that lack of deployed sensors and measurement devices to collect all required data and system states. Thus, the further research of distribution state estimation is recommended as the primary measurement ground for the application of DSM based ANM distribution control actions with estimated measurements.

- Finally, demand profiles are also required to be investigated for the information of available time schedule and acceptable control depth. Although the industrial demands have much higher security level most of which are inapplicable to be curtailed during the operation period, DSM control potential still exists in shifting peak demand to off peak, adopting improved technologies with higher efficiency, and involving in DNO schedule programs. Thus, a DSM application roadmap can be drawn with the identification of all the potential opportunities from various demand profiles that are categorized with different DSM control schemes.

6.3 Reference for Chapter 6

[1] S. C. E. Jupe and P. C. Taylor, "Distributed generation output control for network power flow management," *Renewable Power Generation, IET,* vol. 3, pp. 371-386, 2009.

[2] M. J. Dolan, "The Application and Assessment of Active Network Management Techniques for Distribution Network Power Flows," PhD Thesis, Electronic and Electrical Engineering, University of Strathclyde, 2012.