Smart Grid Technologies and Implementations

By

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Abstract

Smart grid has been advocated in both developing and developed countries in many years to deal with large amount of energy deficit and air pollutions. However, many literatures talked about some specific technologies and implementations, few of them could give a clear picture on the smart grid implementations in a macro scale like what is the main consideration for the smart grid implementations, how to examine the power system operation with communication network deployment, how to determine the optimal technology scheme with consideration of economic and political constraints, and so on. Governments and related institutions are keen to evaluate the cost and benefit of new technologies or mechanisms in a scientific way rather than making decision blindly. Decision Support System, which is an information system based on interactive computers to support decision making in planning, management, operations for evaluating technologies, is an essential tool to provide decision makers with powerful scientific evidence.

The objective of the thesis is to identify the data and information processing technologies and mechanisms which will enable the further development of decision support systems that can be used to evaluate the indices for smart grid technology investment in the future.

First of all, the thesis introduces the smart grid and its features and technologies in order to clarify the benefits can be obtained from smart grid deployment in many aspects such as economics, environment, reliability, efficiency, security and safety.

Besides, it is necessary to understand power system business and operation scenarios which may affect the communication network model. This thesis, for the first time, will give detailed requirements for smart grid simulation according to the power system business and operation.

In addition, state of art monitoring system and communication system involved in smart grid for better demand side management will be reviewed in order to find out their impacts reflecting to the power systems. The methods and algorithms applied to the smart grid monitoring, communication technologies for smart grid are summarized and the monitoring systems are compared with each other to see the merits and drawbacks in each type of the monitoring system.

In smart grid environment, large number of data are need to be processed and useful information are required to be abstracted for further operation in power systems. Machine learning is a useful tool for data mining and prediction. One of the typical machine learning artificial algorithms, artificial neural network (ANN) for load forecasting in large power system is proposed in this thesis and different learning methods of back-propagation, Quasi-Newton and Levenberg-Marquardt, are compared with each other to seek the best result in load forecasting.

Bad load forecasting may leads to demand and generation mismatch, which could cause blackout in power systems. Load shedding schemes are powerful defender for power system from collapsing and keep the grid in integral to a maximum extent. A lesson learned from India blackout in July 2012 is analyzed and recommendations on preventing grid from blackout are given in this work. Also, a new load shedding schemes for an isolated system is proposed in this thesis to take full advantage from information sharing and communication network deployment in smart grid.

Lastly, the new trend of decision support system (DSS) for smart grid implementation is summarized and reliability index and stability scenarios for cost benefit analysis are under DSS consideration. Many countries and organizations are setting renewable penetration goals when planning the contribution to reduce the greenhouse gas emission in the future 10 or 20 years. For instance, UK government is expecting to produce 27% of renewable energies EU-wide before 2030. Some simulations have been carried out to demonstrate the physical insight of a power system operation with renewable energy integration and to study the non-dispatchable energy source penetration level. Meanwhile, issues from power system reliability which may affect consumers are required to take into account. Reliability index of Centralized wind generations and that of distributed wind generations are compared with each other under an investment perspective.

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Glossary of Terms

ACL	Agent Communication Language
AI	Artificial Intelligence
AIS	Artificial Immunity System
AMI	Advanced Metering Infrastructure
ANN	Artificial Neural Network
APE	Absolute Percentage Error
BAU	Business as Usual
BP	Back-propagation Algorithm
CA	Computational Algorithm
CIS	Customer Information System
CLAP	Collaborative Pattern
CSS	Customer Side Systems
CV	Computer Vision
DER	Distributed Energy Resources
DFIG	Double-Fed-Induction-Generator
DFR	Digital Fault Recorders
DLR	Dynamic Line Rating
DMS	Distribution grid Management System
DOE	Department of Energy, United States
DPR	Digital Protective Relays
DSS	Decision Support System
DTR	Dynamic Thermal Rating
EDB	Extensional Database
EMD	Empirical Mode Decomposition
EMI	Electromagnetic Interference
ERP	Enterprise Resource Planning
EV	Electric Vehicle
EWEA	European Wind Energy Association
FACTS	Flexible Alternating Current Transmission Systems\

FDR	Frequency Disturbance Recorders
FNET	Frequency monitoring network
G2V	Grid to Vehicles
GIS	Geographic Information System
GPS	Global Positioning System
HAN	Home Area Network
HSML	Hybrid System Modeling Language
HTS	High-Temperature Superconductors
HVDC	High Voltage DC Systems
IaaS	Infrastructure as a Service
ICT	Information and Communication Technology
IDB	Intentional Database
IEA	International Energy Agency, United States
IED	Intelligent Electronic Device
IEEE	Institute of Electrical and Electronics Engineers, United States
KBS	Knowledge Based System
LED	Light-Emitting Diode
LLS	Local Load Shedding Scheme
LM	Levenberg-Marquardt Algorithm
LTE	Long-Term Evolution (Communication)
MAPE	Mean Absolute Percentage Error
MCU	Microcontroller Unit
MDMS	Meter data management system
MG	Micro Grid
MLP	Multi-layer Perceptron
NETL	National Energy Technology Laboratory, United States
NILM	Nonintrusive Load Monitoring
NIST	National Institute of Standard and Technology
NREL	National Renewable Energy Laboratory, United States
NS-2	Network Simulator 2
OLAP	Online Analytical Processing
OMS	Outage Management System
ORNL	Oak Ridge National Laboratory
PaaS	Platform as a Service

PDC	Phasor Data Concentrator
PLC	Power Line Carrier
PMU	Phasor Measurement Units
PQ	Power Quality
PV	Photovoltaic
RFI	Radio-Frequency Interference
RMSE	Root Mean Squared Error
RTU	Remote Terminal Unit
S2V	Storage to Vehicles
SaaS	Software as a Service
SCADA	Supervisory Control and Data Acquisition
SSL	Secure Socket Layer
SVM	Support Vector Machine
TKEO	Teager-Kaiser energy operator
TTU	Telephone Terminal Unit
TVE	Total Vector Error
UHF	Ultra High Frequency
UPS	Uninterruptible Power Supply
V2G	Vehicles to Grid
V2S	Vehicles to Storage
WAAPCA	Wide-Area Adaptive Protection, Control and Automation
WAMS	Wide-Area Monitoring Systems
WASA	Wide-Area Situational Awareness
WIMAX	Worldwide Interoperability for Microwave Access
WMS	Workforce Management System
XDSS	DSS Based on Expert Systems Approach
NETL	National Energy Technology Laboratory, United States
IEA	International Energy Agency, United States
IEEE	Institute of Electrical and Electronics Engineers, United States

Copyright Declaration

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Chapter 1

Introduction

1.1 Background and Objectives

With the extremely increasing of the large industry and commerce, energy supply deficit and air pollution issues are becoming more and more critical. In order to solve the problems in both developed and developing countries, smart grid with many advanced architectures, outstanding algorithms and creative frameworks has been advocated [1].

There are few “definitions” to explain what it is, though the conception of smart grid has been proposed for several years, many institutes of power system around the world concentrate on explanations of its functions and technical applications. In addition, many countries and regions research and develop their specific smart grid in accordance with their situations like energy resource distribution and consumption, environment and climate, and commercial, industrial and residential daily life customs. For instance, in Europe, people devote themselves to develop the renewable energies and distributed generation systems, while in the US, smart metering and demand response are the main direction in smart grid implementation. State Grid Corporation of China has proposed to establish the “strong and robust smart grid”, which makes every effort to build HVDC and FACTS in order to transmit electric power from the western region, which is rich in energy, to eastern region in China.

One of the significant differences is that communication networks deployment in many areas of a smart grid is much more critical than that of traditional grid. Many computer-based remote monitoring, control and automation devices are beginning to apply to the electricity delivery systems, to form a bi-communication channel linked through the grid from power plants to any consumers like residential, commercial, industrial and agricultural. In addition to the information exchange within power systems, all other systems such as petroleum, natural gas dispatch systems, weather forecasting will also share the information with power systems. With the increasing penetration level of the non-dispatchable energy resources like wind and solar and application of demand response, the effect from weather is playing more and more significant role to power systems.

Load forecasting mechanism is one of a great application for information exchange between weather forecasting and power systems. Accurate short-term load forecasting may contribute to the power economic dispatch and design an appropriate demand response or load shedding plan to prevent the loads from over-withdrawing energy from the grid. Long-term load forecasting can offer a consultative reference to further planning for optimizing energy resource allocation.

It is a step-by-step procedure towards smart grid to replace the old power system elements or build facilities based on existing grid instead of build up a brand new grid. Thus, planning for smart grid may not only consider the effect that comes from the creative technologies, but also respecting for diverse stakeholders' interests. Cost benefit analysis has to be carried out to make a correct or reasonable decision. One of the most effective tool for estimating the smart grid technologies and implementations is to build the Decision Support System, which is an information system based on interactive computers to support decision making in planning, management, operations for smart grid.

Objectives: This thesis aims to identify the data, specify and develop the information processing technologies and mechanisms which will further contribute to the development of decision support systems for the smart grid. These will contribute to the evaluation of the investment indices for smart grid technology of the future.

Regarding to these objectives, the thesis is organized as follows in Section 1.2.

1.2 Organization of Thesis

This thesis consists of 7 Chapters. The main focus is on Smart grid technologies and implementations.

Chapter 2 Smart Grid Overview

Chapter 2 overviews smart grid definitions, features and its technologies. Moreover, the differences between traditional grid and smart grid will be discussed. Strategy planning, motivations, challenges and implementations will also be summarized in this chapter. The key points of the chapter have been published in "An Overview on Smart Grid Simulator".

Chapter 3 Smart Grid Monitoring with Communication Technologies

Chapter 3 will give a state of the art review on smart grid monitoring systems and communication systems. New technologies applied into intelligent system in many technical fields will be discussed. The development of condition monitoring and smart grid monitoring like wide-area monitoring technologies and commercial electronic monitoring is demonstrated to examine the critical needs for smart grid systems. Mechanisms and algorithms applied into intelligent monitoring system will be summarized in order to find out their impacts reflecting to the power systems. A novel framework for smart grid decision support system design will be proposed. Some of the points have been published in "Monitoring System for Smart Grid".

Chapter 4 Smart Grid Load forecasting by Artificial Neural Network

Artificial Neural Network (ANN) and Back-Propagation training is introduced in Chapter 4 to achieve load forecasting for its excellent mapping approximation ability such that there is a high potential for industrial use. A paper named "Artificial Neural Network for Load Forecasting in Smart Grid" has been generated for this chapter.

Chapter 5 Self-healing and load shedding in Smart grid

Chapter 5 reports lessons learned from India blackout in this chapter as a negative example of real-life case study in load shedding. Also, ideas in published paper "Lessons Learned from July 2012 Indian Blackout" and "Survive Distribution Networks Using an Automatic Local Load Shedding Scheme" are derived in this chapter.

Chapter 6 Decision Support System for Smart Grid Implementation

Chapter 6 reports the development of decision support systems (DSS) for smart grid deployment. Cloud computing and agent-based DSS are discussed in this chapter for smart grid implementation. Reliability, security and stability indices for smart grid are considered for decision support systems through a cost-benefit analysis approach. The integration of these elements together will form a new and novel application. Three conference papers "New Trends for Decision Support Systems", "Research on Wind and Solar Penetration in a 9-bus Network", and "Reliability and Investigation Assessment for Wind Energy Generation" have been published from this chapter.

Chapter 7 Conclusions

Chapter 7 summarizes the work done and based on the current finding; direction for future study will be discussed.

1.3 Original Contribution

1. Comparison, analysis and summary of smart grid technology and implementation solutions. This work summarizes the smart grid technologies and its benefits in different aspects. Various requirements have been considered and it will provide tutorial values to the field, and also it will provide a direction for the academics, researchers, engineers and decision makers as an important reference. (Chapter 2)

2. Monitoring systems and Communication system for smart grid has been analyzed. This work summarizes the methods and algorithms applied to the smart grid monitoring, communication technologies for smart grid. Comparison on different types of monitoring systems has been made, which could see the merits and drawbacks in each type of the monitoring system. (Chapter 3)

3. A reasonable method for achieving power system and communication co-simulation by taking into account real-life power system business and operation is proposed. (Chapter 3)

4. Smart grid load forecasting system framework design for Ontario, Canada. This work introduces a smart grid load forecast design procedure with consideration of general influencing factors and Ontario local factors. (Chapter 4)

5. An Artificial Neural Network based load forecasting system design for Ontario, Canada. This work compares results from different ANN training algorithms and provides a novel explanation for the differences. (Chapter 4)

6. July 2012 India blackout was investigated and lessons learned from India blackout will be discussed. The importance of load shedding will be demonstrated to reduce the possibility of blackout occurrence. (Chapter 5)

7. Development of decision support systems to implement smart grid is summarized. Past, present and future of the decision support systems are compared with each other and new findings are discussed. (Chapter 6)

8. Reliability indices of the system with large scale wind generations are compared to that with distributed generations, investment and cost were considered with power utilities' benefits for decision making. (Chapter 6)

9. Stability indices of the system with wind and solar generations are discussed and penetration levels of the wind and solar with stability performance in a 9-bus network are presented. This work demonstrates the physical insight of the system, and also provides stability indices for cost-benefit analysis and decision making. (Chapter 6)

Chapter 2
Smart Grid Overview

2.1 Introduction

Smart grid has been advocated in both developing and developed countries these days to deal with the bottleneck of feeding large requirement in energy consumption as the growing of industry and commerce. As a new concept for power delivery system, smart grid involves plenty of advanced technologies, outstanding methodologies, novel algorithms and creative architectures in service, business and operation to solve problems like carbon emission deduction, resources allocation optimizations, grid security and reliability enhancement and deliver power energy in a more efficient, reliable, and optimal way.

This chapter will critically overview smart grid definitions, features and its technologies. Moreover, the differences between traditional grid and smart grid will be discussed. Benefits from smart grid technology aspects will be illustrated. Strategy planning, motivations, challenges and implementations will also be summarized in the chapter.

2.2 The Smart Grid Definitions

The smart grid concepts have been discussed, expanded, developed by famous organizations, research institutes and government departments around the world. There is no agreed definition for smart grid, even different countries has different concept on the future grid. For instance, China aims to establish massive strong smart grid which includes all sections from generation, transmission, and distribution to utilization, while the smart grid is defined within distribution network by National Grid, UK [9]. Many publications concentrate on explain “what the features are in smart grid” or “what kind of technologies will be involved in smart grid” instead of “what is smart grid”. Fig. 2.1 illustrates the main applications which are involved in smart grid, including compatibility with any energy generations, electric vehicles infrastructures, more battery storage options, and more power quality options for consumers, demand side management, and self-healing capability and so on.

With understanding of the smart grid, some new issues for smart grid which have never happened in conventional power system need to be considered carefully when planning and operation. For example, with increasing number of consumers participating into power system, how should the system be operated in the most efficient way? If there is a cyber-attack “noise” injected to the communication channel, how could the smart grid detect the attacking “noise” and prevent the network from damaging?

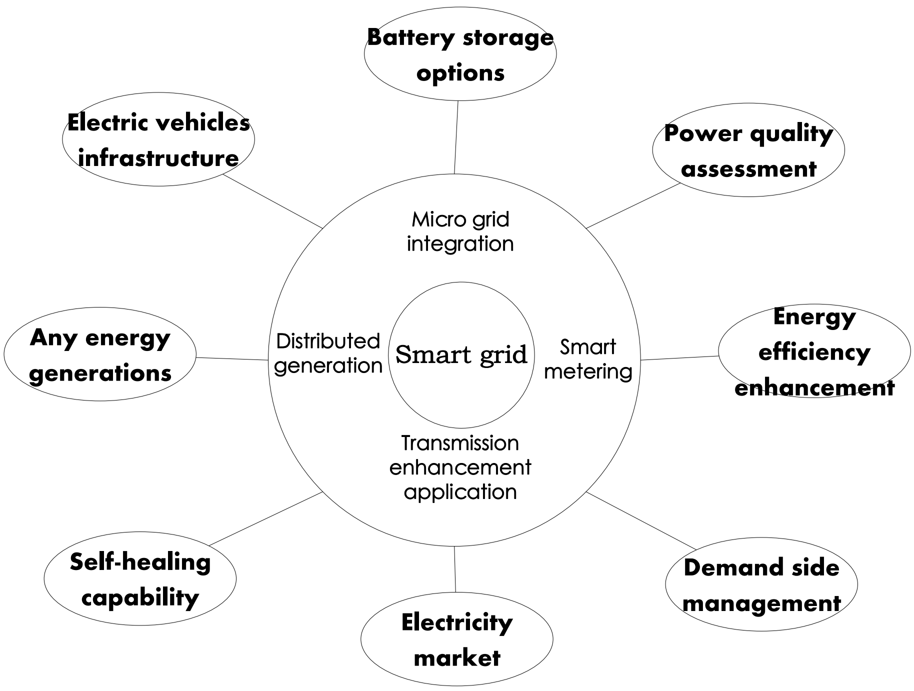


Fig. 2.1 Applications involved in smart grid

According to DOE NETL (Department of Energy, National Energy Technology Laboratory, US), a smart grid uses digital technology to improve reliability, security, and efficiency (both economic and energy) of the electric system from large generation, through the delivery systems to electricity consumers and a growing number of distributed generation and storage resources. Smart grid deployment covers a broad array of electricity system capabilities and services enabled through pervasive communication and information technology, with the objective of improving reliability, operating efficiency, resiliency to threats, and our impact on the environment [1, 2].

IEA (International Energy Agency, US) denotes smart grid as “an electricity network that uses digital and other advanced technologies to monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users” [3]. A Smart grid is an electricity network that can intelligently integrate the actions of all users connected to it – generators, consumers and those that do both – in order to efficiently deliver sustainable, economic and secure electricity supplies [10], demonstrated by European Technology Platform. The "smart grid", described by IEEE, is a next-generation electrical power system that is typified by the increased use of communications and information technology in the generation, delivery and consumption of electrical energy [11].

A general future smart grid network vision is shown in Fig. 2.2. No matter which is the most accurate definition, the conception includes following information at least, smart grid:

1. combines digital technologies throughout the whole power systems from generation to end-users
2. improves reliability, security, and efficiency of the power delivery systems
3. contains both bulk generations and distributed generations, non-renewable energy conversion and renewable energy conversion

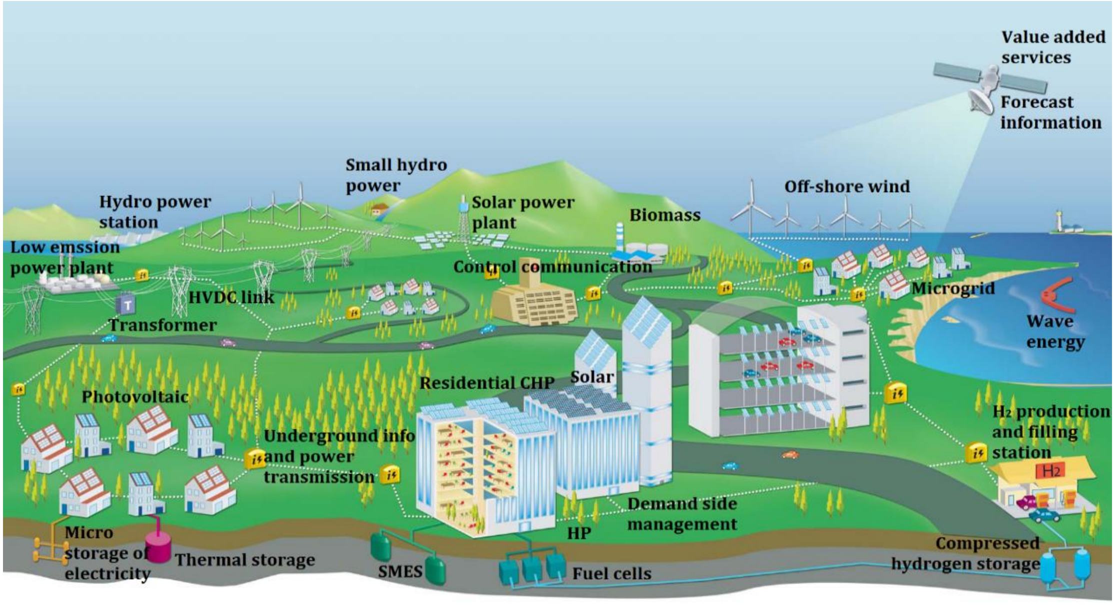


Fig. 2.2 Future network vision [7]

2.3 Differences between Traditional Grid and Smart Grid

Table. 2.1 illustrates the differences between the smart grid and conventional power grid. Smart grid will apply bi-communication technologies to enable customers participate the grid action. For instance, photovoltaic solar panels which are installed on the roof of the customers' houses could generate electricity in daytime and sells the redundant energy to the grid; in the night time, solar panels cannot generate energy in home, and the electricity will supply the load at home as usual. Besides, new technologies such as distributed generation, electric vehicles charging and discharging, Flexible Alternating Current Transmission Systems (FACTS) and so on will apply to the power grid to enhance energy efficiency and reduce carbon emission. New problems are appearing or getting worse with some new applications deployed. Table. 2.2 gives information about different technical solutions addressed with power systems characteristics. Cost benefit Analysis needs to be considered very carefully to determine a better solution.

Aspects	Traditional Grid	Smart Grid
Interaction between Grid and Customers	Customers passively accept service from grid	Customers participation on the grid action
Renewable Energy Integration	Having trouble with renewable penetration	Integration with renewable resources enhancement
Options for Customers	No choice for customer, monopoly market	With digital market trading, PHEV, introduce bids and competition, more choice for customer
Options on Power Quality (PQ)	No choice on power quality, no price plan options for consumers	Power quality levels for different consumers
System Operation	Ageing power assets, no efficient operation	Assets operating optimization, less power loss
Protection	Only rely on protection devices, fault detect manually	Have capability of self-healing, less damage affected by fault
Reliability and Security	Susceptible to physical and cyber attack	More reliable for national security and human safety

Table. 2.1 Comparison between conventional grid and smart grid [12]

Technology Solutions	Reliability	Economics	Efficiency	Environmental	Safety	Security
AMI	Yes	Yes	Yes	Yes	Yes	Yes
CSS		Yes	Yes	Yes		
DER	Yes	Yes	Yes	Yes		Yes
DMS	Yes		Yes	Yes	Yes	Yes
Network Optimization			Yes	Yes	Yes	Yes
Transmission enhancement application	Yes		Yes	Yes		Yes
ICT	Yes	Yes	Yes	Yes	Yes	Yes
EV Charging and Discharging	Yes	Yes	Yes	Yes		

Table. 2.2 Smart grid technology solutions .vs. benefits

2.4 Smart Grid Features and Technologies

Comparing to the conventional power system, smart grid is the next generation of power delivery system, which includes thousands of creative features and new technologies. NIST (National Institute of Standard and Technology, U.S. Department of Commerce) divided the smart grid into seven domains, as shown in Fig. 2.3, with considerations about supporting planning, requirements developments, documentation, and organization of the diverse, expanding collection of interconnected networks and equipment that will compose the smart grid [13].

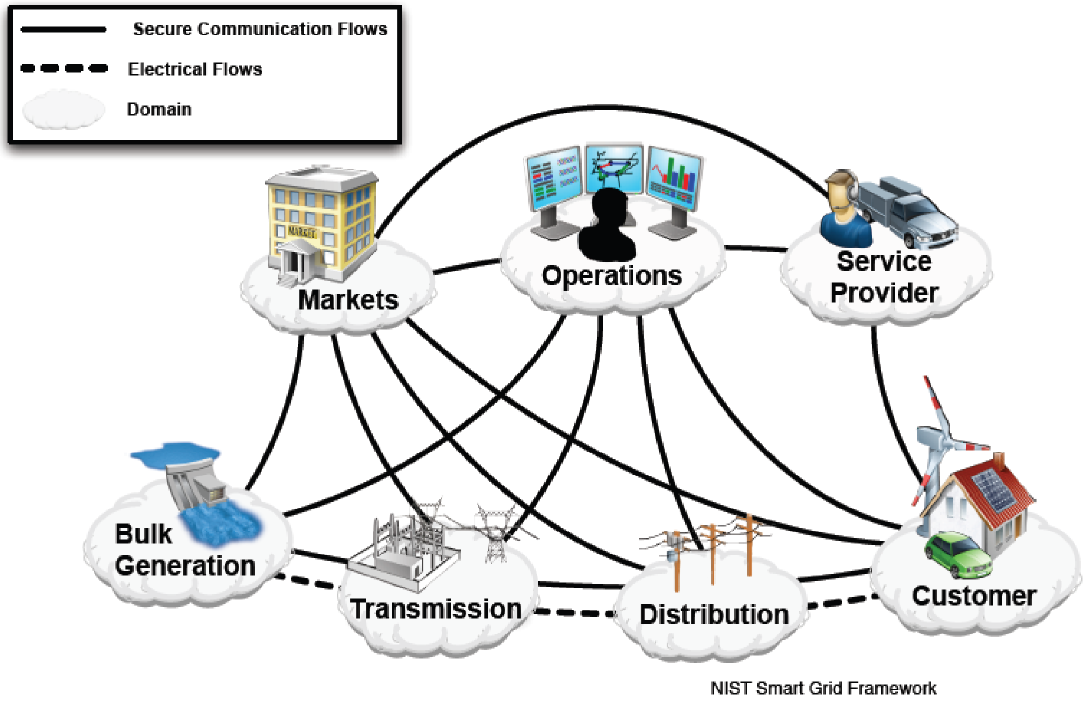


Fig. 2.3 NIST smart grid framework composed by secure communication and electrical flows throughout 7 smart grid domains [13]

NETL has addressed 8 technology solutions to achieve improvement on reliability, economics, efficiency, environmental, safety and security, as shown below:

1. Advanced metering infrastructure (AMI)
2. Customer Side Systems (CSS)
3. Electric vehicle charging systems (EV)
4. Transmission enhancement application
5. Distribution grid management system (DMS)
6. Integration with renewable energy and distributed energy resources (DER)
7. Information and communication technology integration (ICT)
8. Wide-area monitoring, measurement and control [14].

Different technology areas deploy into all over the power system grid from generation to customer side (see Fig. 2.4). To feed consumer's demand, virtual electricity market will be built to investigate more options for customers.

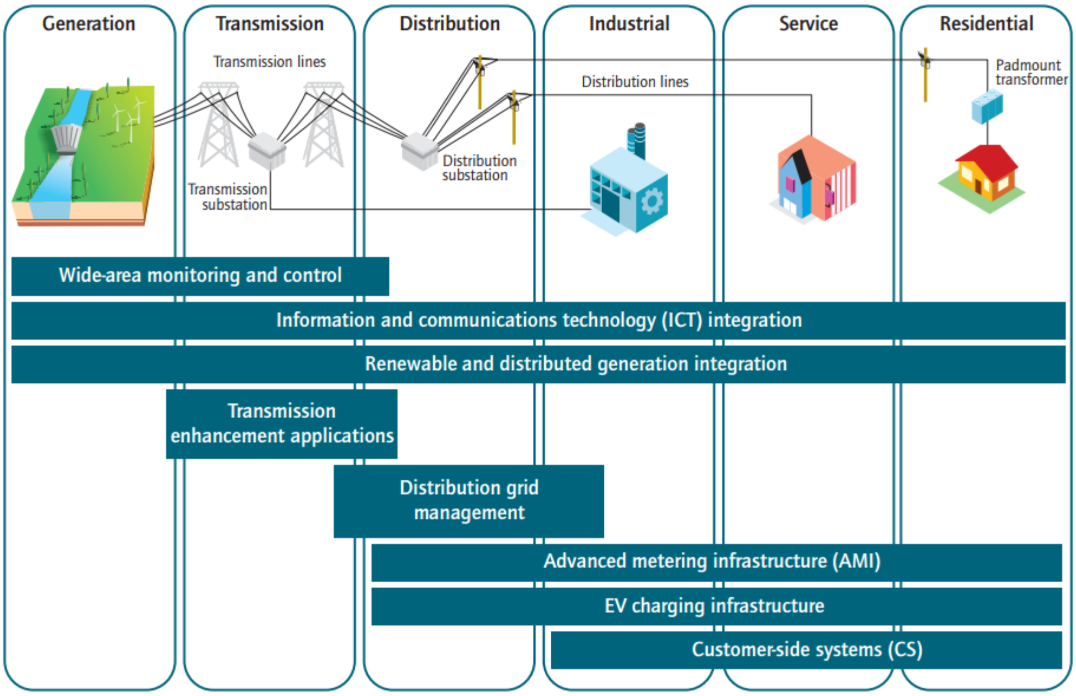


Fig. 2.4 Smart grid technologies deployment in power systems [3]

2.4.1 Advanced Metering Infrastructure (AMI)

AMI provides bi-directional communication channel to enable customers and utilities obtain the real time price and electricity consumption. Power losses and electricity theft detection function is provided by AMI [3]. The AMI provides consumers required information like information to make intelligent decisions, the ability to execute those decisions and a number of options benefit customers themselves. At the same time, system can improve utility operation and asset management processes by AMI data in order to ameliorate customer services. In addition, AMI provides an essential link between the grid, consumers and their loads, generation and storage resources through the integration of multiple technologies like smart metering, home area networks, integrated communications, data management applications, and standardized software interfaces [15]. The AMI technologies and interface to residential, commercial and industrial are shown in Fig. 2.5.

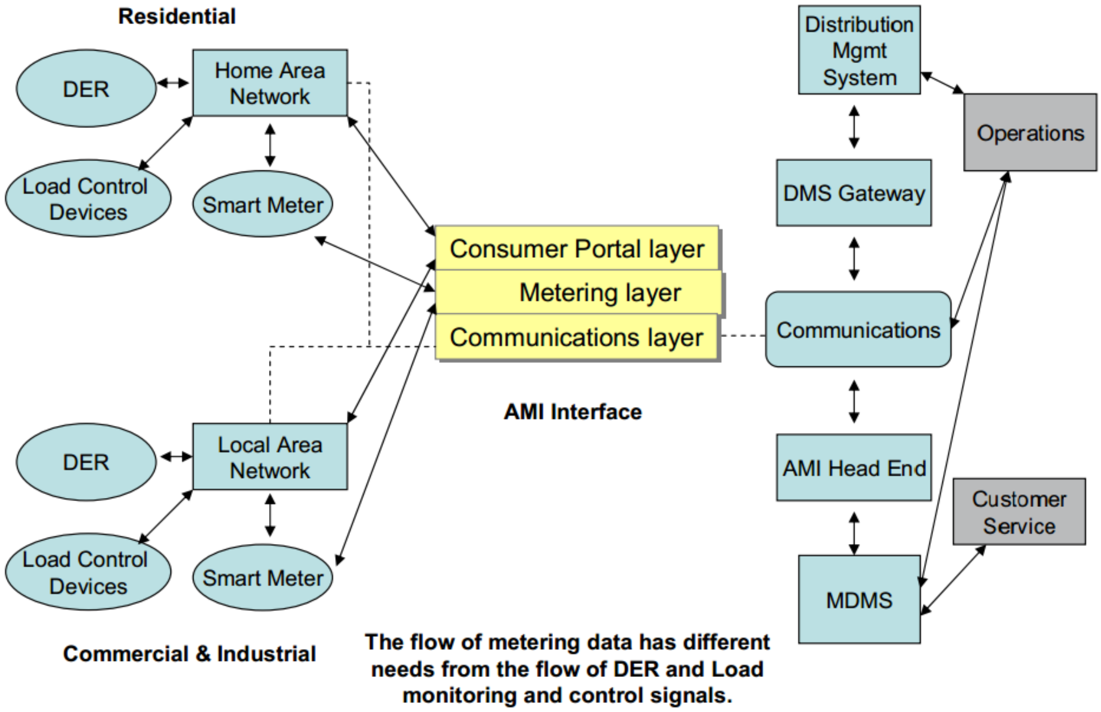


Fig. 2.5 AMI Technology and Interface [15]

However, with the deployment of AMI, the risk from communication, which is the inherent factor, will be brought into the smart grid, and will do harm to the national economy, public health, trust in government, public safety and environmental integrity. The risk to economic and trust in government could be rise from low to moderate where there is a clear conflict between regulators and utilities and when residential customer rates are increased [16]. Therefore, system security requirements have to be proposed and identify what the smart grid security objectives are meant to prevent [17].

2.4.2 Customer Side Systems (CSS)

Customer side systems are deployed for helping manage energy consumption in utilization level such as industrial, commercial, service and residential levels. Four aspects are involved in customer side systems [3], which are:

- energy management systems
- energy storage devices

- intelligent electronic devices
- distributed generations

In-home displays like energy dashboards, smart appliances and load storage deployment could accelerate the profit of energy efficiency and reduction of peak demand. Demand response is end-use customers reducing their use of electricity in response to power grid needs, economic signals from a competitive wholesale market or special retail rates [18]. Both manual customer response and automated, price-responsive appliances and thermostats connect to Energy Management System or controlled with a signal from the utility or system operator [3].

2.4.3 Electric Vehicle Charging and Discharging

Electricity vehicles charging infrastructure can regulate the demand by charging and discharging. There are four operation modes for Electric vehicles charging and discharging, which are grid to vehicles (G2V), vehicles to grid (V2G), storage to vehicles (S2V), and vehicles to storage (V2S). With the increasing penetration of demand response and dynamic price, vehicles could operate as moving storage components to grid. When the grid is under peak demand and the state of EVs is fully charged, EVs will discharge to grid to release the heavy load or discharge to home storage devices to support residential electricity consumption. When the grid is under peak demand and the state of EV is out of electricity, home storage devices will charge the EV for daily utility; when the grid is under low energy demand and the electricity price is getting lower, the EVs will charge from power grid.

2.4.4 Transmission Enhancement Applications

There are plenty of technologies applying to the transmission for improving the controllability, transferring capability and reducing power loss. Four main applications are shown below:

1. Flexible AC Transmission Systems (FACTS)
2. High Voltage DC Systems (HVDC)
3. Dynamic Line Rating (DLR)
4. High-Temperature Superconductors (HTS) [3]

2.4.5 Distribution Grid Management System

The function of DMS is through real-time information processing, deploying advanced sensors and meters to:

- reduce the outage and repair time
- maintain voltage level
- detect the fault locations
- improve asset management
- reconfigure feeders automatically
- optimize voltage and reactive power
- control distributed generation [3]

2.4.6 Integration with Renewable Energy and Distributed Energy Resources

Different scales of the renewable energy resources deploy in different power grid levels: large scale renewable energy resources at the transmission level, medium scales at the distribution level and small scales at customer side buildings. Controllability and dispatchablity are still the main challenge issues for integrations of renewable energy and distributed energy resources in power system operation. Both electrical and thermal energy storage devices can alleviate the impact from renewable energy intermittence, especially wind and solar [3]. DG integrations can improve power grid reliability and reduce the heavy load.

2.4.7 Information and Communication Technology Integration (ICT)

Information and communication technology integration (ICT) is to support data transmission for deferred and real-time operation, and during outages, no matter which communication networks is using, private (including radio networks, meter mesh networks), or public (involving internet, cellular, cable and telephone). Stakeholders are able to use and manage the grid in an efficient way with deploying communication devices, significant computing, system control software and enterprise resource planning software into bi-directional communication infrastructure [3].

2.4.8 Wide-area Monitoring, Measurement and Control

Wide-area monitoring and control supervise every power system component and performance in a real-time way by interconnecting within large geographic areas, and optimize power system components, behaviour and performance via assisting system operators to understand them. Advanced system operation tools encompassing wide-area situational awareness (WASA), wide-area monitoring systems (WAMS), and wide-area adaptive protection, control and automation (WAAPCA), avoid blackouts and facilitate the integration of variable renewable energy resources. In addition, data generated by Wide-area Monitoring, Measurement and Control systems could also facilitate system operating by

- informing decision making;
- mitigating wide-area disturbance;
- improving transmission capacity and reliability [3].

Table. 2.3 denotes the hardware and software which are related to each of technology area and issues in smart grid. As can be seen in this table, communication network elements are the essential parts for smart grid establishment, and deploying in many technology areas in smart grid. Communication network would be employed to transfer the energy consumption and storage level data to the control centre. Industry standard

PC and Ethernet would be applied in smart grid to communicate between substations and control centre. Universal monitoring and controlling devices which are installed inside the control centre would fully be responsible for the energy generation, storage and utilization. It will regulate the renewable energy generation, energy storage, and consumptions according to the fluctuating generation forecasting (especially the renewable energy) and dynamic energy load curve. Besides, new algorithms would be built into the control and monitoring device. For instance, the micro-grid energy management system needs to be more intelligent to deal with uncertainty and variability of the demand and generation. Computational algorithm (CA) is one of intelligent algorithms which can update information during the system operation.

Smart Grid Technologies and Issues	Hardware	Systems and Software
Cyber Security	Communication equipment (Power line carrier, WIMAX, LTE, TF mesh network, cellular), routes, relays, switches, gateway, computers (servers)	Supervisory control and data acquisition (SCADA), distribution management system (DMS), Firewall rules, Vulnerability management
Protection	Fiber communication network, routes, relays, switches, computers (servers)	wide-area adaptive protection, control and automation (WAAPCA), wide-area situational awareness (WASA), distribution management system (DMS), Agent-based Supervision
Wide-Area Monitoring and Control	Phasor measurement units (PMU) and other sensor equipment	Supervisory control and data acquisition (SCADA), wide-area adaptive protection, control and automation (WAAPCA), wide-area situational awareness (WASA)
Information and Communication Technology integration	Communication equipment (Power line carrier, WIMAX, LTE, TF mesh network, cellular), routes, relays, switches, gateway, computers (servers)	Enterprise resource planning software (ERP), customer information system (CIS)
Renewable and Distributed Generation Integration	Power conditioning equipment for bulk power and grid support, communication and control hardware for generation and enabling storage technology	Energy management system (EMS), distribution management system (DMS), SCADA, geographic information system (GIS)
Transmission Enhancement	Superconductors, FACTS, HVDC	Network stability analysis, automatic recovery systems
Distribution Grid Management	Automated re-closers, switches and capacitors, remote controlled distributed generation and storage, transformer sensors, wire and cable sensors	Geographic information system (GIS), distribution management system (DMS), outage management system (OMS), workforce management system (WMS)
Advanced Metering Infrastructure	Smart meter, in-home displays, servers, relays	Meter data management system (MDMS)
Electric Vehicle Charging Infrastructure	Charging infrastructure, batteries, inverters	Energy billing, smart grid-to-vehicle charging (G2V) and discharging vehicle-to-grid (V2G) methodologies
Customer Response Side	Smart appliances, routes, in-home display, building automation systems, thermal accumulators, smart thermostat	Energy dashboards, energy management systems, energy applications for smart phones and tablets

Table. 2.3 Hardware and software employed into smart grid [3]

2.5 Benefits of Smart Grid

According to NETL, the benefit of the smart grid can enhance system operation and utilization in six key areas, shown as follows:

1. Reliability — by reducing the cost of interruptions and power quality disturbances and reducing the probability and consequences of widespread blackouts
2. Economics — by keeping downward prices on electricity prices, reducing the amount paid by consumers as compared to the "business as usual" (BAU) grid, creating new jobs, and stimulating the gross domestic product (GDP).
3. Efficiency — by reducing the cost to produce, deliver, and consume electricity
4. Environment — by reducing emissions when compared to BAU by enabling a larger penetration of renewables and improving efficiency of generation, delivery, and consumption
5. Security — by reducing the probability and consequences of manmade attacks and natural disasters
6. Safety — by reducing injuries and loss of life from grid-related events [12]

Generally, the benefits brought from smart grid are:

- Improved system performance meters
- Better customer satisfaction
- Improved ability to supply information for rate cases; visibility of utility operation / asset management
- Availability of data for strategic planning, as well as better support for digital summary
- More reliable and economic delivery of power enhanced by information flow and secure communication
- Life cycle management, cost containment, and end-to-end power delivery is improved in the smart grid design
- Improved ability to supply accurate information for rate cases- with compounding impact in regulatory utilities

- Input visibility of utility operation to asset management
- Impact access to historical data for strategic planning [19]

Different group of stakeholders could obtain benefits from smart grid deployment and operation. NETL divided stakeholders into 4 groups, which are Delivery Company, Electricity Supplier, Residential Consumer and Broader Societal. Table. 2.4 and Table. 2.5 show benefits that brought to different stakeholders from smart grid key areas.

Key Areas	Delivery Company Benefits	Electricity Supplier Benefits
Reliability	• Reduced operational costs • Improved employee safety • Increased revenues • Higher customer satisfaction ratings and improved relations with the regulator, the community, etc. • Reduced capital costs as fewer devices fail in service	• Reduces the down time for some generators
Economical	• Numerous opportunities to leverage its resources and enter new markets created by the smart grid • Increased revenues as theft of service is reduced • Improved cash flow from more efficient management of billing and revenue management processes	• New market opportunities for distributed generation and storage • The demand for lower cost, new options for DER businesses • Accommodate larger increases in wind and solar generation • Reduce operating and maintenance (O&M) costs at base-load generating plants
Efficiency	• Increase asset utilization • Reduction in lines losses • Reduction in transmission congestion costs • Deferral of future capital investments • Increased asset data and intelligence enabling advanced control and improved operator understanding • Reduction in capital expenditures • Extended life of system assets • Improved employee productivity • more accurate predictions on when new capital investments are needed • Reduced use of inefficient generation	• More competitive generators greater access to markets • Efficiency of generation is improved • Opportunity to expand green power portfolio • Fewer forced outages
Environmental	• Increased capability to integrate intermittent renewable resources • Reduction in emissions • Opportunity to improve environmental leadership image • Increased capability to support the integration of electric-powered vehicles • Reduction in frequency of transformer fires and oil spills	• New opportunities for renewable generation and storage created by the ability of the smart grid to support increased levels of intermittent resources
Security and Safety	• Reduction in the probability that a deliberate man-made cyber or physical attack • Improved restoration times following natural disaster • Reduction in theft and vandalism of property • Reduction in injuries and deaths of employees	• Reduced exposure of generation plants to potentially damaging and dangerous disturbances due to a more secure transmission system

Table. 2.4 Smart grid benefits delivered to delivery company and electricity supplier [14]

Key Areas	Residential Consumer Benefits	Broader Societal Benefits
Reliability	• Improved level of service with fewer inconveniences caused by outages and poor power quality • Reduced out-of-pocket costs	• Reduced cost of losses suffered by large consumers from outages • Reduced cost of losses suffered by large consumers from poor power quality • Virtual elimination of blackouts • Improved conditions for economic development
Economical	• Downward pressure on energy prices and total customer bills • Increased capability, opportunity, and motivation to reduce consumption • Opportunity to interact with the electricity markets • Opportunity to reduce transportation costs • Opportunity to sell consumer-produced electricity back to the grid	• Downward pressure on prices • Creation of new jobs • Growing the U.S. economy • Creation of new electricity markets
Efficiency	• Increased capability, opportunity, and motivation to be more efficient on the consumption end of the value chain • Increased influence on the electricity market • Ability to switch from gasoline to electricity for transportation	• Deferral of capital investments • Reduced consumption provides for a better utilization of resources • Sustained downward pressure on prices as the smart grid enables these efficiency improvements to endure
Environmental	• Increased capability, opportunity, and motivation to shift to electric vehicle transportation • Optimize energy-consumption behaviour resulting in a positive environmental impact • shift from a carbon-based to a “green economy”	• Reduced emissions • Improved public health
Security and Safety	• Increased peace of mind that the electric grid on which they depend is less likely to be vulnerable to terrorist activity • Increased ability of grid workers when outages or power quality events occur	• Increased national security • Reduction in the probability of widespread and long-term outages due to terrorist activity • Reduction in the number of injuries and deaths associated with the public’s contacts with grid assets

Table. 2.5 Smart grid benefits delivered to residential consumer and broader societal [14]

2.6 Motivations and Challenges towards Smart Grid

2.6.1 Motivations

As the next generation intelligent electricity delivery system, smart grid optimizes the energy efficiency by grafting information technologies onto the existing network and exchanging real-time information between electric suppliers and customers [20]. Besides the benefits to every group of stakeholders from smart grid, there are many driving forces of the smart grid implementation.

Firstly, the conventional grid is aging, old-designed, and with poor reliability, one example is the blackout occurring in many countries. The most serious blackout events occurred in countries around the world are list as following:

1. 9 Nov. 1965, Northeast U.S. and Ontario blackout, over 30 millions of people affected [21]
2. 11 March 1999, Southern Brazil blackout, most of the southern third of the country affected [22]
3. 28 Sept. 2003, Italy, Switzerland blackout, about 45 millions of people affected [23]
4. 14–15 Aug. 2003, Northeast blackout, 50 millions of people affected [24]
5. 18 Aug 2005, Indonesia Java–Bali blackout, 100 millions of people affected[25]
6. 10–11 Nov 2009, Brazil and Paraguay blackout, 190 millions of people affected [26]
7. 30–31 July 2012 July 2012 India blackout, over 700 millions of people affected [27]

Secondly, transmission congestion is one of the significant problems for conventional grid. It occurs when the dispatching of transactions causes the violation on the transmission system [28]. Several reasons like transmission line and generators outages, energy demand heavily changes, and uncoordinated trading may lead to congest in transmission. Consequently, system operators may not dispatch power in a flexible way even though the generators could provide more power. Furthermore, it may leads to infeasibility in existing and future contracts.

In addition, environmental impact is also one of the chief reasons for driving to smart grid. With the dramatically climate changes during the last few decades, large quantities released greenhouse gas and any other pollution gases from combusting fossil fuels in conventional power plants are regarded as the main incentives to develop renewable energies. Besides, improving energy efficiency becomes one of the significant strategic objectives. Plenty of technical solutions (like FACTS, HVDC, UPS, STATCOM and so on), and innovative ideas were applied into the system to promote transmission efficiency and energy conversion efficiency [20].

2.6.2 Challenges

As the brand new concept and with plenty creative technological implementation, smart grid is facing hundreds of challenges.

1. Safety and Security

   With communication network integration into power grid, smart grid also brings the issues which never happen in traditional networks. Cyber security issues need to be taken greatly care in order to prevent power grid from operation modification disruption or wrong message inserting. Targets for Power grid self-healing technologies deployment also need to carefully consider to against natural disaster and physical attack.

2. Reliability

   Communication network integrate brings reliability problem to the power system networks. There is no doubt that the communication system could deliver message efficiently which can make power system operators respond faster when facing some critical situation. However, the wrong messages produced by hackers sent to the power network may be accompanied by serious consequences, and ultimately results in power blackout. In addition, reliability index need to be reconsidered. Besides some traditional indices like SAIDI, CAIDI, SAIFI CAIFI, new indices with considering communication network deployment need to be produced to illustrate the reliability properly.

3. Power Quality

   Disturbance identification and Harmonics suppression technology need to be developed to provide power with a high quality level to consumers. Disturbance identification is still in the early stage of research [30]. Non-dispatchable energy resources like wind and solar need to be forecasted more accurately and exactly with its increasing penetration as well as load consumption.

4. Interactivity between Grid and Customers

   In order to produce more reliable power and improving energy efficiency, customer have to participate into grid activities like demand response, choose power quality according their willingness, installing small Distributed Generation devices and purchase electric vehicles, which also need communication network to provide security environment to prevent consumer personal information from leaking deliberately.

2.7 Smart Grid Standards

There are many institutions and organizations in the world attempt to standardize smart grid in technologies and implementations in both regional and national. Some of the most famous organizations and institutions are listed as follow:

1. European Union Technology Platform
2. National Institute of Standards and Technology, U.S. Department of Commerce
3. American National Standards Institute (ANSI)
4. International Electro technical Commission (IEC)
5. Institute of Electrical and Electronics Engineers (IEEE)
6. International Organization for Standardization (ISO)
7. International Telecommunication Union (ITU)
8. Third Generation Partnership Project (3 GPP)
9. Korean Agency for Technology and Standards (KATS)
10. Joint Information Systems Committee (JISC) [29]

Only in IEEE, over 100 approved and proposed standards are related to smart grid, including the call out in the NIST smart grid Interoperability standards [31]. Table.2.6

listed the international standards related to smart grid.

Name of the Standards	Application	Description
IEC 61970, 61969	EMS	Providing Common Information Model (CIM) in Transmission and Distribution Domains
IEC 61850	Substation Automation	Flexible, future proofing, open standard, communication between devices in Transmission and distribution and substation automation systems
IEC60870-6/TASE.2, 62351 Parts 1-8	Communication & Cyber Security	Defining cyber security for the communication protocol
IEEE P2030 and P1901	Customer-side applications, In-home multi-media and smart grid application	Smart grid inter-operability of energy technology and IT operation with the electric power system (EPS), High speed power line communications
ITU-T G.9955 and G.9956	Distribution Automation, AMI	Contain the physical layer specification and the data link layer specification
OpenADR	Price Responsive and Load Control	Dynamic Price and Demand Response
BACnet	Building Automation	Scalable system communications at custom side
HomePlug Green PHY	Home Area Network (HAN)	Power line technology to connect the smart appliances to HAN
U-SNAP	Home Area Network (HAN)	Providing many communication protocols to connect HAN devices to smart metres
ISA100.11a	Industrial Automation	Open standard for wireless systems
SAE J2293	Electric Vehicle Supply Equipment	Standard for the electrical energy transfer from electric utility to EVs
ANSI C12.22, C12.18, C12.19	AMI	Data network communications, data structure transportation and its flexible metering model
Z-Wave	Home Area Network (HAN)	Dealing with the interference with 802.11/b/g
M-Bus	AMI	European standard and providing the requirements for remotely reading all kinds of utility meters
PRIME	AMI	Open, global standard for multi-vendor interoperability
G3-PLC	AMI	Providing interoperability, cyber security, and robustness
SAE J2836, J2847	Electric Vehicle	Supporting use cases for plug-in electric vehicles communication, and communication messages between PEVs and grid components

Table. 2.6 International standards related to smart grid [29]

2.8 Smart Grid Simulation

One of cost-effective ways to evaluate the smart grid behaviours is via simulation with computer-based software. The reason is that to investment in a test bed will cost a large amount of money without foreseeing the consequence after applying the new technologies. Plus, the test beds are not very flexible when comparing two or more similar technologies while simulators could change the technologies without much expense of time and money. There are many organizations and corporations has developed the smart grid simulators with communication network integration, but none of them are considering the co-simulation cases with accordance of the realistic business.

There are some researchers and organizations co-simulate some functions of smart grid. Some of them are co-simulating the smart grid system by hybrid power system simulators and communication network simulators together. Reference [32] emphasized the importance of developing smart grid simulators and its urgency. It pointed out that optimization of the smart grid operation would require modeling the involvement of all other devices, systems, customers and so on. In order to understand the benefit in terms of reliability and economy etc., it is very difficult to have a practical smart grid to get hold of all the results for various studied scenarios.

Reference [33] briefly states how continuous and discrete events may be synchronized and co-simulated together with continuous events modeled with Simulink while discrete model is programmed by SystemC. Reference [34] describes the ideas of integration between hybrid system modeling language (HSML) model, presenting state events and Matlab model, which is embedding with discrete events. In reference [35], authors connect GE Energy PSLF which is used for simulating power system load flow with NS-2, a simulator for deploying communication network to enhance the relay ability. The authors performed an agent-base communication system for justifying the correction of relay settings. However, this kind of simulation is neglecting the delay of communication network. Whether the method to detect the fault is reliable or not remains to be studied by taken into account the relay and circuit breaker performance together. In reference [36], the authors described the method to calculate the time delay for communication network which is applied into power system. GridSim is an emulator involving power system toolkit and communication toolkit which is proposed by Washington State University [37]. The authors gave state estimator simulation result on several substations for wide-area monitoring and control.

With the communication channel applying into power system network, information around stakeholders will exchange via computing devices and system control software. Meantime, cyber security becomes a significant issue which has to be considered. Governments around the world have set a series of targets to reduce carbon emission and increasing the penetration of renewable energy. Cost benefit analysis is also important for making decisions around several operation and expansion plans in both power system network and electricity market. Whereas, there is no such powerful simulation software involved all of the areas to give a guideline. Also, there is no detailed model for large scale power system network to plan the expansion stages with the introduction of communication capability.

Current Power grid simulators usually focus on a certain professional domain which is very narrow and less connection with any other field. Basically, there are 5 areas for current power grid simulators.

1. Operation models are designed to estimate the reliability and normal, abnormal operation scenarios for current power system.

2. Expansion models are used for assessing new technologies or network expansion, the system operation under normal and abnormal scenarios to estimate the policy feasibility.

3. Contingency analysis is employed into system modeling to discover inherent risk when load is changing or post-fault operation.

4. Power market models research on market activities between stakeholders from generators to customers under competition environment.

5. Specific models are designed for critical assessment when the system is suffered from various disturbances [38].

Data cannot be exchanged among the models in real-time, integration is impossible to both market research and operation research on the same model. Communication network does not exist in current simulator. Additional communication channel needs to apply into power system by cooperating with communication network simulation. Unnecessary obstacles such as synchronizing discrete network with continuous network need to be addressed. Reference [39] is presenting SCADA cyber security problems by co-simulating PowerWorld Server with a network emulator. Protection devices are limited in the power system simulators.

In terms of smart grid functions, power grid models need to simulate three general dimension scenarios as a whole, such as operation, system expansion and disruption.

In operation scenario, besides the basic functions such as load flow calculation and stability analysis, smart grid simulator is required to carry out contingency analysis and optimization in power system operations. For instance, power flow calculations aim to minimize the power losses, minimize the cost or minimize load shedding need to be presented. Post fault load flow needs to be done to study power transfer margins or inherent risk inside the power system. In addition, power system market operation needs to include simulation of behaviours between stakeholders and market participants [38].

System expansion simulates the new technologies applied into existing grid for assessing power system operation. Researching on scenario feasibility is modeled to meet the future task. For example, to meet the target on renewable energy 30% penetration in 2030, variability and uncertainty of renewable energy need to be simulated and analyzed in a virtual but realistic environment before applying so many wind and solar energy conversion systems in practice.

Last but not least, there is a need to simulate unwanted disasters and malicious physical and cyber-attacks. This kind of modeling needs to integrate power system and communication system together for stochastic events. Generally, power system modeling is continuous while communication system is discrete. The two systems can be synchronous with limited time scale. Reference [40] employs a global scheduler to synchronize two systems implicitly to simulate the failure on primary protection and remote protection devices.

Fig. 2.6 illustrates the purpose for different organizations to utilize smart grid simulator. Generally, industrial companies will pay for the existing software for building electrical network models. Commercial companies such as Siemens and ABB will do the same simulation as power system utilities do, however, commercial companies sell products to the power system utilities. To conduct national security and social safety, electricity network operation may need to be under government's supervision. Self-healing capability which is an important property of smart grid is also considered by government. Higher education including universities pays its attention to improve models accuracy and innovations on new technical methods and requirements [38].

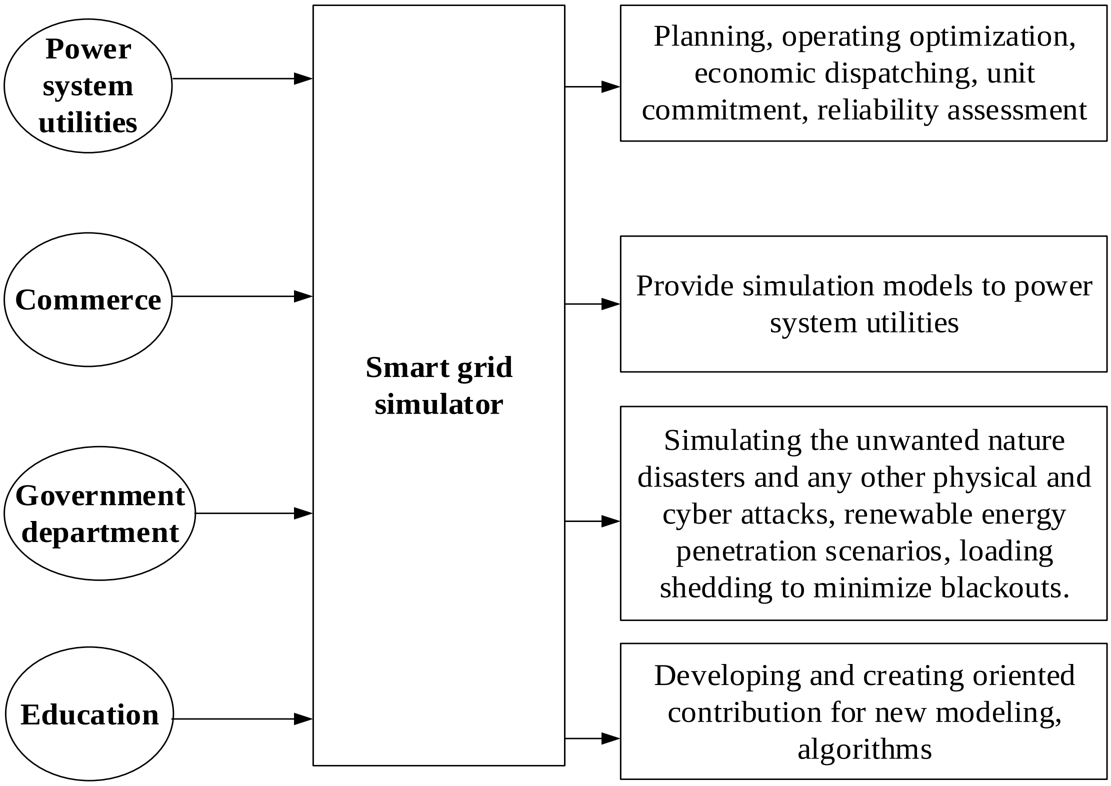


Fig. 2.6 Purposes for smart grid simulator

To satisfy as many groups of people as possible, smart grid simulators will not only concentrate on technical modeling and stability analysis, but also focus on connecting with some other field such as economy, environmental issues, transportation, communication, policy responding and security issues. In the year of 2008, US department of Homeland Security, and Science and Technology Directorate hold 2 days to discuss developing future grid simulation capability issues.

2.8.1 Additional Simulation Requirement of Smart Grid

A. Data accuracy, management and processing

To create a smart grid simulator, there are large number of data involved in building models and operating status. Data accuracy is a significant problem to deal with. Data quality and accuracy need to be justified and guaranteed for applying into models. Since equipment is replaced and reset, data in smart grid simulators also need update and version upgrade, which could be controlled to meet the realistic situation. Moreover, according to the user classifications, data security needs to be warranted by authority.

B. New model functions

As mentioned above, operation in market would be modeled to find the relationship between stakeholders and any group of people attending market activity. Stochastic modeling is built for researching on dynamic behaviour of the market activities [41]. Forecasting on renewable energies such as wind and solar, market price must include into smart grid simulator to determine how to optimize power flow, and power dispatch and so on. Besides, appearance of new market products such as electric vehicles will lead to simulate charging and discharging models in power grid. AMI will lead customer charging their electric car during off-peak load time for saving money. As a consequence, customer behaviours would also be modeled to achieve more accurate load forecasting. Models integration to each other would give a whole picture from energy generation to energy consumption.

C. Old model updating

Old models need to be updated to keep consistent with real world. Detailed models would simulate the specified situation. For instance, single phase air conditioner model cannot represent by 3-phase model for stability research [42].

D. Algorithm improvement

For academia such as university and research community, modeling method and algorithms draw more attention for improving model robustness and promoting accuracy. Modeling template and self-programming capacity should build into the smart grid simulator.

E. Interface integration

Interface between simulator and real system could help industries test and improve the equipment to meet the requirement of utility. More detailed model and simulation could bring the evolution in grid research. Instead of considering the simulation event unilaterally, more comprehensive integrated models could emulate the event more realistic. Reference [43] describes the communication and information capacity could improve the market operation for dispatching energy. Meanwhile, the author also doubted about the capability on grid response since so many conventional power plants connect to the grid and require more time to starting-up. With model integration, this kind of problem will become explicit. Some simulation laboratories intend to combine controls, communications and electro-mechanical dynamics together. Oak Ridge National Laboratory (ORNL) connects power system models to communication network with discrete event [44].

2.9 Conclusion

This Chapter critically overview smart grid definitions, features and its technologies. In addition, the differences between traditional grid and smart grid have been discussed. Also, this work summarized the smart grid technologies and its benefits in different aspects. Strategy planning, motivations, challenges and implementations are summarized in the chapter as well.

Besides, the chapter, for the first time, is to provide critical overview on smart grid simulator. Further to the report generated by National Power Grid Simulator workshop, which is organized by US Department of Homeland Security in 2008, there is no such powerful simulator so far. Cases need to be considered carefully in order to simulate with communication tools. Some organizations have managed to a small degree of achievement to integrate communication with power system in simulation. As the sampling frequency is too small, communication system information loss cannot be avoided. No software has been available for smart grid researchers. A natural way is to integrate two simulators or packages together with an interface between them. Because of different electrical applicants and new devices in power system and communication systems, detailed models and data requirement will be a huge challenge and opportunity for the very near future. Various requirements have been considered and this chapter will provide tutorial values to the field and also it will provide a direction for the academics, researchers, engineers and decision makers as an important reference.

Chapter 3
Smart Grid Monitoring with Communication Technologies

3.1 Introduction

This chapter intends to give a critical overview about intelligent system monitoring in power grid over the last decade. As an essential aspect for achieving smart grid, intelligent system monitoring needs to be deployed into the system to deliver data and messages timely. New technologies applied into intelligent system in many technical fields will be discussed. The development of condition monitoring and smart grid monitoring like wide-area monitoring technologies and commercial electronic monitoring is demonstrated. Mechanisms and algorithms applied into intelligent monitoring system will be summarized. In addition, this chapter category the power system network cases and scenarios with communication deployment according to the operation and business, and organize the scenarios by the different business to study in which level power systems need to co-simulate with communication network, and in which level power systems need integrate with communication not as critically as co-simulation.

According to U.S. Department of Energy 2010 smart grid system report, smart grid was defined as "uses digital technologies to improve the reliability, security, and efficiency of the electricity system, from large generation through the delivery systems to electricity consumers. Smart grid deployment covers a broad array of electricity system capabilities and services enabled through pervasive communication and information technology, with the objective of improving reliability, operating efficiency, resiliency to threats, and our impact on the environment" [1]. Communication network plays a significant role in the entire smart grid businesses and operations, such as wide-area monitoring and control, integrating distribution management systems, automation electricity dispatch and automation distribution.

One of cost-effective ways to evaluate the smart grid behaviours is via simulation with computer-based software. The reason is that to investment the test beds will cost a large amount of money without foreseeing the consequence after applying the new technologies. Plus, the test beds are not very flexible when comparing two or more similar technologies while simulators could change the technologies without much expense of time and money. There are many organizations and corporations has developed the smart grid simulators with communication network integration, but none of them are considering the co-simulation cases with accordance of the realistic business.

3.2 Intelligent System Monitoring

Intelligent monitoring system involves functionalities like video analysis, behaviour recognition and business intelligence. The functionality of video analysis is to gather data and information through computer vision (CV) and artificial intelligence (AI) to create a close mapping link from images to the event description. Behaviour recognition contains analysis, monitoring and alarming functionality. Business intelligence is the most extremely crucial part in the intelligent system, which provides the key video business for users. Hierarchical structure of the intelligent technology is deployed within the network, equipment and software to achieve information integration and scheduling via system management platform [45].

Three main problems of the data capture have been realized by M. D. Judd, et al. in reference [46]. Firstly, the quantities of the raw data were too large for engineers to deal with. Secondly, the relationship between the plant item, health and condition monitoring data could not be understood all the time so that it was difficult to extract the meaningful information from condition monitoring data. Lastly, estimating the lifetime expectation only from the health of the item is not easy as it is not always apparent. The structure of the integrated approach to power transformer condition monitoring by Ultra High Frequency (UHF) sensors was illustrated in Fig. 3.1, and the model has been further developed by the authors in 2004 [47], which is shown in Fig. 3.2. An agent-based system with self-contained functional software in each module was proposed in the architecture. The information exchange and co-operation among the independent modules were implemented via a standardized Agent Communication Language (ACL).

A literature survey about condition monitoring techniques for power transformer, generator and inductive motor was made in reference [48]. The authors found out that a novel condition monitoring system requires signal processing and Artificial Intelligent as tools for developing the next generation condition monitoring with high level of sensitivity, reliability, intelligence and accuracy.

Monitoring applications improved by integrating the temporal and spatial aspects of data and information was shown in reference [49]. Two new monitoring functions were depicted in the paper, to show how the smart grid technologies could help reach more accurate fault location results. Intelligent electronic devices (IEDs) including digital protective relays (DPRs) and digital fault recorders (DFRs), are synchronized to the GPS clock to tie to the absolute time. Transparent allocation of time and space across many IEDs in a common infrastructure, which need data integration and information exchange, is the future trend of monitoring function. Intelligent condition monitoring has been applied in many technology fields such as clinic, industry, traffic, agriculture and geography.

With the advancement of communication technology, monitoring based on web has also been proposed in the last 10 years or so. A distributed intelligent monitoring system based on 3G network has been proposed in monitoring the health of the railway bridges [50]. Devices in gas stations for oil products retail network have been monitored by embedded web [51]. An Extended Neuro Fuzzy System has been integrated into monitoring system in reference [52]. Information obtained from fault diagnosis and prognosis integration ensured that the monitoring reliability was improved. Overload intelligent monitoring for trucks has been proposed in [53]. For clinical area, monitoring system also plays an important part in artificial heart monitoring [54]. Temperature and humidity intelligent monitoring for Chinese medicine via ZigBee wireless networks has been proposed in [55].

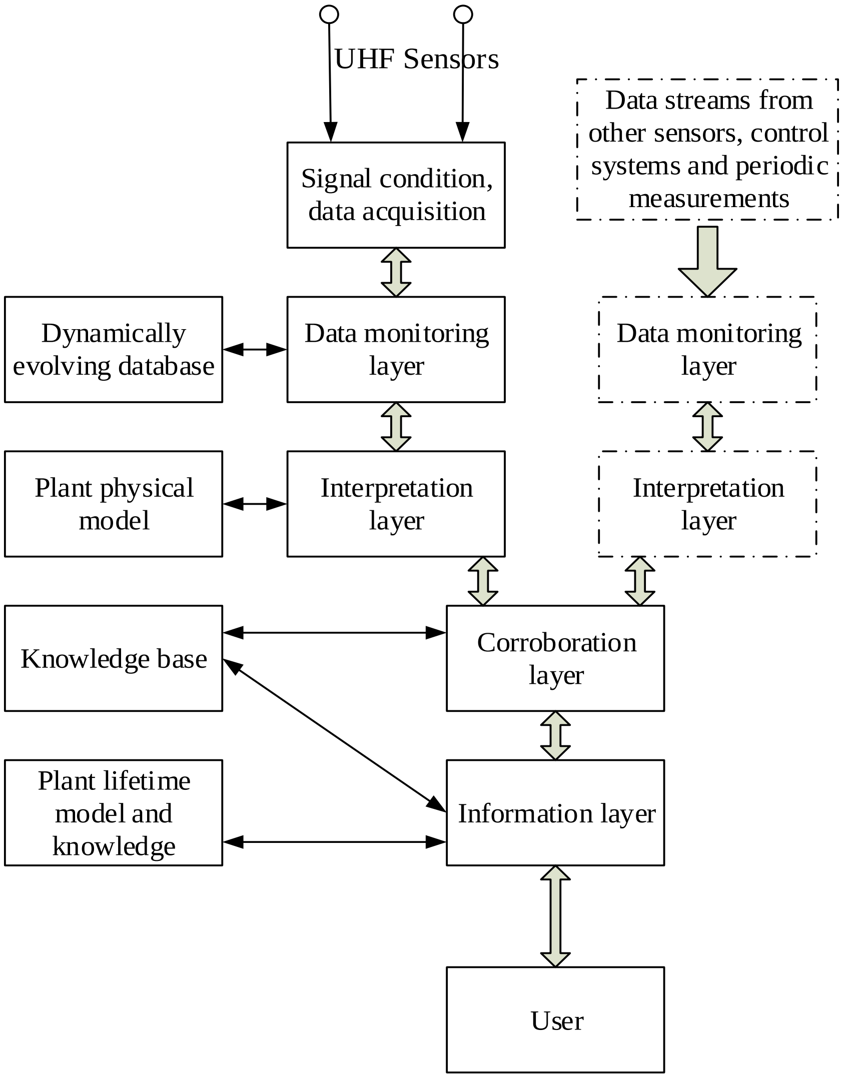


Fig. 3.1 Structure of the integrated approach to condition monitoring and plant lifetime modeling [46]

3.3 Power System and Smart Grid Monitoring

Since the smart grid been proposed and started to develop in both developed and developing countries, intelligent monitoring has been paid more attention for smart grid and power system monitoring. In addition to single equipment condition monitoring such as transformer health monitoring [46, 47, 56] and distribution insulator monitoring

[57], monitoring applications for smart grid technology, for instance, smart grid fault location [49], commercial electronic device monitoring and wide-area monitoring have been realized and discussed.

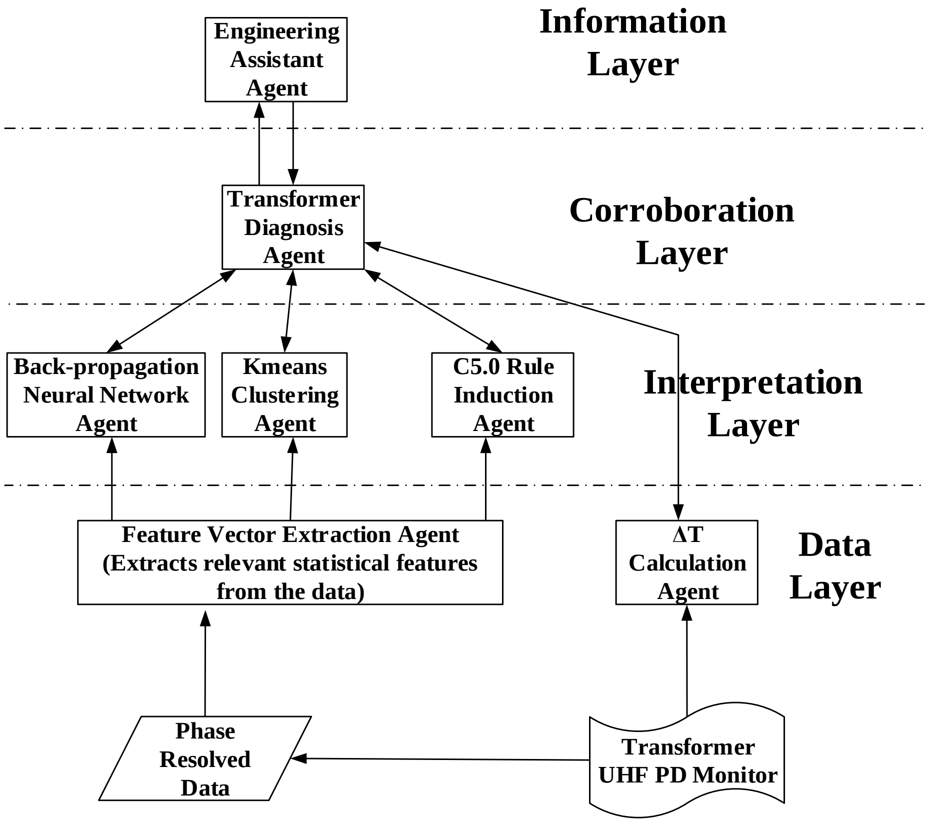


Fig. 3.2 COMMAS architecture [47]

At the early beginning of 21th Century, before the smart grid concept being proposed, power quality monitoring with intelligent systems had been reported in reference [58]. A critical overview was given in the paper on power quality monitoring with intelligent technology deployment in the 20th century. The author noticed that the power quality indicators, which are developed in 1980’s and most of which are inexpensive, could not provide the accurate data and information to make a decision as several LED indicators stayed on. Two problems of the indicators were pointed out: firstly, information only can be collected when the indicators were plugged and communicated with other parts; secondly, the users do not understand how to deal with the collected information. The author proposed four characteristics for the intelligent power quality monitoring system. First of all, data requires to be gathered, including voltages, currents, time and any other parameters. Secondly, data needs to be transferred to a useful location rather than a power quality indicator on an outlet. Thirdly, other sources of data combination with power quality are important. Last but not least, data requires converting into information to take action.

Condition monitoring is a very hot topic in many aspects in power system. Authors in [59] illustrated agent-based detection architecture for power plant operation and maintenance monitoring. The proposed architecture is shown in Fig. 3.3. The agents were classified into 4 categories by functionality, containing data abstraction, data processing, analysis and presentation and administration. According to the authors, agents were deployed into power plants to provide the dynamic linking of data source to data processing functions. Correlation between different measurements would be learned, knowledge concerning the data and models of plants behaviour would be improved by continued detection. Comparing with other systems, the proposed architecture by the authors was flexible, and achieved reusable agent with data processing abilities, communication and cooperation ability for abnormal detection.

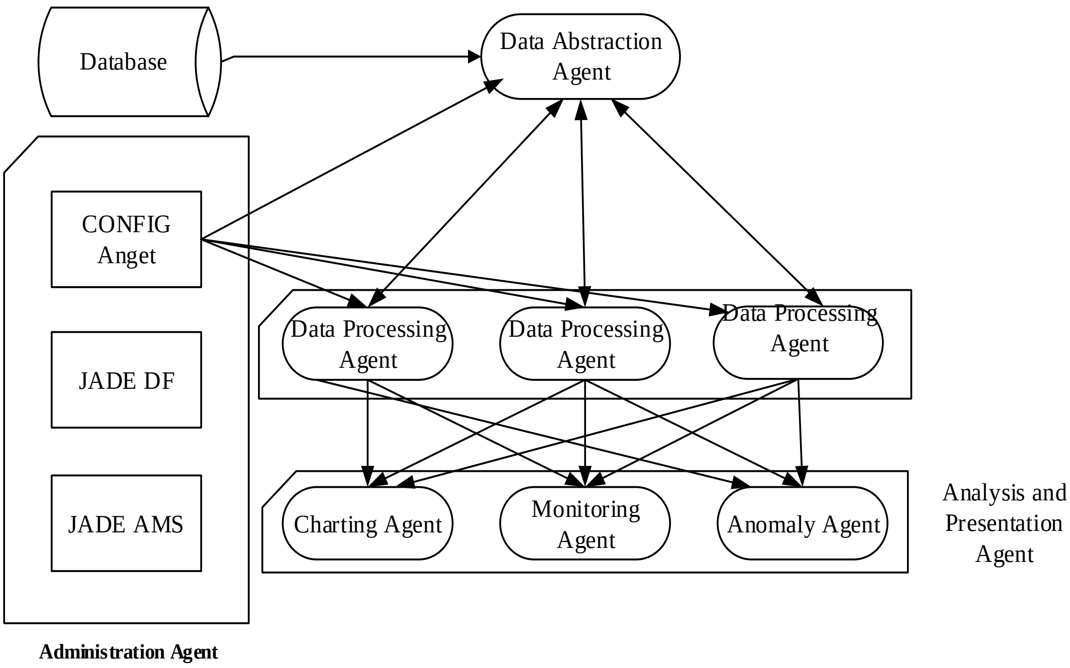


Fig. 3.3 Anomaly detection agent architecture [59]

Since 2010, papers and researches on smart grid have paid attention to intelligent system monitoring. Some of the last implementations of Power system frequency monitoring network (FNET) applications on wide-area monitoring systems (WAMS) were discussed in [60]. Fig. 3.4 shows the building blocks of the FNET system. Widely installed sensors such as frequency disturbance recorders (FDRs) are collecting and transmitting phasor measurements from the North American Power grids to a local client or a remote data centre. In Fig. 3.5, a modularized FNET application system was demonstrated. Due to its hierarchical framework, any particular element could be rearranged easily. The applications of FNET system are explored in many fields in power systems such as dynamic monitoring, stability estimation, real-time control and smart grid solutions. A wavelet-based method for achieving frequency and voltage derivatives characteristics was proposed in [61] in order to do disturbance analysis. In [62], an energy efficient security algorithm was developed for smart grid WAMS. Three principles were proposed in the paper. First of all, energy consumption is one of the important considerations. Three factors named energy, security and time need to be balanced. In addition, encryption algorithms could increase the implementation efficiency and reduce energy consumptions by code optimization. Lastly, the security strength of encryption algorithms has close relationship with operation model, key length and the number of iterations, which could be changed in affecting total energy consumption.

The next generation monitoring functions were described in reference [63]. The authors stated that the next generation monitoring functions should offer useful information rather than raw data to operators. Besides, more data would be required, but it does not mean more information needed. Advanced visualization techniques are required to help the operator individually to obtain information efficiently.

In order to achieve the on-line real time monitoring on smart grid, communication technologies such as local area sensor network, high-resolution meter reading, and wireless sensor network played a huge role to deliver data and information. However, new problems would be appeared with the deployment of the wireless communication networks such as cyber-attack and fault disturbance. Monitoring on smart grid transmission and distribution technologies was discussed and monitoring on equipment like transformers, wind generators are demonstrated in this period. An overview on smart grid standards for protection, control, and monitoring applications was made in reference [64].

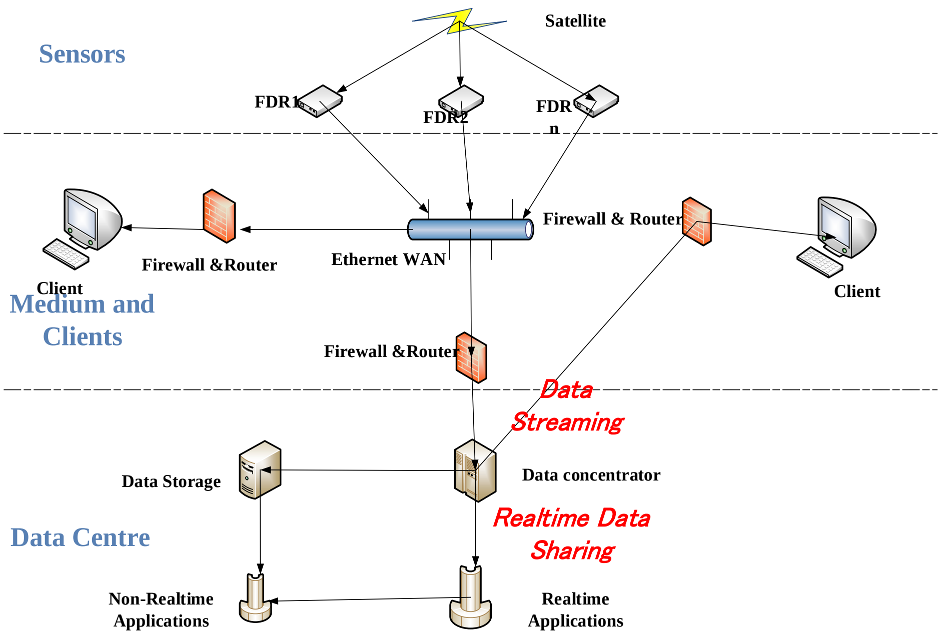


Fig. 3.4 Building blocks of the FNET system [60]

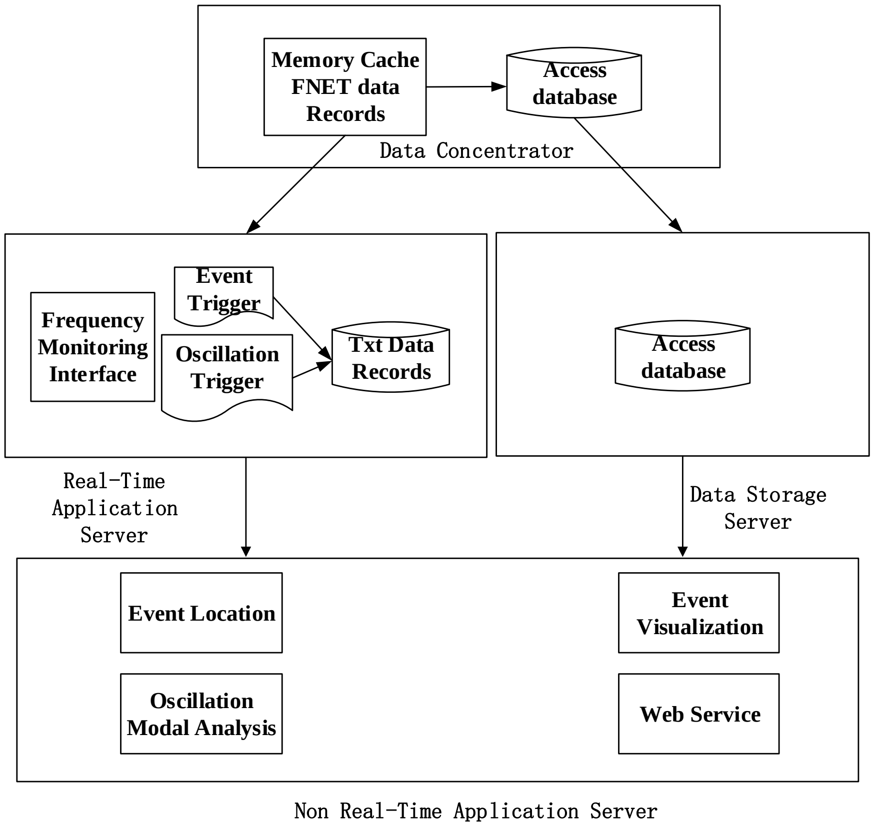


Fig. 3.5 FNET application hierarchy and data flow paths [60]

According to the U.S. Department of Energy, Information and Communication Technology (ICT) is one of the key technologies applying into smart grid. A service-oriented architecture for Micro-grids (MGs) integration monitoring is proposed in [65]. The core component of the architecture is an MG engine for executing the MG management functions. A dynamic monitoring and decision systems for enabling sustainable energy services was proposed in [66]. It also addressed anti-islanding and reconnecting problems in micro-grids and distributed generation. Authors in reference [67] found that the use of PMUs need low values of total vector error (TVE). A specifically developed PMU based on synchron-phasor estimation algorithm was shown in the paper to meet the requirement in active distribution networks monitoring. According to the author, the provided information by PMUs could improve the control and management system in reliability and ease of applications. Also the information coming from the PMUs appears to have ability in helping distribution system operator to do decision making when there are critical instances experienced by the system. In addition, the functionality of phase angle difference measurement at the terminals of the short cable links could let the implementation of protection algorithm become true.

	First Category	**Second Category**	**Third Category**
Motor	Washing Machine, Fan, Mixer	Air Conditioner, Freezer	Smoke exhauster, Frequency-alterable AC, Refrigerator, Microwave ovens
HR	Rice Cooker	Rice Cooker	Heater, Hair dryer, Cooker
EC	NULL	PC, TV	NULL

Table. 3.1 Application classification list [70]

A non-contact method based on magneto-resistive sensors which involves measuring emanated magnetic field from a line conductor used to monitor the voltage sag and electric current in the high-voltage transmission-line in reference [68]. The author demonstrated the method as applicable, low-cost, non-contact and accurate. The phase conductor current and line position were determined by measuring the emanated magnetic field from the transmission line. Moreover, a stochastic optimization, which could enable to handle various line configurations, namely, artificial immunity system (AIS) is applied to deal with complex scenarios.

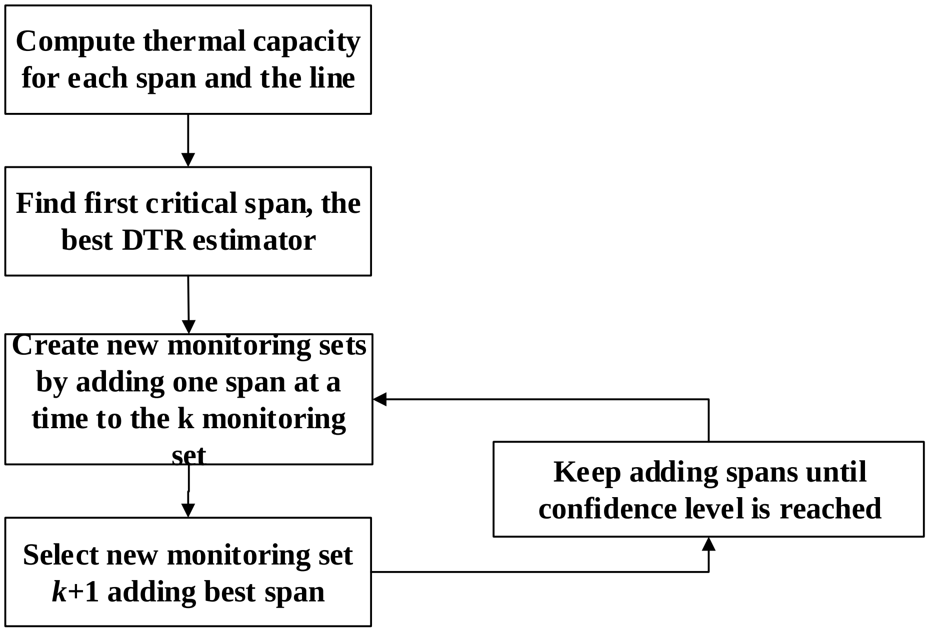


Fig. 3.6 Heuristic flow diagram [69]

Besides condition monitoring the grid itself, smart grid monitoring also involves monitoring the dynamic thermal rating for power system planning and commercial electronic devices. A novel heuristic, whose flow diagram is illustrated in Fig. 3.6, was proposed in [69] to identify the quantity and locations of the critical monitoring spans for the implementation of dynamic thermal rating (DTR). The historical-simulated weather data was generated by a Mesoscale weather model and the statistical analysis of the thermal capacities from each span. By comprising tables between the total number of monitoring stations needed for a given confidence level in each segment and the one for a given confidence level in the paper, it was noticed that fewer monitoring was required in the proposed heuristic, and also the proposed heuristic showed better performance. Reference [70] illustrated a new nonintrusive load monitoring method (NILM) for residential appliances identification and monitoring. Residential applications were classified into three categories according to working style shown in

Table.3.1. Three steps have been done to establish the platform of the appliance identification. The first step is to identify the event detection with advantages of both steady-state and transient analysis. The second step is to classify the load categories into three areas. Finally, general multidimensional linear discriminate with function feature has been used to make power evaluation. The advantages of the NILM methods were also discussed by the author. Firstly, there is no need to have study sample requirement. Secondly, a multifunction meter is applied to the sensor. Thirdly, the non-working of internal MCU in multifunction meter could achieve a real-time system by event detector, and no large space is required to store the raw data. Finally, although under noisy measurements, the NILM was still working. The summarization of Methods and algorithms that are applying to the smart grid monitoring is shown in Table.3.2.

3.4 Smart Grid Communication Business and Operation

Smart grid communication technologies are deployed in the entire power systems in different levels and for different utilizations. From smart grid business and operation perspective, the communication network is mainly deploying implement technologies in Advanced Distribution Automation, Feeder automation, Wide-area monitoring and control, substation automation systems, self-healing technology, distributed generation, electricity storage, renewable energy and micro-grid operations.

	Purposes	Algorithms, key characteristics, hardware and software
Protection relays	Allow new power system problem-solving, cost saving	Microprocessors and intelligent electronic devices
Local area sensor network	Provide benefits to power quality, grid efficiency and health monitoring	Smart meters, Telephone Terminal Unit (TTU) local area network, IP address, Logging
Cyber security, fault detection, and communication	Facilitate the linear quadratic Gaussian control of power system, collect gas flow data, and detect small leaks and theft.	Discrete-time linear state space model, new locally optimum method, high-resolution meter reading, Wireless sensor network,
Smart grid control centre	Implement parallel computing infrastructure	Human-centered, comprehensive, proactive coordinated, self-healing
Distribution networks	Improve customer satisfaction, improve the delay of the network, improve the control and management system of the active distribution network	Proactive approach, quality of Service, a synchrophasor estimation algorithm for PMU
Transmission networks	Monitor and optimize the electric transmission, real-time monitoring of changes in the characteristic signature of electromechanical oscillations	Wireless network based architecture, smart wireless transformer sensor node, smart controlling station, smart transmission line sensor node, smart wireless consumer sensor node, data aggregation and synchronization algorithm, remote monitoring and control, Rule Identification Algorithm, Negative Data Oriented Compensation Algorithm, Magneto-resistive Sensors, empiricalmode decomposition (EMD) method with masking technique, and the non-linear Teager-Kaiser energy operator (TKEO)
Micro grids	Integrate MG modeling, monitoring and control	The service-oriented architectures
Power quality and stability	Track the modes of voltage collapse and identify areas vulnerable areas	Eigen-decomposition on Thevenin impedance matrix

Table. 3.2 Methods and algorithms applying into the smart grid monitoring

3.4.1 Advanced Distribution Automation

Advanced distribution automation cannot be achieved without widespread communication deployment from the controllable devices to one control unit at least [116]. Within distribution system communication deployment, there are three chief categories involving Power Line Carrier (PLC), Landline and wireless [117]. According to EPRI, PLC works successfully in functionalities of automatic meter reading and load control applications. However, distribution applications suffer from open circuit problem when deploy PLC as communication channel [116]. Landline communication can be classified in two categories, telephone and fiber optics. Telephone lines are leased, which usually communicate from SCADA to RTU. Fiber optics can work within high-voltage operating environment because of its dielectric and EMI/RFI noise immunity, but its price is too high to apply in distribution system. Wireless network as its communication to anywhere with low costing is the most popular communication method in distribution automation achievement. Although the public wireless network such as cellular network will save capital and maintenance cost, security reason is always a main point for utilities consideration. From the EPRI's perspective, security risks can be neglected with deployment of security features like secure socket layers (SSL), 128-bit encryption and frame relays.

3.4.2 Feeder Automation

Feeder automation includes

A. Fault location, isolation and service restoration

B. Optimal network reconfiguration

C. Planned islanding [118]

3.4.3 Wide-Area Monitoring and Control

Wide-area network can be deployed in both transmission and distribution systems. WAMS could transmit current and voltage information to the control centre with a very high rate via applying phasor measurement unit (PMU) on power system. Generally, phasor data concentrators (PDC) collect data from PMU via wide area networks, and then, control centre PDC gathered data through system-wide wide area networks. In [5], three wide area measurement applications with communication network were described in detail. Firstly, power system monitoring involves state estimation, seams between state estimates and instrument transformer calibration for all-PMU estimators. Secondly, power system protection includes adaptive dependability and security, monitoring apparent impedances towards relays characteristics, adaptive out-of-step, and supervision of back-up zones, adaptive loss-of-field, intelligent load shedding, intelligent islanding and system-wide implantation, and integration of system integrity protection schemes. Lastly, power system control contains sustained oscillations, large oscillations control, remedial action schemes and system restoration.

3.4.4 Substation Automation Systems

A substation automation scheme requires features like control and monitoring of all substation electrical equipment from a central point, interface to remote SCADA system, control and monitoring of electrical equipment in a bay locally, status monitoring of all connected substation automation equipment, system database management, energy management and condition monitoring of substation electrical equipment such as switchgear, transformer, relays and IED's [120]. In order to achieve this, high-performance communication network with international standard IEC 61850 is required to connect all IEDs to the substation human-machine interface. Unlike the distribution automation, the communication for substation automation deployment only deploys inside the substation to control and monitor the electrical devices.

3.4.5 Self-Healing Technology

The self-healing technology allows processors installed in each component of a substation like breakers, switches, transformers and busbars to communicate with each other. Besides, a parallel information connection must be installed in each high voltage connection to the device, whose parameters, status and analog measurements from sensors have permanent information. When a new device is added into a substation, the central control computer will update data after received from new device automatically [121]. Ideally, a self-healing strategy should assure both the frequency and the dynamic voltage stability, following a contingency [122]. The speed of communication devices and switching actions will determine the speed of the tripping action in load shedding scheme when applying self-healing in the real-time implementation [123].

3.4.6 Distributed Generation, Electricity Storage, Renewable Energy and Micro-Grid Operation

Distributed generation with intended islanding function require communication infrastructure to make a practical solution [124]. Also, in order to save or shift electricity consumption, distribution systems with digitally controlled power electronics, which form grid interface of the distributed power system elements like distributed generation and storage, and many controllable loads, could evolve more when a suitable communication infrastructure is present [125].

3.5 Co-Simulation and Power-Communication Integration

It is known that the advanced communication network will evolve power systems into a new level. However, the traditional power system simulation tools cannot meet the demand of such increasing research requirements. Co-simulations and technology integration need to be added into simulators in order to research on impact of power systems when deployed smart grid technologies. In reference [126], the authors listed the communication standards and protocols according to different applications. Although each application is related to energy and power, not all of them need to co-simulate with power systems. The following table lists the applications and its standard and protocols for smart grids. Besides, applications with co-simulation requirements are marked in Table.5.1.

Applications	Standards and Protocols	Co-simulation or Not	Objects
Energy Management Systems	IEC61970 and IEC61969	No	Consumer, Power Company
Substation Automation	IEC61850	Yes	Power Company
Inter-Control Centre Communications	IEC60870-6/TASE.2	Yes	Power Company
Cyber Security	IEC62351 Part 1-8	Yes	Power Company
Industrial Automation	ISA100.11a	No	Consumer
Dynamic Pricing and Demand Responds	OpenADR	Yes	Consumer, Government
Customer-Side Applications	IEEE P2030, BACnet,	Yes	Consumer
Advanced Metering Infrastructure (AMI)	ANSI C12.22, ANSI C12.18, ANSI C12.19, ITU-T G.9955, G.9956, M-Bus, PRIME, and G3-PLC	No	Power Company
In-Home Multimedia, Home Area Network (HAN)	IEEE P1901, Home Plug Green PHY, U-SNAP, and Z-Wave	No	Consumer
Electric Vehicle	SAE J2293, SAE J2836, SAE J2847	Yes	Consumer, Power Company, Government

Table. 3.3 Smart Grid Standard and Co-simulation

Those applications without co-simulation also have closed relationships with power systems, but not as critical as co-simulation ones. Different organizations or groups of people consider smart grid from different aspects according to different objectives. For example, government would like to know the impact to the society when applying smart grid technologies, such as carbon emission deductions, blackout reductions, and policy making etc. the power delivery company cares about the profits from smart grid technologies, investment and benefits and so on. While the consumers concern the bills and price drop by applying distribution generations, smart applicants and energy-saving lamps. These smart grid applications need to be considered from different aspects to feed the requirements for different groups of people.

Technologies integration includes demand side management integration, distributed generation integration, renewable energy sources integration and energy storage Integration etc. [127]. To deploy these technologies, communication network and monitoring systems are the essential parts to achieve all kinds of operation modes and to improve power system reliability. Although some of the issues do not need to co-simulate by combining the communication and power system together, the impacts of the technologies require the integration with the power systems.

Whether an objective issue needs co-simulation or not depends on the time scale, real time or off-line. The time scale of wide area monitoring and control scheme is very critical, which makes its communication scheme to deliver and deal with information urgently. Whereas, the time scale for generation dispatch is few minutes, which is not as short as wide-area or protection scheme.

In reference [128], the authors reviewed integrated power system and communication network simulators and applications. After that, the authors proposed their own co-simulation method “GECO” which with combines PSLF and NS2 together. Reference [129] studied IEEE P2030 to build a communication and power system co-simulation environment by linking OMNet++ with OpenDSS. The case involved in the paper is to control plug-in electric vehicles to reduce critical voltage durations. Since 2006, a simulation engine called “EPOCHS” which combines PSCAD/EMTDC, PSLF and NS2 have been proposed to demonstrate electric power scenarios with communication issues and protection problems [130]. So far, the co-simulation has been applied to achieve 4 objectives: Dynamic simulation for WAMS applications [128, 130-132], remotely controlled power devices [133, 134], general network controlled system [135] and SCADA cyber security [136, 137].

Time Scales	Business and Operations
Milliseconds	Protection
Few Seconds	Transient
1 minute	Electric Vehicles and Device Control
Few minutes	Power Dispatch
Minutes to hours	Blackout and Contingency
1 Day	Unit Commitment

Table. 3.4 Business and Operations and time scales

Table. 3.4 illustrates the Business and operation durations of a power system. Although the communication network is covered the whole power system to build so called "Smart grid", only the power system business and operations with short time scale, for instance, protections and transient, need co-simulate with communication networks.

3.6 Conclusion

A critical overview on smart grid monitoring and intelligent monitoring system was given in this chapter. Algorithms and mechanisms which may be applied into the monitoring systems have been discussed. To maximize the benefit of asset management, it is essential to fully utilize resources and an efficient and reliable monitoring system for smart grid technology deployment. Also the fully utilization of information is one of the main strategies to take the full benefits of smart grid and promote its acceptance. Another contribution of this chapter is that a reasonable method for achieving power system and communication co-simulation by taking into account real-life power system business and operation is proposed. In the smart grid, the information and communication technology play a very critical role; however, there are many limitations of the current power system on combining with communication system. It is necessary to develop a smart grid and communication co-simulation simulator for further research.

Chapter 4

Smart Grid Load Forecasting by Artificial Neural Network

4.1 Introduction

The Forecasting technologies are vitally beneficial to the power system and smart grid in many aspects like load forecasting, wind generation forecasting, dynamic price forecasting. As an essential part in the smart grid, high accuracy of the load forecasting is required to give the exact information about the power purchasing and generation [71] in electricity market, prevent more energy from wasting and abusing and making the electricity price in a reasonable range. Besides, accurate load forecasting can improve power stability to a certain degree by further actions like unit commitment, power dispatching and load shedding.

Load forecasting could be classified into three categories according to different time duration, namely, short-term load forecasting, medium-term load forecasting and long-term load forecasting. Short-term load forecasting basically predict a period from minutes level to a week, while medium-term load forecasting and long-term load forecasting generally considers from one week to one year ahead, and longer than one year but up to 10 years respectively. Load forecasting is associated with multiple factors such as season differences, climate changes, working days or weekends and holidays, disasters and political reasons, operation scenarios of the power plants and faults occurring on the networks which lead to changes of the load demand and generations [72].

Different load forecasting has differences in its purpose of decision making, even in factors consideration. Short-term load forecasting usually aims to achieve a better plan for electricity production in order to minimise energy & money wasting and reduce greenhouse emissions. The factors for short-term load forecasting consideration are usually time, weather and human behaviours. Medium-term load forecasting is used in maintenance scheduling, and to plan for outages and major works in the power system [73]. Medium-term load forecasting considers growth factors like main events, addition of new loads, seasonal variations, demand patterns of large facilities, and maintenance requirements of large consumers [73]. While long-term load forecasting is important for energy system planning and determine peak load in next few years and may focus on the factors like economic variation which may affect power consumptions, Fig. 4.1 presents an example of day ahead load forecasting.

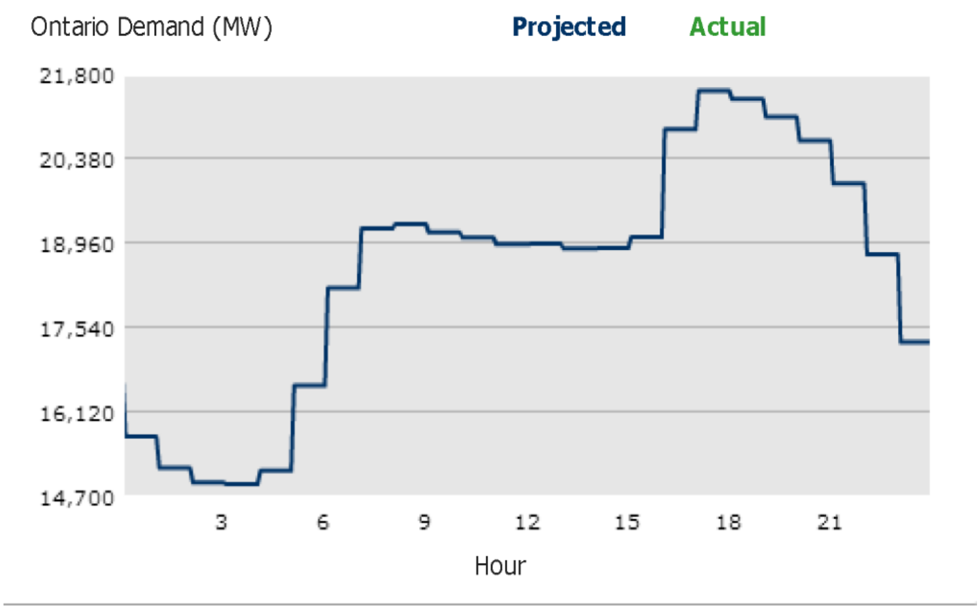


Fig. 4.1 Load forecasting on December 10, 2013 for Canadian Ontario Demand by IESO [74]

Many ways such as Expert Systems, Grey System Theory, and Artificial Neural Network (ANN) and so on are employed into load forecasting. Since 1990, the artificial neural network (ANN) has been researched to apply into forecasting the load [71]. Owing to the transcendent characteristics, ANNs is one of the most competent methods to do the practical works like load forecasting.

This Chapter intends to illustrate the representation of the Artificial Neural Network applied in load forecast based on practical situation in Ontario Province, Canada, and concerns about the behaviours of artificial neural network in load forecasting. Historical data of power consumption from 2007 to 2009 will be applied to the simulation. Analysis of the multi-influencing factors like weather conditions, and weekdays or weekends which are affecting the load demand in Ontario, Canada will be made to give an effective way for load forecasting.

4.2 Introduction to Artificial Neural Network (ANN)

Artificial Neural Network is inspired by Biological Neural Networks (Appendix I). Extending the characteristic of the biological neurons, the key features of the processing elements of artificial neural networks are:

1. the processing element receives many signals
2. Signals may be modified by a weight at the receiving synapse.
3. The processing element sums the weighted inputs
4. Under appropriate circumstances (sufficient input), the neuron transmits a single output
5. The output from a particular neuron may go to many other neurons (the axon branches)
6. Information processing is local (although other means of transmission, such as the action of hormones, may suggest means of overall process control).
7. Memory is distributed:

   a. Long-term memory resides in the neurons' synapses or weights.

   b. Short-term memory corresponds to the signals sent by the neurons.
8. A synapse's strength may be modified by experience.
9. Neurotransmitters for synapses may be excitatory or inhibitory [78].

According to the features illustrated above, neuron working procedure can be abstracted as Fig. 4.2. In Fig. 4.2, x_1 to x_n are signals received from other neurons. These signals pass to neuron body cell with added weights w_1 to w_n respectively. After a summarization and processing function, an output y is generated.

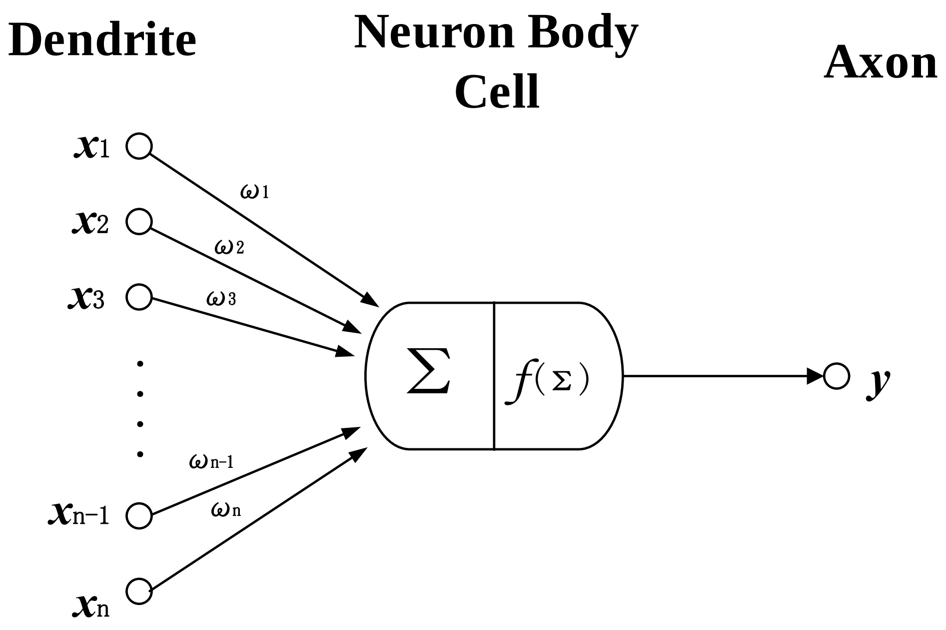


Fig. 4.2 Neuron working procedure

Since its transcendent characteristics and capability of dealing with non-linear problems, artificial neural networks has been widely applied into various research fields and areas such as signal processing, control, pattern recognition, medicine, speech production, speech recognition, business.

Because the outstanding characteristic of the statistical and modeling capabilities, ANN could deal with non-linear and complex problems in terms of classification. As the problem defined, the relationship between the input and target is non-linear and very complicated. ANN is an appropriate method to apply into the problem to forecast the load situation.

4.3 Perceptron

4.3.1 Perceptron Model

The theory of perceptron is regarded that was first introduced by Frank Rosenblatt in 1958. Typically, a perceptron consisted of three layers, namely, sensory (or input) units, associate units and a response (or output) unit. The sensory layer is connected to associate layer via paths with fixed weights. A bias representing as the threshold value simply can be treated as any other weight, and can be adjustable, but with a unit activation is always 1. A typical Perceptron neuron model is showing in Fig. 4.3. A summarization is made with all inputs with their weights including bias *b*, goes through the activation function *f*. Generally, the output is a function of the sum of bias and weight multiplied by the input. The activation function could be any kinds of functions. However, the generated output is different.

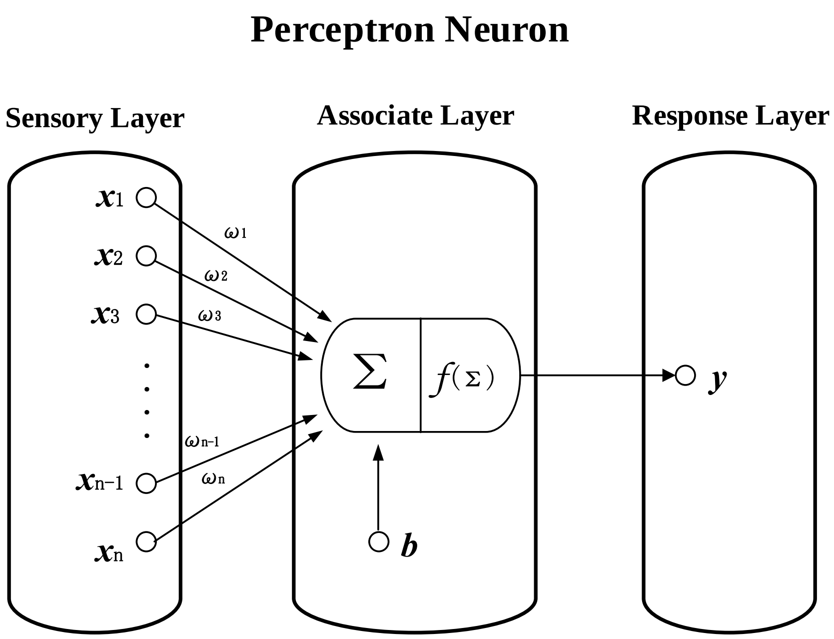


Fig. 4.3 Perceptron neuron model

The relationship between output and input in perceptron model can be expressed in Equation 4.1 in terms of Fig. 4.3 above.

$$y = f(\sum_{i=1}^{n} \omega_i x_i + b) \tag{4.1}$$

4.3.2 Activation Functions

Activation function is one of the key factors for determining the behaviours of a neuron. Non-linear functions are popular in neural network applications. The output value of activation functions is limited by an upper and a bottom value. Four activation functions are introduced below.

1. Identity linear function

Identity linear function is illustrated in Fig. 4.4, which also can be written as Equation 4.2. Identity linear function usually applied in Back propagation algorithm, which will be introduced in Equation 4.4.

$$f(x) = x \tag{4.2}$$

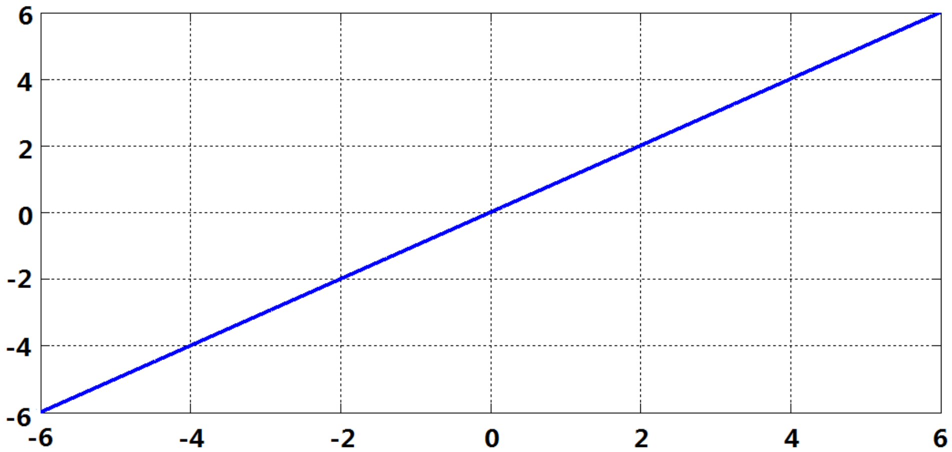


Fig. 4.4 Identity linear function for activation function

2. Binary step function

The output of binary step function is either 1 or 0. When the net input is less than the threshold, the output is 0; when the net input is greater than the threshold, the output is 1. This function is usually applied in single layer perceptron network.

$$f(x) = \begin{cases} 1, & x \geq \alpha \\ 0, & x < \alpha \end{cases} \tag{4.3}$$

Where α is threshold. Fig. 4.5 gives binary step functions with threshold equals to -1 (blue), 0 (green), and 1(red).

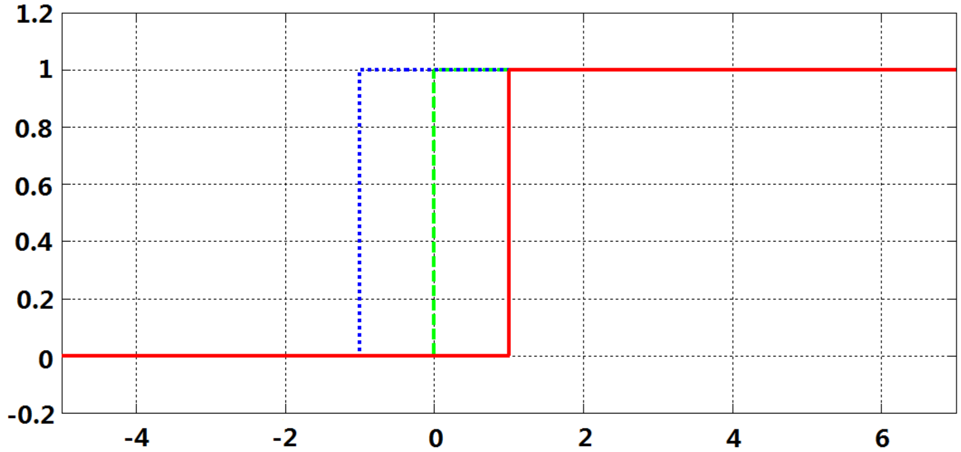


Fig. 4.5 Binary Step function for activation function

3. Binary sigmoid function

Another common and useful logistic function is sigmoid function. As the feature of differentiable and the capability of reducing training computational burden, sigmoid function is beneficial for applying to back propagation training algorithms.

$$f(x) = \frac{1}{1+e^{-\alpha x}} \tag{4.4}$$

Where α is steepness parameters. Sigmoid functions with steepness parameter α equals to 1 (red), 2 (green), 3(blue) are showing in Fig. 4.6. The output range of a sigmoid function is limited from 0 to 1.

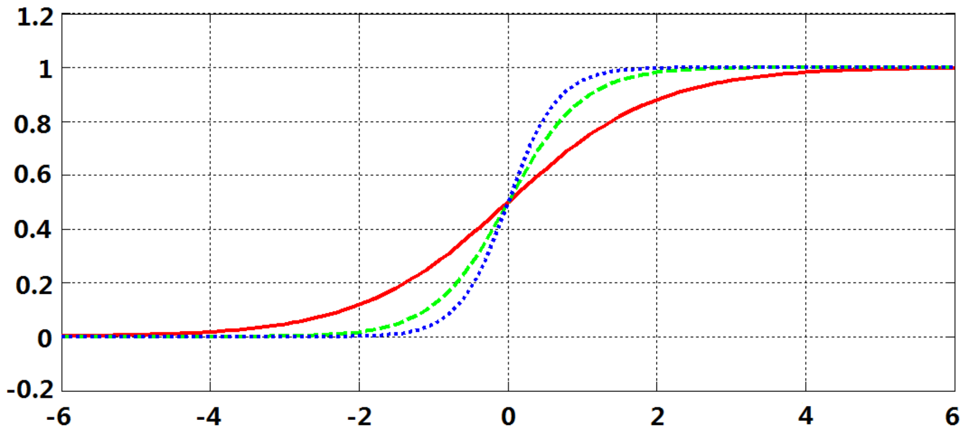


Fig. 4.6 Binary Sigmoid function for activation function

4. Bipolar Sigmoid

For given problem with the function output limited from -1 to 1, bipolar sigmoid is another common activation function for neuron network. The function equation can be represented as following in Equation 4.5.

$$f(\mathrm{x}) = \frac{1 - e^{-\alpha x}}{1 + e^{-\alpha x}} \tag{4.5}$$

Where α is steepness parameters. Bipolar sigmoid functions with steepness parameter α equals to 1 (red), 2 (green), 3(blue) are showing in Fig. 4.7. The output range of a sigmoid function is limited from 0 to 1.

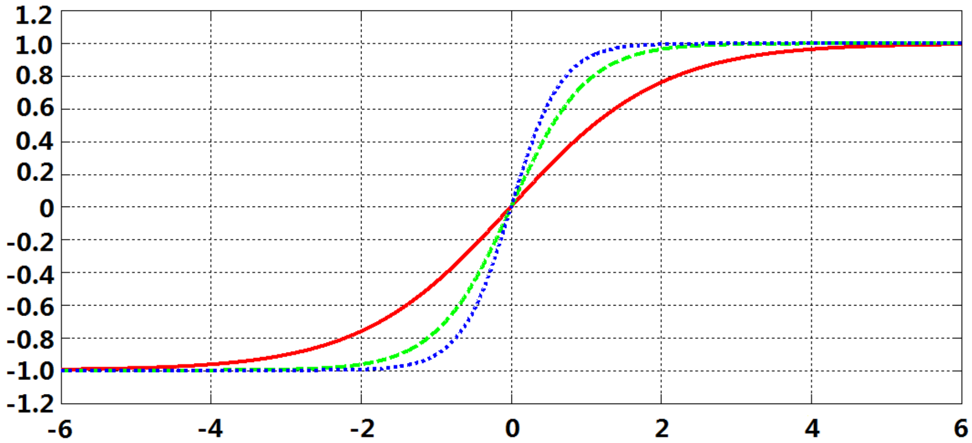


Fig. 4.7 Bipolar Sigmoid function for activation function

4.3.3 Multi-Layer Perceptron (MLP)

In general, at least one hidden layer before the output layer is needed to form a feed-forward network. Fig. 4.8 depicts a MLP's architecture with three types of layers (input layer, hidden layers and output layer). Perceptron neurons are existed in hidden layers and output layers. The dimension of the input vector in a neural network determines the amount of neurons in input layer. Between each adjacent layer, the outputs from the neuron in the layer ahead to the neurons in the rear layer are multiplied by synaptic weights, which play a key role in neural network training. The amount of hidden layers and the number of neurons in each hidden layer are able to change according to users' willingness. Usually, three-layer network is selected as the architecture for program training, because this kind of architecture can approximate any function with a few discontinuities [80]. The amount of neurons in output layer is affected by the output vectors which are also determined by users.

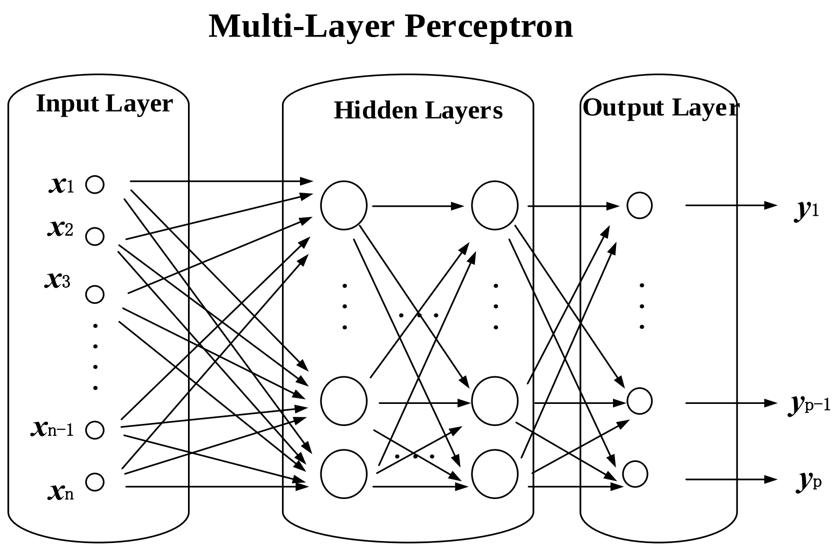


Fig. 4.8 Architecture of Multi-layer perceptron feed-forward network

4.4 Back-Propagation Training

To date, Back propagation is widely used in neural networks, which is a feed-forward network with continuously valued functions and supervised learning [77]. It can match the input data and corresponding output in an appropriate way to approach a certain function which is used for achieving an expected goal with some previous data in the same manner of the input.

There are two types of training methods named supervised training and unsupervised training. Supervised training is usually accomplished by presenting a sequence of training vectors, or patterns, each with an associated target output vector. The weights are then adjusted according to a learning algorithm. While in the unsupervised training, neural nets are self-organized and group similar input vectors together without the use of training data to specify what a typical member of each group looks like or to which group each vector belongs. A sequence of input vectors is provided, but no target vectors are specified [78]. In other words, supervised learning has a training target to guide a learning system to approach a preferred output, while unsupervised learning does not have such a target.

4.4.1 Gradient Descent and delta learning rule

Gradient descent learning attempts to minimize an error function by finding an optimized point in some parameter space. It is a first-order optimization algorithm to find the minimum of a function with taking proportional to the negative of the gradient. This method can be introduced in Equation 4.6.

$$x_{n+1} = x_n - \eta_n \nabla f\left(x_n\right) \tag{4.6}$$

Where η is the learning step size.

Delta learning rule is a learning method for updating neural network weights by implementing a gradient descent and moving the weight vector from the point on the surface of the parabolic down toward the lowest point [81-82].

4.4.2 Back-Propagation Theory

Back-Propagation is a learning method by generalizing the delta rule. Generally, the back-propagation training contains three stages:

1. Input feed-forwarding
2. Error propagating
3. Weight updating

In the input Feed-forwarding stage, the input signal is broadcasted to the hidden layer via input unit, then activation is calculated in hidden layer and the signal is sent to output unit, finally the output unit calculates the activation and generates the temporary output as a response to the input signal. In the Error propagation stage, the error between target and temporary output generated in input feed-forwarding stage is compared and generating relative factors based on the error, then the factors are distributed from output layer to input layer (Fig. 4.9). In the weight updating stage, weights are updated according to the factors generated in the error propagating stage.

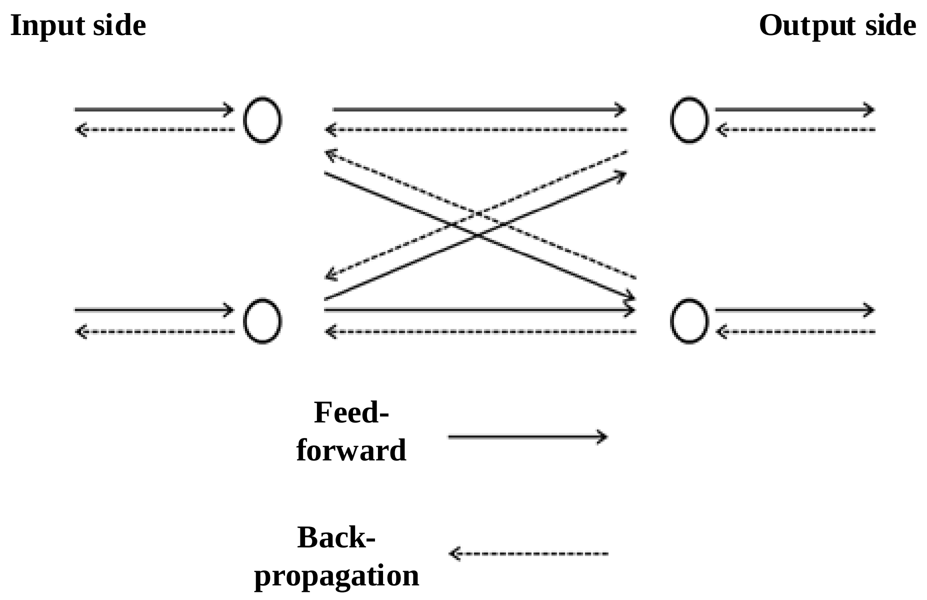


Fig. 4.9 Feed-forward and back-propagation

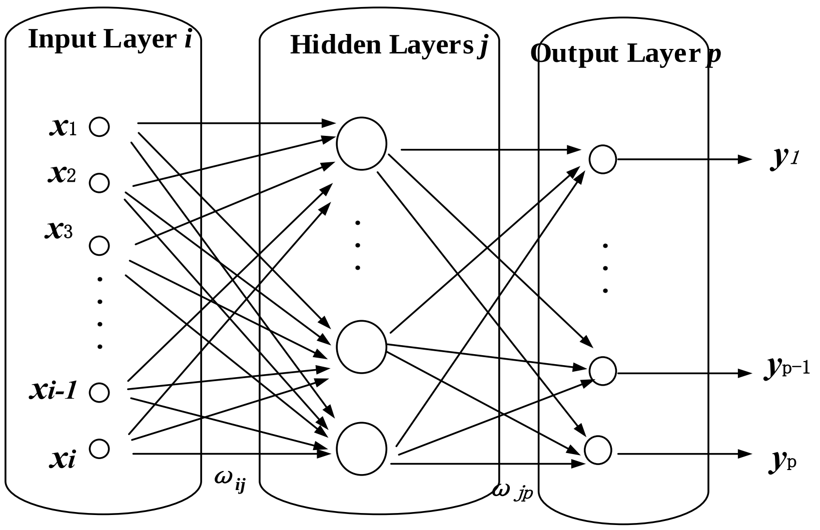


Fig. 4.10 Three-layer Network

Assume the training set $X = [X_1, X_2, \ldots, X_N]$ contains N groups of input vectors. In each input vector $X_k= [x_{k1}, x_{k2}, \ldots, x_{kI}]$, $(k=1,2,\ldots,N)$. I is elements number, which is the same as neurons' number in input layer i. The actual output corresponding to the k_{th} input vector is $Y_k = [y_{k1}, y_{k2}, \ldots, y_{kI}]$, the same as the model's output number. The expected output corresponding to the k_{th} input vector, so-call target, is $t_k=[t_{k1}, t_{k2}, \ldots, t_{kp}]$. Assume the training process is at the n_{th} epoch.

The function that wished to be achieved minimum is batch training average error E_{av} in equation 4.7.

$$\left.\begin{aligned} E_{av}(n) &= \frac{1}{N}\sum_{k=1}^{N} E_k(n) \\ E_k(n) &= \frac{1}{2}\sum_{p=1}^{P} e^2{}_{kp}(n) \\ e_{kp}(n) &= t_{kp} - y_{kp}(n) \end{aligned}\right\} \tag{4.7}$$

For the k_{th} input vector from training input set:

- e_{kp} is the error between target and actual output at the p_{th} element in the output vector at the n_{th} iteration.
- E_k is the Least Mean Square error between the whole target vector and the output vector corresponding to the k_{th} input vector at the n_{th} iteration.
- E_{av} is the target function whose minimum is interested. It is the batch learning error considering the errors corresponding to all the training input vectors at the n_{th} iteration.

Due to the Delta rule, the weights updating obeys relationship in Equation 4.8.

$$\left.\begin{aligned} \omega_{ij}(n+1) &= \omega_{ij}(n) + \Delta\omega_{ij}(n) = \omega_{ij}(n) - \varepsilon\,\frac{\partial E_{av}(n)}{\partial \omega_{ij}} \\ \omega_{jp}(n+1) &= \omega_{jp}(n) + \Delta\omega_{jp}(n) = \omega_{jp}(n) - \varepsilon\,\frac{\partial E_{av}(n)}{\partial \omega_{jp}} \end{aligned}\right\} \tag{4.8}$$

Where

- ω_{ij} is the weight between the i_{th} input element and the j_{th} neuron in the hidden layer.
- ω_{jp} is the weight between the j_{th} neuron in hidden layer and the p_{th} neuron in the output layer.
- The whole Equation 4.8 reveals that the variation direction of the weights is towards the negative gradient and the step length is controlled by a parameter ε.

Forward Calculation

For batch learning, the whole training input set is passed to the ANN in every epoch. At the n_{th} epoch, when the k_{th} input vector arrives at the input layer, forward calculation of the ANN model is shown in Equation 4.9.

$$\left.\begin{array}{ll} u_{kj}(n)=\sum_{i=1}^{I}\omega_{ij}(n)x_{ki} & v_{kj}(n)=f_j(u_{kj}(n))=f_j(\sum_{i=1}^{I}\omega_{ij}(n)x_{ki}) \\ u_{kp}(n)=\sum_{j=1}^{J}\omega_{jp}(n)v_{kj}(n) & v_{kp}(n)=f_p(u_{kp}(n))=f_p(\sum_{j=1}^{J}\omega_{jp}(n)v_{kj}(n)) \\ & y_{kp}(n)=v_{kp}(n) \end{array}\right\} \tag{4.9}$$

Equation 4.9 description: this is the forward calculation corresponding to the k_{th} input vector at the n_{th} epoch.

- x_{ki} is the i_{th} element in the input vector.
- ω_{ij} is the weight between the i_{th} neuron in input layer i and the j_{th} neuron in hidden layer j; ω_{jp} is the weight between the j_{th} neuron in hidden layer j and the p_{th} neuron in output layer p.
- u_{kj} is the input of the j_{th} neuron in hidden layer j, which is achieved by the sum of all the output in the previous layer multiplied with their weights; u_{kp} is the input of the p_{th} neuron in output layer p.
- v_{kj} is the output of the j_{th} neuron in hidden layer j; v_{kp} is the output of the p_{th} neuron in output layer p; y_{kp} is the p_{th} element in the output vector.
- f_j is the activation function in the hidden layer j; f_p is the activation function in the output layer p.

Error Propagation

To look backward from the output side in Fig. 4.10, weights between the hidden layer j and the output layer p are firstly updated. Considering Equation 4.8, the variation of weights is determined by the negative gradient and a small length step controlling variable ε as Delta-rule revealed in Equation 4.10.

$$\Delta\omega_{jp}(n)=-\varepsilon\frac{\partial E_{av}(n)}{\partial\omega_{jp}} \tag{4.10}$$

With Equation 4.7:

$$\left.\begin{array}{c}\dfrac{\partial E_{av}(n)}{\partial \omega_{jp}} = \dfrac{1}{N}\sum_{k=1}^{N}\dfrac{\partial E_k(n)}{\partial \omega_{jp}} \\ \dfrac{\partial E_k(n)}{\partial \omega_{jp}} = \dfrac{\partial E_k(n)}{\partial e_{kp}} \cdot \dfrac{\partial e_{kp}(n)}{\partial y_{kp}} \cdot \dfrac{\partial y_{kp}(n)}{\partial u_{kp}} \cdot \dfrac{\partial u_{kp}(n)}{\partial \omega_{jp}}\end{array}\right\} \tag{4.11}$$

Consider Equations 4.11 with 4.7 and 4.9, the second equation in Equation 4.11 could be solved in Equation 4.12.

$$\frac{\partial E_k(n)}{\partial e_{kp}} = e_{kp}(n); \frac{\partial e_{kp}(n)}{\partial y_{kp}} = -1; \frac{\partial y_{kp}(n)}{\partial u_{kp}} = f_p^{'}(u_{kp}(n)); \frac{\partial u_{kp}(n)}{\partial \omega_{jp}} = v_{kj}(n) \tag{4.12}$$

In Equation 4.12, f'_p is the differentiation of f_p in Equation 4.9. With Equations 4.11 and 4.12, the variation $\Delta\omega_{jp}$ could be calculated:

$$\left.\begin{array}{c}\dfrac{\partial E_k(n)}{\partial \omega_{jp}} = -e_{kp}(n) \cdot f_p^{'}(u_{kp}(n)) \cdot v_{kj}(n) \\ \delta_{kp}(n) = -e_{kp}(n) \cdot f_p^{'}(u_{kp}(n)) \\ \dfrac{\partial E_{av}(n)}{\partial \omega_{jp}} = \dfrac{1}{N}\sum_{k=1}^{N}\left\{\delta_{kp}(n) \cdot v_{kj}(n)\right\} \\ \Delta\omega_{jp}(n) = -\varepsilon \dfrac{\partial E_{av}(n)}{\partial \omega_{jp}}\end{array}\right\} \tag{4.13}$$

When weights between output layer p and hidden layer j finish their updates, propagation procedure updates the weights between hidden layer j and input layer i. The variation of weights is still from Equation 4.8.

$$\Delta\omega_{ij}(n) = -\varepsilon \frac{\partial E_{av}(n)}{\partial \omega_{ij}} \tag{4.14}$$

Consider Equations 4.14, 4.7 and 4.9:

$$\left.\begin{array}{c}\dfrac{\partial E_{av}(n)}{\partial \omega_{ij}} = \dfrac{1}{N}\sum_{k=1}^{N}\dfrac{\partial E_k(n)}{\partial \omega_{ij}} \\ \dfrac{\partial E_k(n)}{\partial \omega_{ij}} = \dfrac{\partial E_k(n)}{\partial v_{kp}} \cdot \dfrac{\partial v_{kj}(n)}{\partial u_{kj}} \cdot \dfrac{\partial u_{ki}(n)}{\partial \omega_{ij}} = \dfrac{\partial E_k(n)}{\partial v_{kp}} \cdot f_j^{'}(u_{kj}(n)) \cdot x_{ki}\end{array}\right\} \tag{4.15}$$

Consider Equations 4.7 and 4.15

$$\frac{\partial E_k(n)}{\partial v_{kp}} = \sum_{p=1}^{P} e_{kp}(n) \cdot \frac{\partial e_{kp}(n)}{\partial v_{kp}} = \sum_{p=1}^{P} [e_{kp}(n) \cdot \frac{\partial e_{kp}(n)}{\partial u_{kp}} \cdot \frac{\partial u_{kp}(n)}{\partial v_{kp}}] \tag{4.16}$$

With Equation 4.9, the two partial differentiations in Equation 4.16 could be revised in 4.17:

$$\left.\begin{aligned} \frac{\partial e_{kp}(n)}{\partial u_{kp}} &= -f_p^{'}(u_{kp}(n)) \\ \frac{\partial u_{kp}(n)}{\partial v_{kj}} &= \omega_{jp}(n) \end{aligned}\right\} \tag{4.17}$$

With Equations 4.15, 4.16, 4.17 and 4.13, the variation $\Delta\omega_{ij}$ could be calculated in Equation 4.18.

$$\left.\begin{aligned} \frac{\partial E_k(n)}{\partial \omega_{ij}} &== \delta_{kj}(n) \cdot x_{ki} \\ \delta_{kj}(n) &= f_j^{'}(u_{kj}(n)) \cdot \sum_{p=1}^{P} (\delta_{kp}(n) \cdot \omega_{jp}(n)) \\ \Delta\omega_{ij}(n) &= -\varepsilon \frac{\partial E_{av}(n)}{\partial \omega_{ij}} \end{aligned}\right\} \tag{4.18}$$

Batch Training Procedure

The batch training procedure can be presented in steps as follows:

Step 1. Initialize all the weights into non-zero random value.

Step 2. Use Forward Calculation to calculate the E_{av} in Equation 4.3. Compare E_{av} and the error acceptable limit, goal. If E_{av} is larger than the goal, turn to Step 3. Otherwise turn to Step 5.

Step 3. Compare the iteration number n to its limit. If n is larger, turn to Step 5. Otherwise turn to Step 4.

Step 4. Use Error Propagation to calculate all $\omega_{ij}(n+1)$ and $\omega_{jp}(n+1)$ to update weights. Then turn to Step 2.

Step 5. Output the trained network and finish training.

Fig. 4.11 gives a brief flowchart of the procedure.

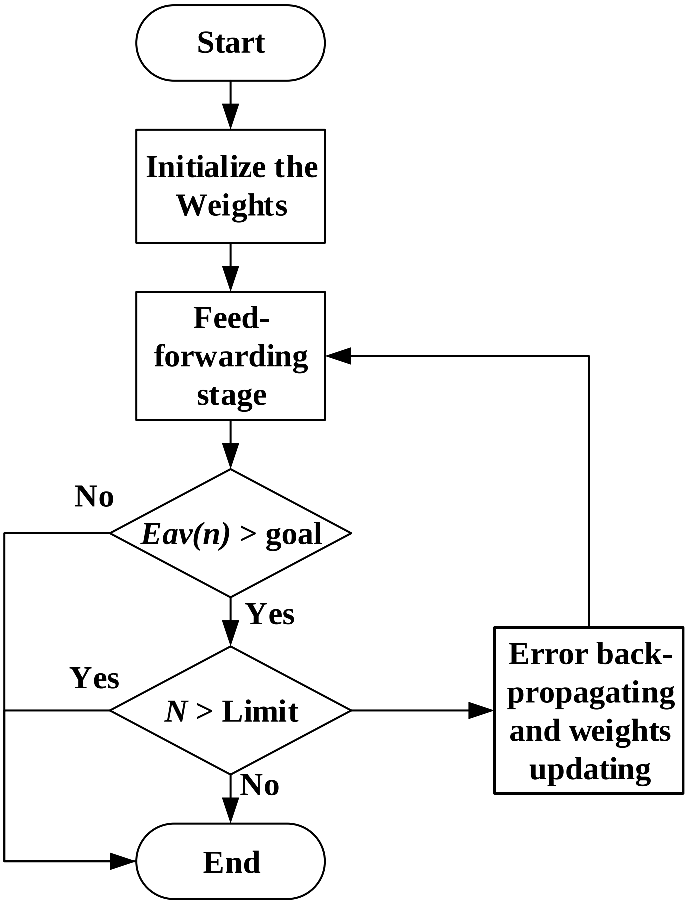


Fig. 4.11 Procedure of Batch Training

4.4.3 Quasi-Newton Algorithm

Quasi-Newton Algorithm is firstly proposed by William C. Davidson in 1959. It is an optimization method which is based on Newton's Method to seek the point of a function with 0 gradient, and find the local minimum and maximum value of the function. Considering ANN network in Fig. 4.10, target function for ANN is the error function E_{av} in Equation 4.3. For Quasi-Newton Algorithm, its expression could be re-written as Equation 4.19.

$$E_{av}(W_n) = E_{av}({\omega_{11}^{ij}}^n, {\omega_{12}^{ij}}^n, \cdots, {\omega_{IJ}^{ij}}^n, {\omega_{11}^{jp}}^n, {\omega_{12}^{jp}}^n, \cdots, {\omega_{JP}^{jp}}^n) \tag{4.19}$$

As from Equations 4.7 and 4.9, the target function is the function for all the weights between layers. So E_{av} could be rewritten as Equation 4.19. W_n is a vector whose elements are all the weights in ANN model. For each element of W_n, for instance, ${\omega_{11}^{ij}}^n$, stands for the weight between the first neuron in the i^{th} layer and the first neuron in the j^{th} layer at the n^{th} iteration.

Expressed by Taylor Series, the target error is given in Equation 4.20:

$$\left.\begin{array}{c} W_{n+1} = W_n + \Delta W_n \\ E_{av}(W_n + \Delta W_n) \approx E_{av}(W_n) + \nabla E_{av}(W_n)^T \cdot \Delta W_n + \frac{1}{2} \Delta W_n{}^T \cdot H_n \cdot \Delta W_n \end{array}\right\} \tag{4.20}$$

In Equation 4.18,

- H_n is the Hessian matrix of the target function.
- $\nabla E_{av}(W_n)$ is the error gradient, which contains all the partial differentiation of each weight.
- ΔW_n is weights variation vector.

Take the gradient of Equation 4.20. For achieving stationary point at $W_{n+1} = W_n + \Delta W_n$, the gradient of stationary point $E_{av}(W_n + \Delta W_n)$ is zero, the weights variation vector could be revealed in Equation 4.21 [79].

$$\left.\begin{array}{c} 0 = \nabla E_{av}(W_n + \Delta W_n) \approx \nabla E_{av}(W_n) + H_n \cdot \Delta W_n \\ \Delta W_n = -H_n{}^{-1} \cdot \nabla E_{av}(W_n) \end{array}\right\} \tag{4.21}$$

The Quasi-Newton Algorithm in ANN is trying to find the weights variance by the Hessian matrix and the target function gradient satisfying Equation 4.21.

Compare to the typical BP method introduced in Section 4.4, the weights variation expression contains one more Hessian matrix. Due to complex calculation will be processed for Hessian matrix, BFGS method offers an approximation calculation to the Hessian matrix, which is recognized as a modification of Quasi-Newton Algorithm. Equation 4.22 introduces the Hessian matrix approximation by BFGS method [79].

$$\left.\begin{array}{c} z_n = \nabla E_{av}(W_{n+1}) - \nabla E_{av}(W_n) \\ H_{n+1} = H_n + \dfrac{z_n \Delta W_n{}^T}{z_n{}^T \Delta W_n} - \dfrac{H_n \Delta W_n (H_n \Delta W_n)^T}{\Delta W_n{}^T \cdot H_n \cdot \Delta W_n} \end{array}\right\} \tag{4.22}$$

With Quasi-Newton Algorithm, by BFGS modification in Equations 4.13, 4.18, 4.21, and 4.22, the weights variance at each epochs could be calculated for training.

4.4.4 Levenberg-Marquardt (LM) Algorithm

Levenberg-Marquardt algorithm is a local optimization method to solve non-linear least square problems by improving Gauss-Newton and gradient descent method. As given by the target function in Equation 4.11, ($E_{av}(W_n) = \frac{1}{2N}\sum_{k=1}^{N}\sum_{p=1}^{P}(e_{kp}^{n}(W_n))^2$) is the sum of squares, LM method proposes another expression of gradient in Equation 4.23.

$$\left.\begin{aligned} \frac{\partial E_{av}(W_n)}{\partial \omega_{ij}} &= \frac{1}{N}\sum_{k=1}^{N}\sum_{p=1}^{P} e_{kp}^{n}(W_n)\cdot\frac{\partial e_{kp}^{n}(W_n)}{\partial \omega_{ij}} \\ \nabla E_{av}(W_n) &= \frac{1}{N} J_e^{n\,T}\cdot \dot{e} \end{aligned}\right\} \tag{4.23}$$

Where:

- $e_{kp}^{n}(W_n)$ is the re-write form of $e_{kp}(n)$ in Equation 4.3. k, p, n have the same meaning as in Equation 4.7.
- $\dot{e}$ is the error vector whose elements are all the $e_{kp}^{n}(W_n)$.
- J_e^{n} is the Jacobian matrix for the error vector $\dot{e}$, respecting to the weights vector W_n at the n^{th} iteration.
- For $\frac{\partial E_{av}(W_n)}{\partial \omega_{jp}}$, the expression is only to use ω_{jp} to take the place of ω_{ij}.

New approximation of Hessian matrix is also given in Equation 4.24 by ignoring second order partial derivative and adding a non-negative damping factor μ [79].

$$H_n \approx \frac{1}{N}(J_e^{n\,T}\cdot J_e^{n} + \mu I) \tag{4.24}$$

Where μ is the damping factor influencing the convergence speed, it changes until the step is a decrease step for target function.

From Equations 4.21 4.23 and 4.24, the weights variance of ANN by LM algorithm is given in Equation 4.25.

$$\Delta W_n = -\cdot(J_e^{n^T} \cdot J_e^n + \mu I)\cdot J_e^{n^T}\dot{e} \tag{4.25}$$

4.4.5 Load Forecasting implemented by Back-Propagation Training

Artificial Neural Network is implemented in load forecasting to map influencing factors including weather conditions, day type, demand of the previous point, and time point index in a time period with the training target, which is the demand at the same time. Architecture for load forecasting is given in Fig. 4.12.

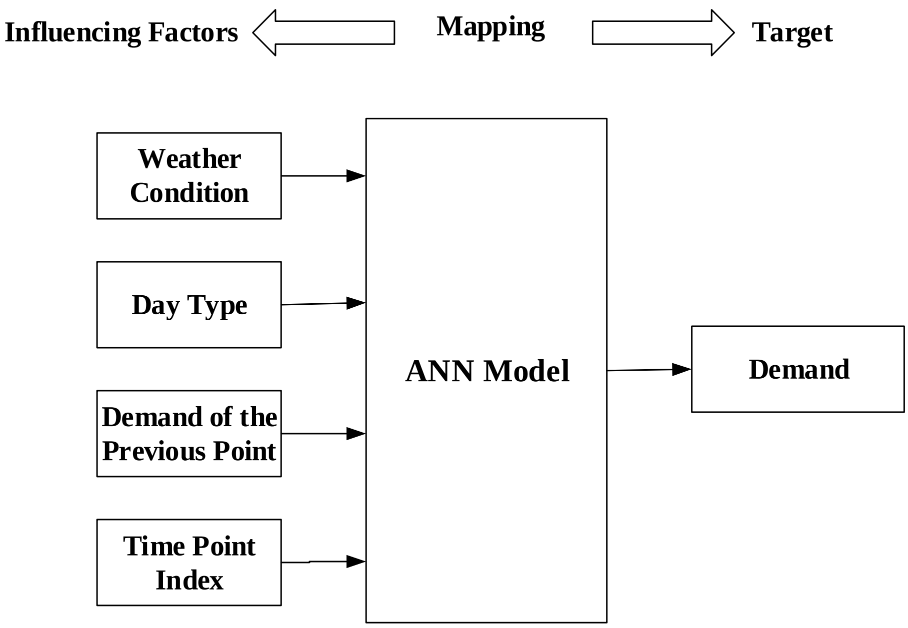


Fig. 4.12 Architecture for load forecasting

Weather conditions make human feel different in comfort level and may change the human behaviours to utilize the load accordingly. 7 factors stimulus human comfort are:

- Temperature
- Dew Point Temperature
- Relative Humidity
- Wind Speed
- Visibility
- Atmosphere Pressure

- Weather Status

The 6 factors in front are the exact values of weather conditions, while the last one is the fuzzy data to describe the weather like. Weather status is including 6 indices:

- Clarity Index (0, 0.5, 1)
- Cloud Index (0, 0.5, 1)
- Fog Index (0, 0.5, 1)
- Rain Index (0, 0.25, 0.5, 0.75,1)
- Thunder and Lighting Index (0, 0.5, 1)
- Snow Index (0, 0.3, 0.6, 1)

As can be seen in the indices listed above, the value of each index is between 0 and 1, which indicate the intensity of the index. For instance, 0 in fog index means no fog in the day, while 1 means the day is very foggy.

Fig. 4.13 reveals the population density of Ontario, Canada in 2006. The population is centralized in east and south part of the entire province. Weather conditions may differ between cities. Thus, cities in different locations are selected for weather data acquisition. In this chapter, three cities located in Thunder Bay, Timmins, and Toronto are selected for weather data acquisition. All weather data are obtained from Weather Office of Canada, the predecessor of Environment Canada [83].

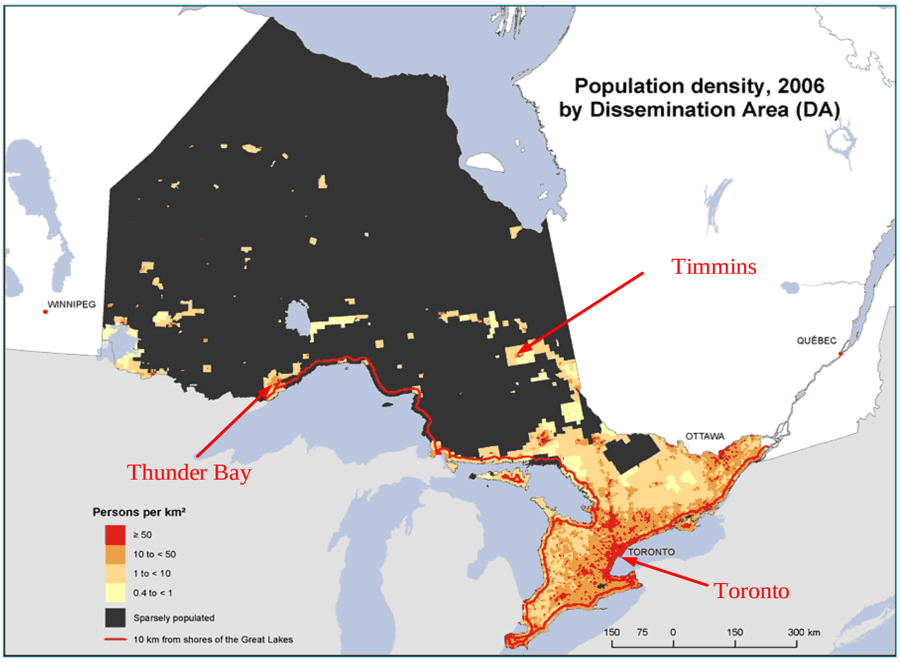


Fig. 4.13 Population density of Ontario, Canada in 2006 [84]

4.4.6 Indices for Performance Measurement and Comparison

The network is required to check whether it can achieve the expectation after training. Another set of input vectors and demand scenarios are needed to test the network. Comparison needs to be made to check out the difference between the test output and real demand. Two Indices are introduced here for performance measurement and comparison, Root Mean Squared Error (RMSE) and Mean Absolute Percentage Error (MAPE).

RMSE is an index to qualify the error between predicted demand and demand in reality. The equation can be written as in Equation 4.7

$$MSE = \frac{\sum_{i=1}^{n}\left(Output_i - Target_i\right)^2}{n} \tag{4.7}$$

Where n is total number of predicted outputs, $Output_i$ is the output value of i^{th} data and $Target_i$ is the corresponding target value of i^{th} data.

MAPE is an index to qualify the error between predicted demand and demand in reality with percentage to the demand in reality. The equation can be written as in Equation 4.8.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{Target_i - Output_i}{Target_{mean}}\right| \tag{4.8}$$

Where $Target_{mean}$ is the mean value of all target values.

According to Equation 4.9, the performance of training by back-propagation neural network is determined by 4 factors:

- **Architecture:** the amount of neurons in the hidden layer of an ANN
- **Learning rate:** Learning step size
- **Goal:** Margin of error
- **Epoch:** The maximum number of batch training iteration

4.5 Load Forecasting by ANN

3 years hourly data from Nov 11^{th}, 2005 to Oct 31^{st}, 2008, was applied to this simulation for training the network. Comparison between the prediction and the target is made with

the data from Nov 11th, 2008 to Oct 31st, 2009 for analyzing. 15% of training data is cut out as validation set for early stopping against over-fitting.

4.5.1 ANN Trained by Delta-Rule

To compare the performance of different ANN architectures, the goal of each architecture is set to 0.0001 uniformly. As different architecture has different best epoch limit and learning rate, here epoch is limited to 300 for each architecture. The training performances of different architectures with 5, 10, 20, 50, 100 neurons in the hidden layers are listed in Table 4.1.

Each network has been trained 10 times to find out the best learning rate. After the best learning rate was found, the networks are trained with different initial weights by back propagation algorithm. The training performance is demonstrated by 3 indices, which are Average training RMSE, Average CPU Time, and Average MAPE. Average train RMSE is the average value of mean squared error of the 10 times training. Average CPU time is the average value of CPU processing time of 10 times training. Average MAPE is the average value of the Mean absolute percentage error by 10 times training. Comparing the training performances in Table 4.1, Network architecture with 20 neurons in its hidden layer is with the lowest Ave Train RMSE and Ave MAPE, which are 0.0059 and 11.18% respectively.

Fig. 4.14 gives another view of training performance with different architectures. Obviously, the overall trend of the indices MAPE and RMSE is decreased with the number of neurons increased and keep steady to some extent. Whereas the CPU time is extremely increased with increasing in the number of neurons. Synthesize every index, 20 neurons in the hidden layer is the best option to provide a relative better performance with less time. One of the load forecasting results of training performance samples with 20 neurons in hidden layer is shown in Table.4.2.

Network Architecture (neurons in hidden layer)	**Network Training Parameter**	**Training Performance**
5	Goal: 0.0001;	Ave Train RMSE: 0.0109
	Epoch Limit: 300	Ave CPU Time: 200.1066s
	Best Learning Rate: 0.05	Ave MAPE: 16.36%
10	Goal: 0.0001;	Ave Train RMSE:0.0080
	Epoch Limit: 300	Ave CPU Time:261.4057s
	Best Learning Rate: 0.055	Ave MAPE: 13.99%
20	Goal: 0.0001;	Ave Train RMSE:0.0059
	Epoch Limit: 300	Ave CPU Time:284.7701s
	Best Learning Rate: 1	Ave MAPE: 11.18%
50	Goal: 0.0001;	Ave Train RMSE:0.0093
	Epoch Limit: 300	Ave CPU Time:420.6352s
	Best Learning Rate: 0.35	Ave MAPE: 11.97%
100	Goal: 0.0001;	Ave Train RMSE:0.0091
	Epoch Limit: 300	Ave CPU Time:447.6930
	Best Learning Rate: 0.35	Ave MAPE: 11.15%

Table. 4.1 ANN Training performances with different architectures

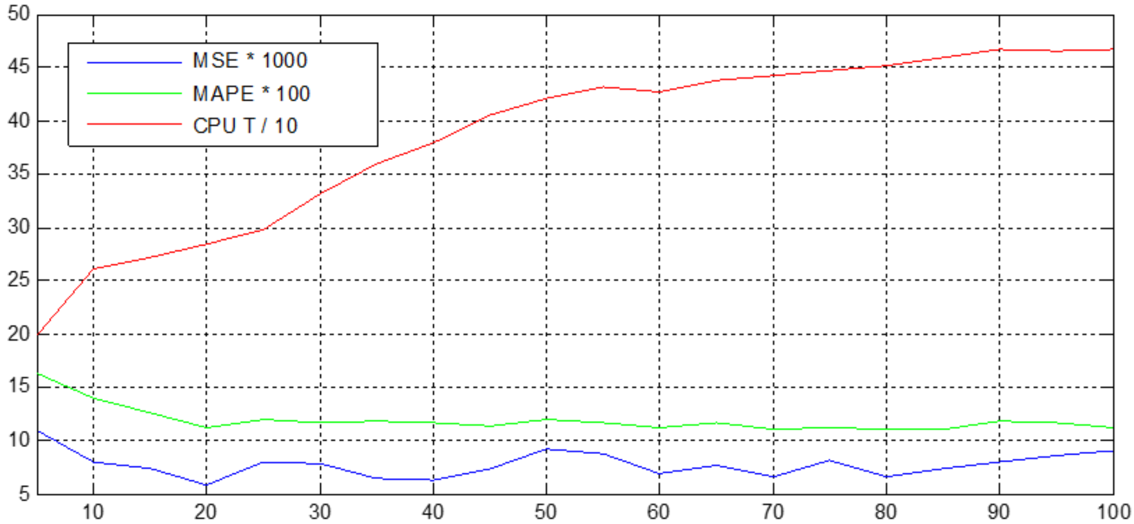


Fig. 4.14 Measurement indices with different neuron number

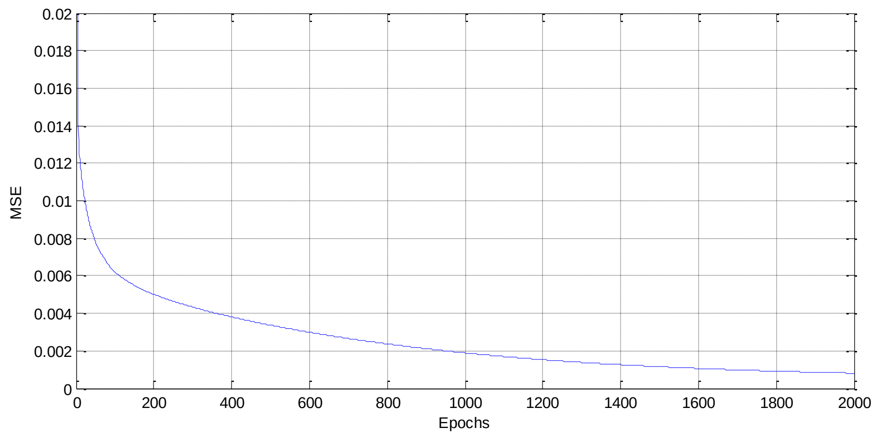
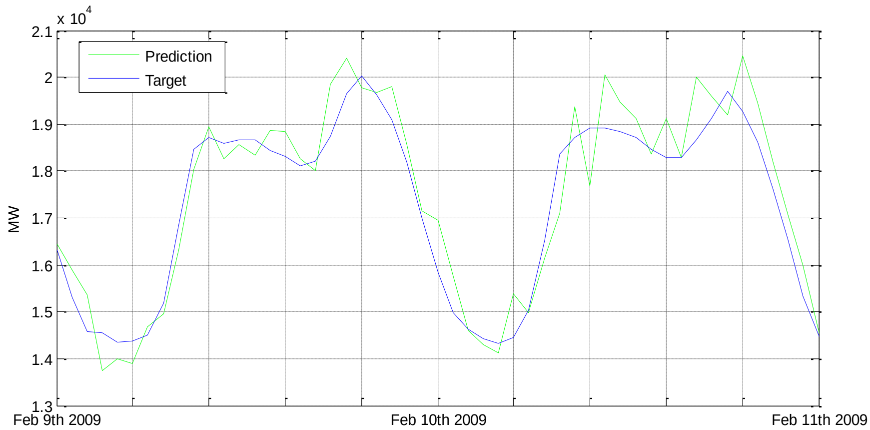
<table>
<tr><th>Network Architecture</th><th>Network Training Parameter</th><th>Training Performance</th></tr>
<tr><td rowspan="3">20</td><td>Goal: 0.0001;</td><td>Train RMSE: 0.00081077</td></tr>
<tr><td>Training Epoch: 2000</td><td>CPU Time: 1695.3s</td></tr>
<tr><td>Best Learning Rate: 1</td><td>MAPE: 5.47%</td></tr>
<tr><td>Sample Training Process</td><td colspan="2">
</td></tr>
<tr><td>Sample Compare Between Target and Prediction of Test Data</td><td colspan="2">
</td></tr>
</table>

Table. 4.2 Load forecasting by an ANN, Delta-rule training with 20 neurons in hidden layer

4.5.2 ANN Trained by Quasi-Newton

Same as the steps in 4.5.1, ANN Trained by Quasi-Newton is applied as the load forecasting algorithm. The training performances of different architectures with 5, 10, 20, 50, 100 neurons in the hidden layers are listed in Table 4.3.

In Table 4.3, both of two indices, MAPE and MSE decreased slightly with the amount of neuron increased from 5 to 50 in the hidden layer. However, the CPU calculation time increased dramatically by approximately a hundredfold from 626.43s to 66775s. There is no doubt that the result with 50 neurons in the hidden layer is the best choice without considering the impact of CPU running time.

Network Architecture (neurons in hidden layer)	**Average Training Performance**	
5 Goal: 1×10^{-5}	Ave Training MSE: 1.23×10^{-4}	Ave Training CPU Time: 626.43s
	Ave MAPE (%): 1.55	Ave Largest (%): 11.34
	Ave APE STD (%): 1.21	Ave Largest (MW): 1470
10 Goal: 1×10^{-5}	Ave Training MSE: 1.03×10^{-4}	Ave Training CPU Time: 805.07
	Ave MAPE (%):1.53	Ave Largest (%): 12.49
	Ave APE STD (%):1.28	Ave Largest (MW): 1450
20 Goal: 1×10^{-5}	Ave Training MSE: 0.87×10^{-4}	Ave Training CPU Time: 3056s
	Ave MAPE (%):1.52	Ave Largest (%): 14.61
	Ave APE STD (%):1.32	Ave Largest (MW): 1665
50 Goal: 1×10^{-5}	Ave Training MSE: 0.55×10^{-4}	Ave Training CPU Time: 66775s
	Ave MAPE (%):1.39	Ave Largest (%): 15.23
	Ave APE STD (%):1.34	Ave Largest (MW): 1784

Table. 4.3 ANN architecture selection for load forecast with Quasi-Newton (BFGS) Method

Some of the utilities do not only use MAPE as the index to indicate the error distance between real demand and prediction, but also introduce indices like Ave Largest and Ave APE STD. Ave Largest index indicates the average largest percentage error of a certain network type, it can be a percentage or an absolute value. Ave APE STD stands for Standard deviation for absolute percentage error (APE), which indicates the error variation of a certain network type. Although MAPE and MSE decreased, the indices Ave Largest and Ave APE STD are increased which means the performance becomes unstable when the ANN architecture increases the complexity. This is due to the more complex architecture brings more capability for ANN to store redundancy, which is generated by training without representing the set sufficiently and uniformly.

In this case, 20 neurons were selected, which averagely spend 3056s on running the algorithm. A sample result is shown in Table 4.4 below:

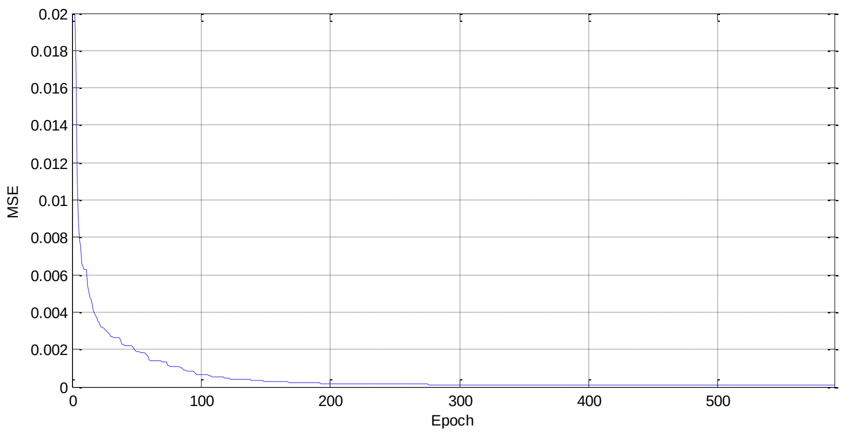
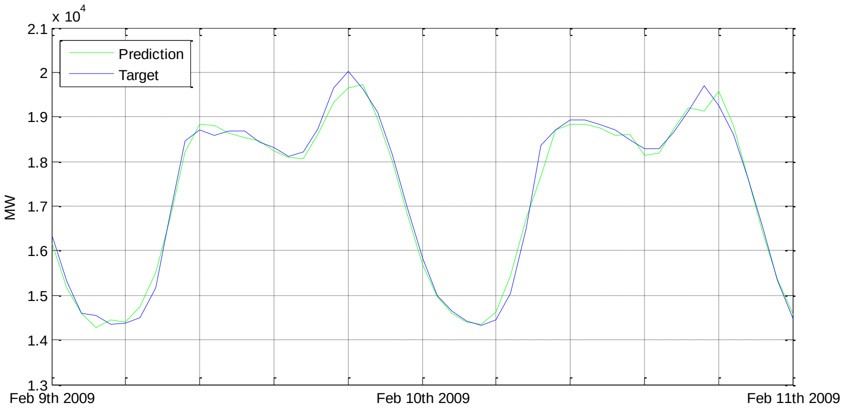
Network Architecture	Network Training Parameter	Training Performance
20	Goal: 1×10^{-5};	Train MSE: 7.74×10^{-5}
	Training Epoch: 591	CPU Time: 4716.3s
	Ave MAPE: 1.25%	
Sample Training Process		
Sample Compare Between Target and Prediction of Test Data		

Table. 4.4 Load forecasting by an ANN, Quasi-Newton training with 20 neurons in hidden layer

4.5.3 ANN Trained by Levenberg-Marquardt

Same as the training procedure in Section 4.5.1, ANN Trained by Levenberg-Marquardt is applied in the load forecasting algorithm. The training performances of different architectures with 5, 10, 20, 50, 100 neurons in the hidden layers are listed in Table 4.3. As shown in Table 4.5, there is only small difference between the values indicated by index MAPE, whereas the index MSE decreases around 50% with the amount of neurons increased from 5 to 50. The CPU running time increases from 362.71s to 1153.48s. A sample of network performance with 10 neurons in hidden layer is shown in Table 4.6 below.

Network Architecture (neurons in hidden layer)	**Average Training Performance**	
5 **Goal:** 1×10^{-5}	Ave Training MSE: 0.549×10^{-4}	Ave Training CPU Time: 362.71s
	Ave MAPE: 1.08%	
10 **Goal:** 1×10^{-5}	Ave Training MSE: 0.403×10^{-4}	Ave Training CPU Time: 595.12s
	Ave MAPE:1.05%	
20 **Goal:** 1×10^{-5}	Ave Training MSE: 0.352×10^{-4}	Ave Training CPU Time: 646.12s
	Ave MAPE: 1.07%	
50 **Goal:** 1×10^{-5}	Ave Training MSE: 0.294×10^{-4}	Ave Training CPU Time: 1153.48s
	Ave MAPE:1.09%	

Table. 4.5 ANN architecture selection for load forecast with LM Method

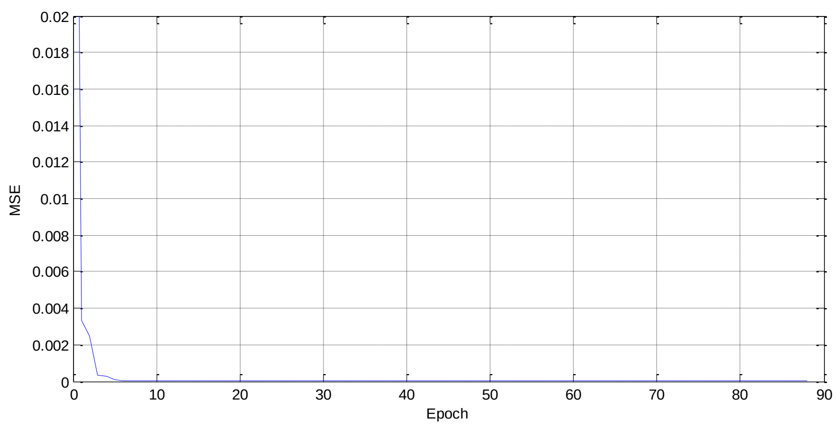
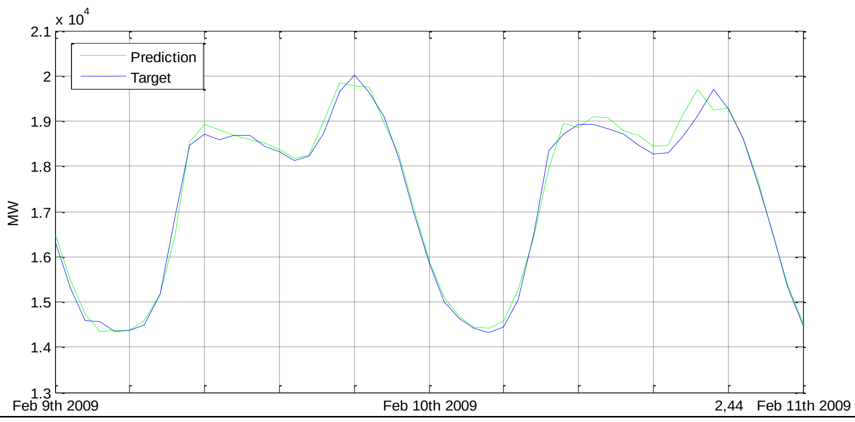
Network Architecture	**Network Training Parameter**	**Training Performance**
20	Goal: 1×10^{-5};	Train MSE: 3.815×10^{-5}
	Training Epoch: 88	CPU Time: 398.5s
	Ave MAPE: 1%	
Sample Training Process		
Sample Compare Between Target and Prediction of Test Data		

Table. 4.6 Load forecasting by an ANN, Levenberg-Marquardt training with 20 neurons in hidden layer

As shown in Table 4.5, there is only small difference between the values indicated by index MAPE, whereas the index MSE decreases around 50% with the amount of neurons increased from 5 to 50. The CPU running time increases from 362.71s to 1153.48s. A sample of network performance with 10 neurons in hidden layer is shown in Table 4.6 below.

4.6 Result Comparison and Analysis

To compare the differences between performances of load forecasting trained by these three ANNs with different back propagation algorithm (BP algorithm, Quasi-Newton algorithm and Levenberg-Marquardt algorithm), architectures with 10 neurons in the hidden layer have been selected.

4.6.1 Convergence Comparison

Fig. 4.15 shows the convergence performances (revealed by index MSE) of these three algorithms for the load forecasting during the first 50 epochs of training. As depicted in the figure, the typical back propagation training by Delta-rule is slowest between these three algorithms. While the performance of the Levenberg-Marquardt algorithm converges faster than the other two algorithms. The differences between performances could also be easily distinguished by examination plots, shown in Fig. 4.16.

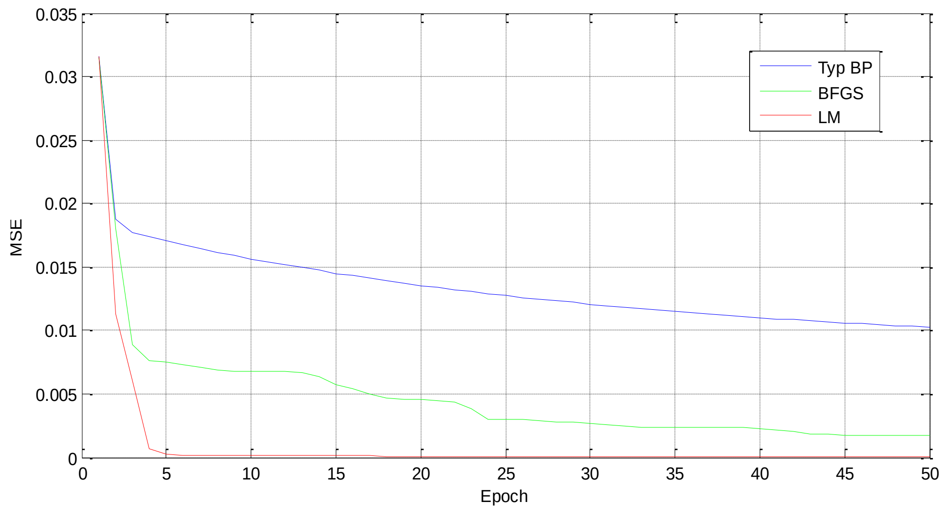
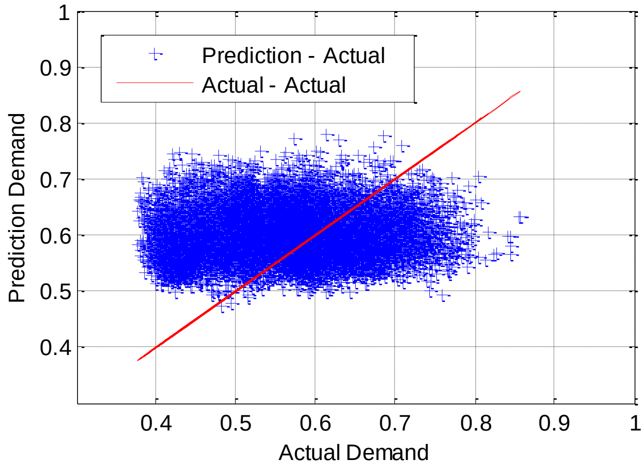
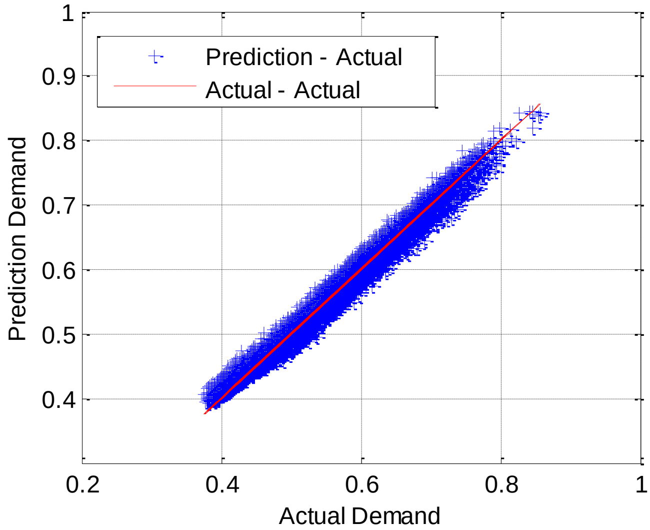


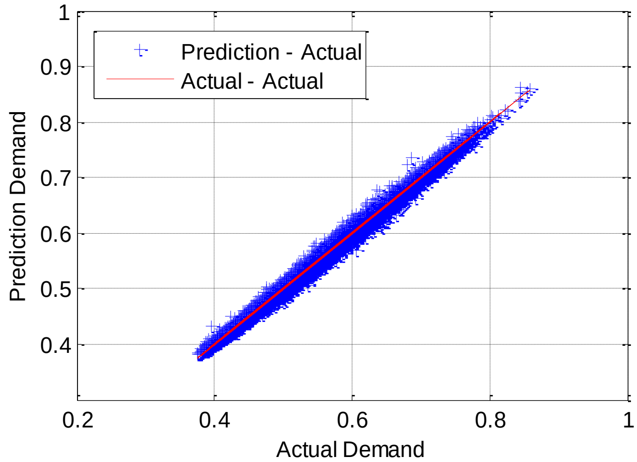
Fig. 4.15 The Epoch of Training with 3 different algorithms vs MSE



(a) ANN Trained by Delta rule



(b) ANN Trained by Quasi-Newton



(c) ANN Trained by LM

Fig. 4.16 Examination plots of actual demand and prediction

The set of plots above in Fig. 4.16 vividly depicted the error between actual demand and predicted demand. The red line in each plot indicates the real demand during a certain period and the blue dots around the red line means the predicted values during the same period. The more dots converged to the red line, the more precisely the load forecasted. Comparing these three plots, obviously, ANN Trained by LM has a better performance.

4.7 Conclusion

This chapter focused on the behaviours of different training algorithms for load forecasting by back propagation algorithm in Neural Network. Smart grid load forecasting system framework design for Ontario, Canada. This work introduces a smart grid load forecast design procedure with consideration of general influencing factors and Ontario local factors. Due to the characteristic of imitating the mode of human beings' thinking, ANN can learn the relationship between input and output. Thus, same function of the relationship can be applied into practical situation to find out the output according to the information already known as input. Besides, this work compares results from different ANN training algorithms and provides a novel explanation for the differences. After research, training with LM algorithm which is integrated in Neural Network Toolbox in Matlab is regarded as one of the best choice to do load forecast. If the accurate results are required to forecast the load, more neurons are needed to apply into the network architecture. On the other hand, over-fitting must be considered to ensure the network can simulate the load situation well. Owing to the condition limitation, the input vectors did not take all of the information into account. A few of the simulation part didn't meet the real demand very well, even large squared error occurred. If the information was gathered enough and the networks were trained more meticulous, better result could be obtained to apply into load forecasting for smart grid.

Chapter 5

Self-Healing and Load Shedding in Smart Grid

5.1 Introduction

The self-healing technology in smart grid allows processors installed in each component of a substation like breakers, switches, transformers and busbars to communicate with each other. A parallel information connection must be installed in each high voltage connection to the device, whose parameters, status and analog measurements from sensors have permanent information. One of the typical instance of self-healing is load shedding.

With the deployments of smart grid technologies and communication networks in modern power systems, frequency relays, which are used for the purpose of power system protection, are to achieve more advanced and reliable performance. Load shedding strategies, which prevent power systems from suffering frequency instability based on the real-time data frequency relays, are facing a challenge to adequately and accurately take shedding actions, as power system loads are varying all the time. On the generation side, increasingly non-dispatchable and inflexible renewable power generations being integrated to the system complicates generation predictions and results in frequent power imbalance.

This chapter investigates the main reasons for the blackout occurred in Indian July 2012, and gives further suggestions to minimize the blackouts in future. In addition, this chapter proposes a load shedding scheme with different magnitudes and load shedding orders for distribution networks, with its effect on power system frequency stability verified in a benchmark IEEE 33-bus distribution system and a large low voltage distribution system, which are simulated in DIgSILENT PowerFactory package.

5.2 Blackout in India

Power system stability is critical to the system operation and quality of supply. Any power system imbalance, which can be caused by load variations or generation closure, will immediately result in an overall frequency change in the system. A system frequency too low can cause destructive damage to the system components. For examples, nuclear power plants usually as base loads are strictly operated a frequency above 48 Hz, whereas some hydro units may work with a frequency as low as 45 Hz for frequency balancing purpose [103].

By means of monitoring the electricity usage continuously via automated instrumentation, system operators will shut down certain pre-arranged electric loads or devices (e.g. electric heaters, stoves, dryers and hot hubs), If the upper threshold of electricity usage is approached. With energetically advocating of smart grid, demand responds, which is changing the human behaviour of using the electrical power in a relatively "controlled" manner, could also act like load shedding.

One of the good lessons is that the grid disturbances occurred on 30th and 31st of July 2012 leaving millions of Indians in the dark for hours. It was understood that in the blackout that occurred on 31st of July, hydro power was slowed down which led to inadequate power generation while people overdrew more power for cooling off since the temperature was extremely high. Three of the Indian Grids were hit by power failure, leaving a huge disturbance in the country. The power outage affected 620 million people in India [91]. Trains were stopped, and a large amount of passengers were stranded on the platform. Traffic was congested in large cities including New Delhi and Kolkata due to failure of traffic lights.

When load is increasing and generators could not respond in time, loads are needed to shed when the frequency is dropping. Otherwise, it will damage the generators connected to the grid. Three of the Indian grids were hit by power failure twice, leaving a huge disturbance in the country on 30th and 31st of July in 2012. The power outage affected 620 million people in India [109]. In 2012, the first blackout was occurring at around 2:35 am on 30th of July in the Northern Region grid, which feeds electricity to 9 states of Northern India. Approximately 36000 MW was affected in this blackout. Only 60 % of load in Northern Region was restored by 11:00 am by means of hydroelectricity in the North Region and withdrawing power from Eastern and Western Regions. And the Northern Region grid was not supplied with the full load until 7:00 pm. Afterwards, on 31st of July, there was another disturbance occurring at 1:00 pm, almost covering the entire power grid in India, including Northern Region, Eastern Region and North-eastern Region. Only some of the small pockets were not affected, such as Narora. There were about 48000 MW of the total loads affected in the second blackout, which was much more serious than the first one. It was reported that over 700 million people in India was suffered from darkness and production slowdown. In 2011, India power losses owing to transmission and distribution issues are approximately 23.7% on average in India, while the value is around 10-15% in Europe and North America [110]. A weak monsoon was blamed as lacking of rain and decelerating the hydro power generation [111]. In terms of India Meteorological Department, the actual rainfall in June, July and August in India were much lesser than expected normal rainfall in these three months in 2012 [110]. Furthermore, because of the price control on coal by Indian government, some coal fire plants cannot afford such expensive coal importation and leave their power stations operating below capacity for their own interests [112]. Also, some experts blamed the disturbance due to the Indian grid infrastructure, which connects with both AC and DC transmission lines. The grids can exchange power with other region flexibly when only DC transmission cables connected between regions under normal operation. In addition, faults in one region are difficult to spread into others in abnormal conditions. Indian grid cannot take advantage from the benefits which bring security effects from only DC connection.

An Enquiry Committee has been founded to investigate the factors which led to the causes of the two grid disturbances on both days, and a report had been generated to investigate the situation and gave some critical recommendations [113]. One of the most serious problems is that the transmission system is very weak since the grid suffered from multiple outages. Besides, the Northern Region loads withdrew too much power from the Western Region grid so that the corridor linked between north and west was overloaded. Ineffective dispatch cannot prevent the Northern part from ‘overload’ electricity from the Western part. Without any fault occurring, zone 3 of the distance relay protecting the Bina-Gwalior link was tripped, and caused Western Region separated from Northern Region.

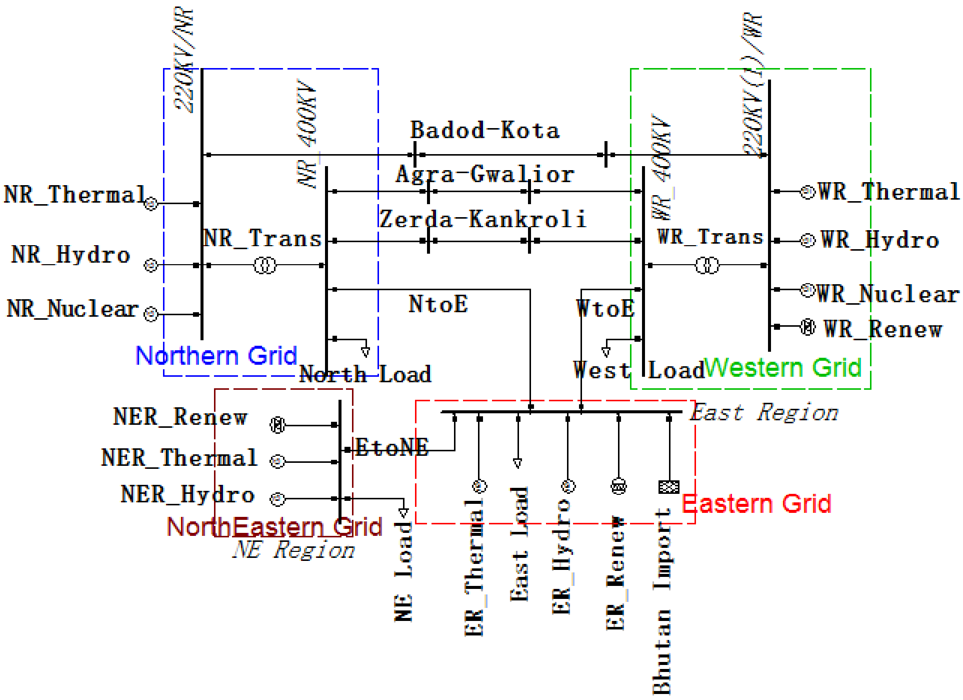


Fig. 5.1 Brief Indian NEW Grid for disturbance study

A brief model was built for simulating the grid behaviour during the disturbance with PowerFactory DIgSILENT software Package. As stated in the Report of the Enquiry Committee report and some media, Northern Region grid imported energy from all the rest of NEW Grid (Eastern Region, Western Region and North-eastern Region) before the disturbance occurrence. Besides, Bhutan, a country located at Northeast of India, also imported 1127 MW from the Eastern Region of Indian grid. The pre-disturbance generation and demand with power importing and exporting conditions on 30th of July in 2012 02:00 am are shown in Table. 5.1. It is worth noting that few lines had been tripped few hours before the collapse happening [114]. Each region in the NEW Grid which is involved in the disturbance has been grouped by a general load and some generation types such as thermal, hydro, nuclear and renewables.

Fig. 5.1 illustrates the India NEW Grid model for analyzing the scenarios of the grid disturbance in DIgSILENT software package. The Northern Region and the Western Region were connected by both 400kV circuit lines from Agra to Gwalior and Zerda to Kankroli, and 220kV circuit lines from Badod to Kota. All lines were assumed to have the same parameters. Each region of these four in the simulation was modeled for hydro, thermal and renewables generations and one load. Eastern Grid is connected to both Northern Grid and Western Grid by AC transmission line. Northeastern Grid comprises of hydro, thermal and renewable generations are connected to Eastern Grid only.

Region	Generation (MW)	Demand (MW)	Import (MW)
Northern	32636	38322	5686
Eastern	12452	12213	-239, (1127 MW to Bhutan)
Western	33024	28053	-6229
Northeastern	1367	1314	-53
Total	79479	79479	

Table. 5.1 Generation and Demand Conditions with Power Import and Export before Disturbances

Table. 5.2 illustrates the pre-disturbance generation power allocated in each region according to the enquiry report. The installed capacities of generations for each region are:

Northern Region:

19830 MW Hydro generations, 34608 MW Thermal generations 1620 MW nuclear generations;

Eastern Region:

3882 MW Hydro generations, 22545 MW Thermal generations and 411 MW from renewable energy sources;

Western Region:

7448 MW Hydro generations, 49402 MW Thermal generations, 1840 MW nuclear generation and 7909.95 MW from renewable energy sources;

Northeastern Region:

1200 MW Hydro generations, 2454.94 MW Thermal generations and 228 MW from renewable energy sources.

Regions / Generations	North	Northeast	East	West
Hydro	10000 MW	267 MW	2000 MW	6000 MW
Thermal	21636 MW	1000 MW	10200 MW	24024 MW
Nuclear	1000 MW	-	-	1400 MW
Renewable	-	100 MW	252 MW	600 MW
Total	32636 MW	1367 MW	12452 MW	33024 MW

Table. 5.2 Generation Power Allocation in Each Region

According to the Enquiry Committee report, load in the northern region were larger than power generated, which means the Northern region needs to import power from other regions unless there is a load shedding in the northern region.

5.2.1 Load changes in Northern Region

The aim of the sensitivity analysis is to find out the increased load at what level will lead to generators in northern region out of step with the rest of the NEW Grid. The increased level of reactive power of the load in the northern Region is fixed at 5 %. The increased level of active power is changed from 1 % to 6 % with a step of 0.5 %, the result of fire angle and frequency response in western, and northern region is shown in Fig. 5.2-5.4. Pole slip has been pointed out in the table that when northern grid power is increased by 6 %, generators in the northern region are out of step. Gaps between maximum value and minimum value for both northern grid frequency and western grid frequency are getting larger in terms of the increasing of the northern region load.

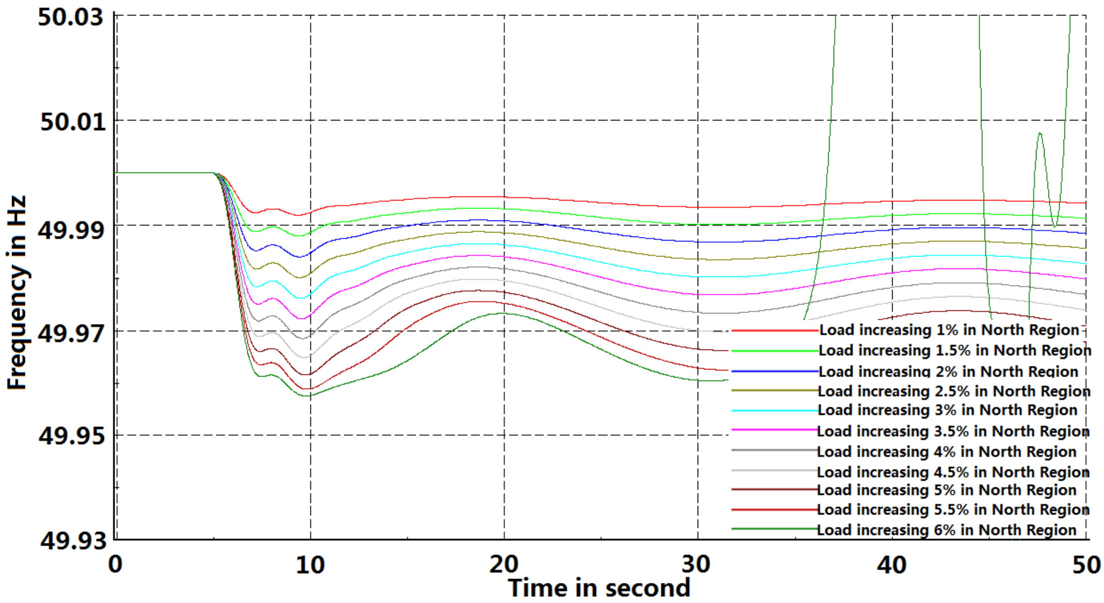


Fig. 5.2 Frequency response in Western Region when load increasing in Northern Region

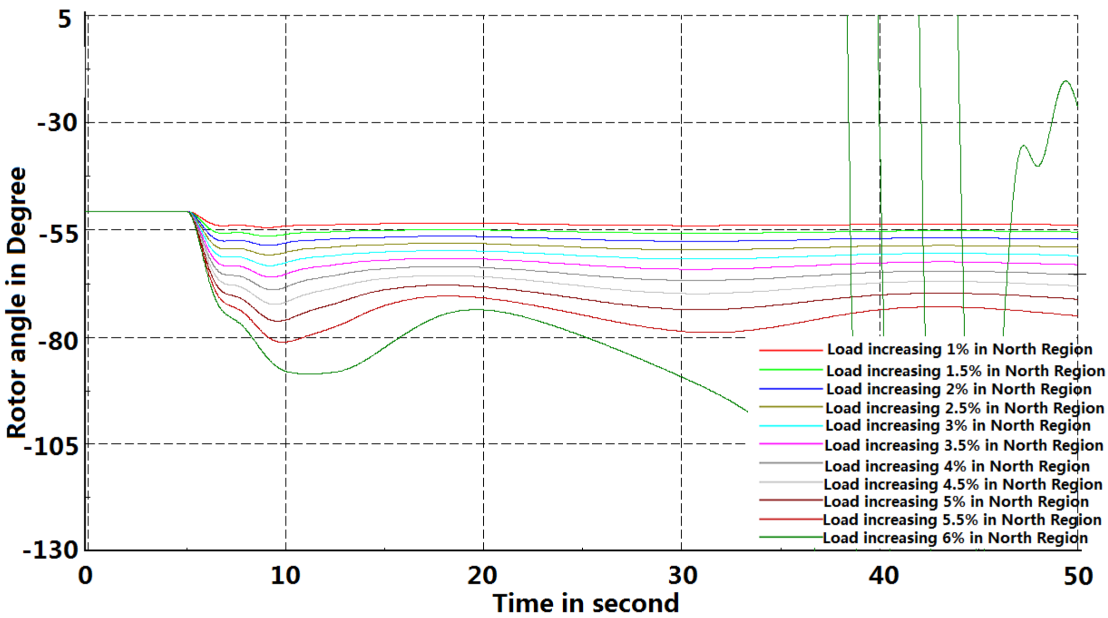


Fig. 5.3 Rotor angle of thermal generator in North with reference to western region when load increasing in Northern Region

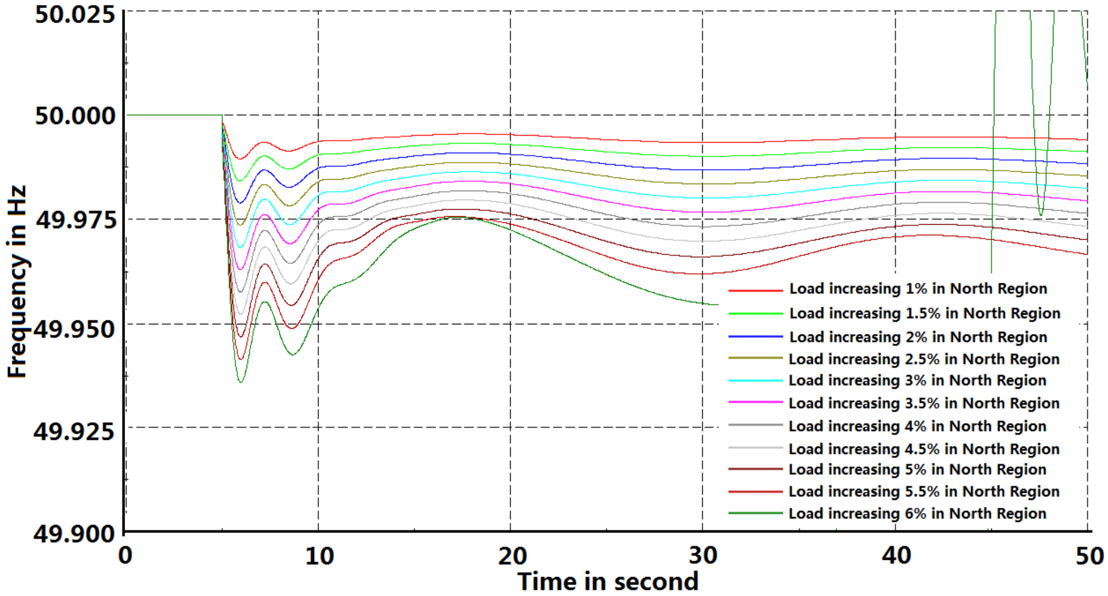


Fig. 5.4 Frequency response in Northern Region when load increasing in Northern Region

The parameters of the governors and the AVR have been taken as the default parameters available in the software. Also both hydro and thermal generation are coupled to the same bus to represent the total inflow of power from a particular region. The steady state power flow indicates that the lines between NR and WR are overloaded substantially while the lines between ER and NR and the lines between WR and ER are almost 100% loaded. The frequency of the system, however, seems to be within the permissible limits. The tripping of the Agra-Gwalior line caused an overloading of the other lines between NR and WR which resulted in the tripping of these lines. The tripping of the lines has been simulated by putting the Agra-Gwalior line out of service at t=5 seconds and Zerda-Kankroliline between NR and WR at t=5.5 seconds. The aim of the case simulation is to observe the effect of cascade tripping of the lines between the North and the West. Fig. 5.5 and Fig. 5.6 respectively illustrate the frequency of Northern Region grid and changes in rotor angle between Northern Region and Western Region when the transmission lines linking these regions trip. Sensitivity analysis for investigating the grid robustness will be done in some cases below.

According to the background and the report, loads in the Northern Region grid are usually larger than the generation, Northern Region grid need to import power from other grids. This case is studying about behaviours of the entire grids when increasing the capacity investment or injecting more spinning reserve power into the Northern Region grid.

The thermal power plant output power is increased from 100% to 125% with a step of 5%. The results of the frequency measured in the Northern Region bus are shown in Fig. 5.5. As can be seen in the diagram, Northern Region frequency fluctuation is getting smaller with the increased thermal generation output power. It is worth noting that after the transmission line was out of service, frequency in the Northern Region can be recovered to the stable range when the thermal generation output power is higher than 120%. Owing to the generation increasing in the Northern Region, it could meet such heavy load without importing energy from other grid.

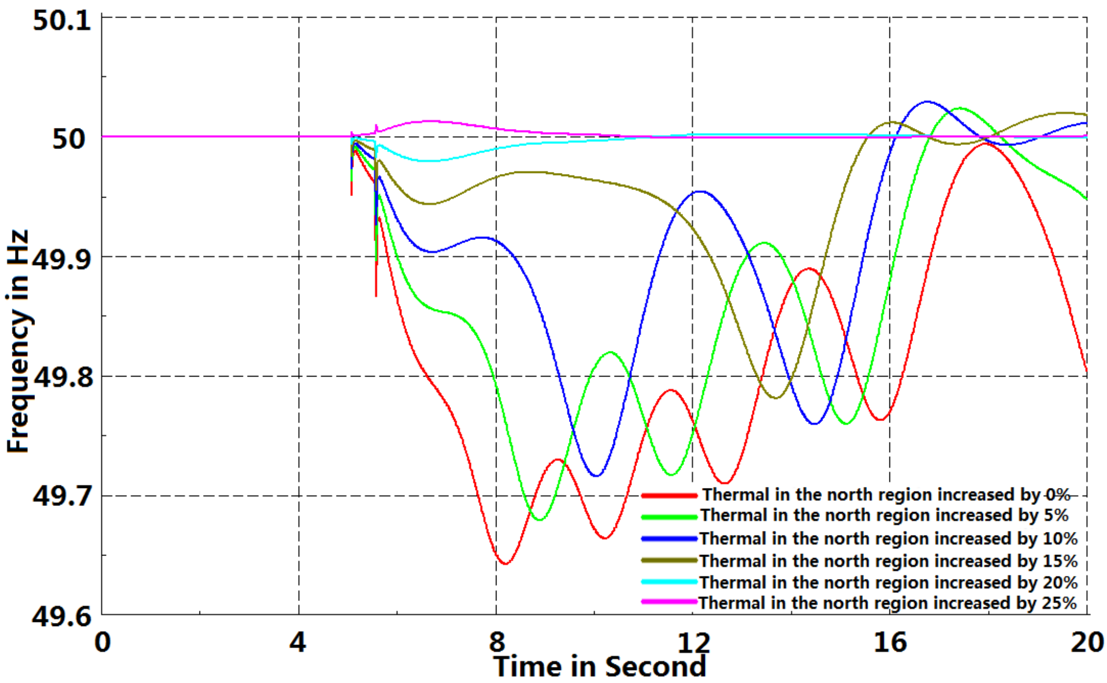


Fig. 5.5 Northern Region grid frequency response when thermal generation is changing from 0% to 25%

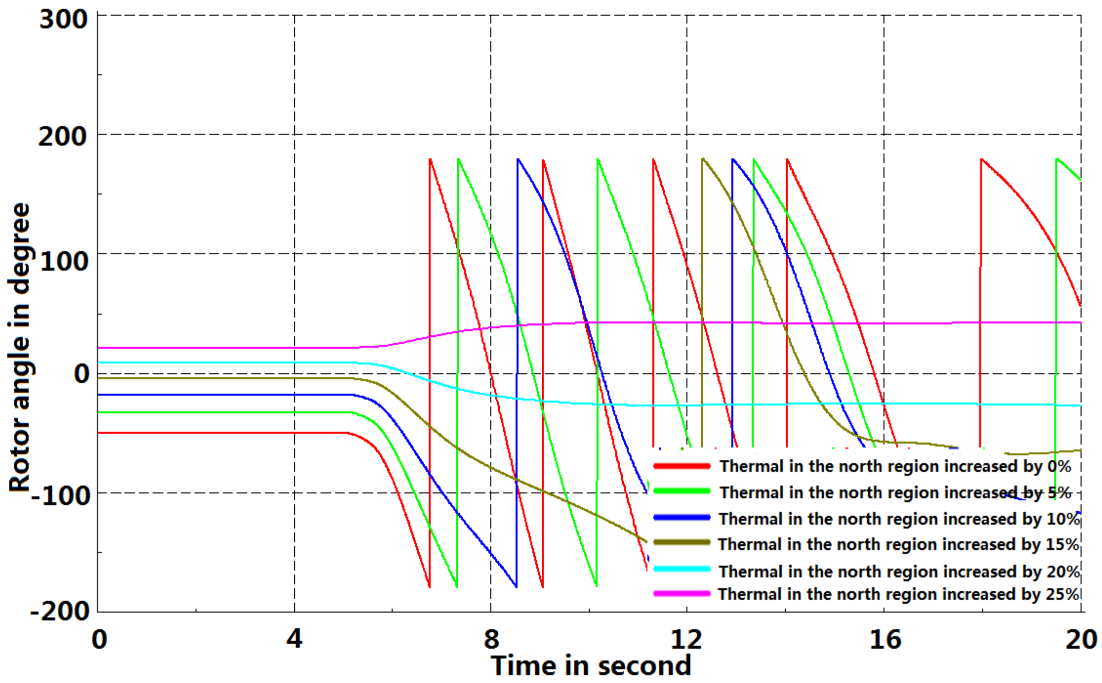


Fig. 5.6 Rotor angle of the thermal generation in northern region when thermal generation is changing from 0% to 25%

5.3 Load Shedding Scheme

Manual disconnecting load to assist the grid largely depends on with power system operators' experiences and judgments as well as the quickness which may lead to mal-operations, whereas automatic disconnecting predetermined loads may provide a fast response for load shedding schemes but requires a deliberately designed control strategies and robust control systems. In recent years, smart grid technologies have been proposed in order to meet the increasingly requirements on reliable, efficient and economic power grids. On this occasion, a large number of innovative technologies, advanced schemes and novel network architectures have been proposed to be implemented in the power systems, which are dedicated to make the power grids "smart". As demonstrated in [138-143], advanced load shedding schemes with intelligent systems and communication technologies are developed for the power system protections for power islanding events. Particularly in [141], a comprehensive intelligent load shedding scheme which is involved with online system data, equipment rating, user-defined control parameters, a knowledge base, system dependencies, predictive analysis, and other advanced technologies is designed. Also as demonstrated in [139], a supervisory control and data analysis (SCADA) system is used to achieve a comprehensive load-shedding strategy.

Nevertheless, load shedding schemes are rarely proposed for small distribution networks, which may continuously operate during its islanded mode by implementing a local load shedding scheme. In the future, distribution generations will be progressively embedded in the distribution networks which may be expected to operate in a sectional split manner with the main grid.

There is a debate on the disconnection steps of the shedding loads as well as the magnitude of the shedding loads to be executed. In [104], it is believed that three to five steps will gives the best effect in stabilizing system frequency, and the load amount for the initial steps should be less than that for later steps in order to provide the best performance. While in [105], it suggests that in the load shedding scheme the first load shedding action should disconnect half of the total loads in the system available for the shedding scheme as soon as the frequency reaches 49.5 Hz. This is to take adequate load shedding actions for preventing frequency from decreasing to an unacceptable level. Fig. 5.7 shows the frequency responses with different magnitudes of load shedding when the distribution grid as illustrated in Fig. 5.9 is subject to a loss-of-main event.

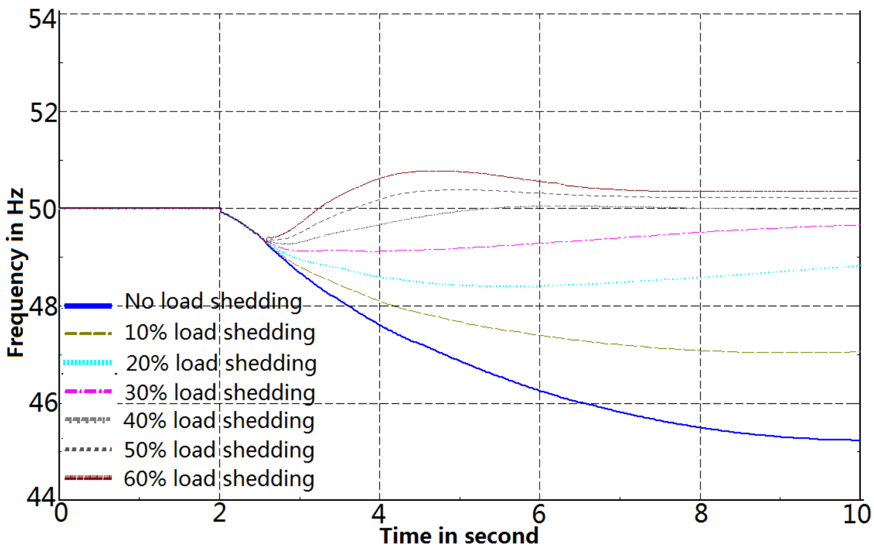


Fig. 5.7 Frequency responses with different magnitudes of load shedding when the grid is subject to a loss-of-main event with system frequency decreased down to 49Hz

5.3.1 Power System Behaviour under Disturbances

For a single generator, the machine motion can be represented by the well-known swing equation as follows:

$$\Delta P = P_m - P_e = \frac{2H}{f_n}\frac{df}{dt} \tag{5.1}$$

Where P_m is the mechanical power of the synchronous machine in per unit, P_e is the electrical power in per unit, ΔP is the power difference between the generator mechanical power and electrical power. H is the inertia constant, which is the ratio of the kinetic energy at rated speed and the machine apparent power. Generally, the unit of inertia constant is identified as seconds. However, in some textbooks, it claims that there is no unit for the inertia constant since the unit of kinetic energy and the apparent power are the same.

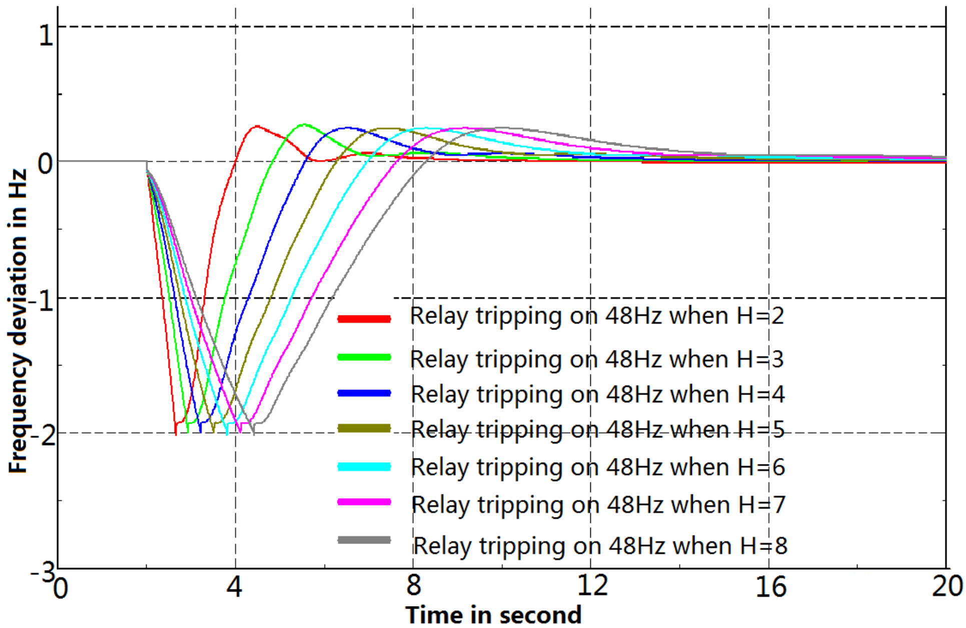


Fig. 5.8 Frequency deviation with different inertia constant when one step load shed is tripped at 48Hz

Fig. 5.8 shows the load shedding under-frequency relays trip at 48Hz with different inertia constant. f_n and f are the rated frequency and frequency in Hz respectively. For a large power system with number N of machines (for both generators and loads), a fictitious inertia centre can be defined to facilitate the analysis, and the total imbalance between generators and loads can be computed as follows [106]:

$$f_c = \sum_{i=1}^{N} H_i f_i \Big/ \sum_{i=1}^{N} H_i \tag{5.2}$$

$$\Delta P = \sum_{i=1}^{N} \Delta P_i = \frac{2\sum_{i=1}^{N} H_i}{f_i} \frac{df_c}{dt} = \frac{2}{f_n} \sum_{i=1}^{N} H_i \frac{df_c}{dt} \tag{5.3}$$

Where ΔP_i is the difference between the i^{th} generation's mechanical and electrical power. f_c is the frequency of the equivalent inertial centre.

The common practice for load shedding actions is executed when there is a distribution network disconnection from the main grid either by opening the primary circuit breaker at a transient event occurring in the grid (e.g. significant grid frequency variations).

To design a load shedding scheme, the extent of system overloading has to be identified in the first instance. However as a matter of fact, such identification may be a challenging task that both the loads and generation in the distribution network are varying all the time. Besides, power production from various DGs, especially renewables, is less predictable and controllable compared to the conventional generators with spinning reserves. This may lead to imprecise load shedding actions. Therefore, a load shedding scheme should be well designed to perform the correct extent of load curtailment and to avoid the mal-operations.

5.3.2 Magnitude of Load Shedding

The magnitude of load required to be shed is basically linked to the degree of the grid contingencies and disturbances. The resulting consequences by grid contingencies and disturbances can be measured by the dynamic imbalance between generators and demand. To determine the amount of load to be shed, a threshold value P_{thr} used to define as the maximum power imbalance which the distribution network tolerates without triggering any load shedding action in the shedding scheme. Then according to the amount of load requiring to be shed can be calculated according to the differences between real-time grid frequency and nominal grid frequency 50 Hz as follows:

$$\Delta P_{LLS} = -k_p(f - f_n) \tag{5.4}$$

Where k_p is the LLS gain obtained according to the characteristics of system effective inertia as shown in Equation (5.3).

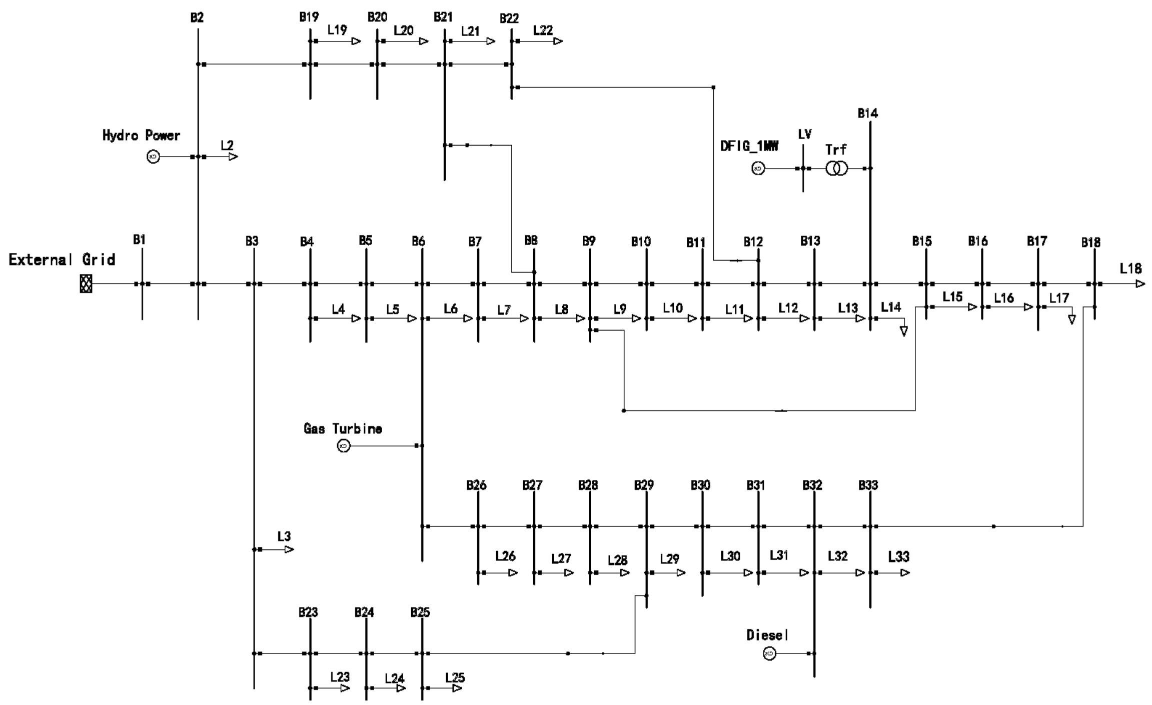


Fig. 5.9 IEEE 33-bus distribution system configuration

The amount of load required to be shed can be illustrated in Equation (5.4) which continuously estimates the appropriate load shedding amount ΔP_{LLS} according to the real-time frequency deviation (f-f_n) with a deliberately selected proportional gain k_p.

$$\sum_{i=1}^{N} P_i < \Delta P < \sum_{i=1}^{N} P_{i+1} \tag{5.5}$$

Equation (5.5) demonstrates the proposed load shedding scheme, where the estimated load shedding amount given by Equation (5.4) continuously decides the load available for the scheme with priorities i (the higher i is, the less priority the corresponding load has in the load shedding scheme). When the estimated load amount reaches the threshold of a specific load value, this load should be tripped to fulfill the scheme requirement. For example, the 0.2MW single load with priority of i=1 has to be tripped off when ΔP_{LLS} is accumulated to be 0.2MW due to a network disturbance, while the second single 0.3MW load with priority i=2 has to be tripped off when it is increased up to 0.5MW (0.2MW+0.3MW), and the rest can be done in the same manner.

5.3.3 Load Disconnection

The load disconnection order should be done in an optimal manner where the adequate discriminations for the loads available for the proposed LLS are to cover the maximum frequency drop. For instance, the LLS in the following case study section covers the operational frequency from 48 to 49 Hz. The frequency above 49 Hz should not trigger the load shedding action, whereas the load shedding actions only take place between 48 Hz and 49 Hz. Frequency below 48 Hz as a severe case is not liable to the proposed LLS as the power system could be compensated immediately (e.g. generator spinning reserve to restore the system frequency) and protected by other means (e.g. generator under-frequency and over-current protections).

5.3.4 LLS Relay Operating Delay Impact

By taking the action of LLS, the distribution network frequency may still fall further to a lower value. This is because there are various delays associated with signal data transmission time, signal receiving and processing delays, and opening time period of circuit breakers at load terminals. A high performance communication system as well as robust load circuit breakers is preferable for the proposed LLS scheme. According to [107], the nominal range of relay tripping time period using telecommunications is between 5ms and 40ms.

5.3.5 Case Study

The load shedding scheme is studied with an IEEE 12.66kV 33-Bus distribution system

[108] modelled by DIgSILENT PowerFactory, and system generator data shown in Appendix II. In this meshed distribution network, 5 primary circuit switches interconnect the networks between busbar B22 and B12, B8 and B21, B9 and B15, and B18 and B33 respectively. 4 generators which are a hydro powered generator, gas powered, diesel generator and double-fed-induction-generator based (DFIG) small wind farm are connected with the distribution network in busbar B2, B6, B32 and B14 respectively.

The loads in this distribution network available for the proposed LLS scheme include L2, L11, L23, L24, L25, L30 and L32, which occupy 40% of the total load in this distribution network. The following three case studies are to examine the performance of the proposed LLS scheme at loss-of-main event caused by a fault event occurring on B2 at t=2s, after which the circuit breaker B1 opens the grid connection immediately to result in a power island for the distribution network. As the distribution system initially imports extra power from the transmission grid, the disconnection of the breaker results local generation less than the total load in the temporarily islanded distribution system and the frequency begins to fall down before the generator governors take effect.

Fig. 5.10 illustrates the effect of disconnecting the loads available in the LLS scheme (40% of the total) for one time to response the frequency deviation. It can be seen that the protective relay operates at an earlier stage of 49.3 Hz rather than 49 Hz, 48.5 Hz and 48 Hz gives the best effect of preventing the frequency from falling low. This coincides with the claim as referred in [105] and concludes that the action of the LLS should be taken the earlier the better.

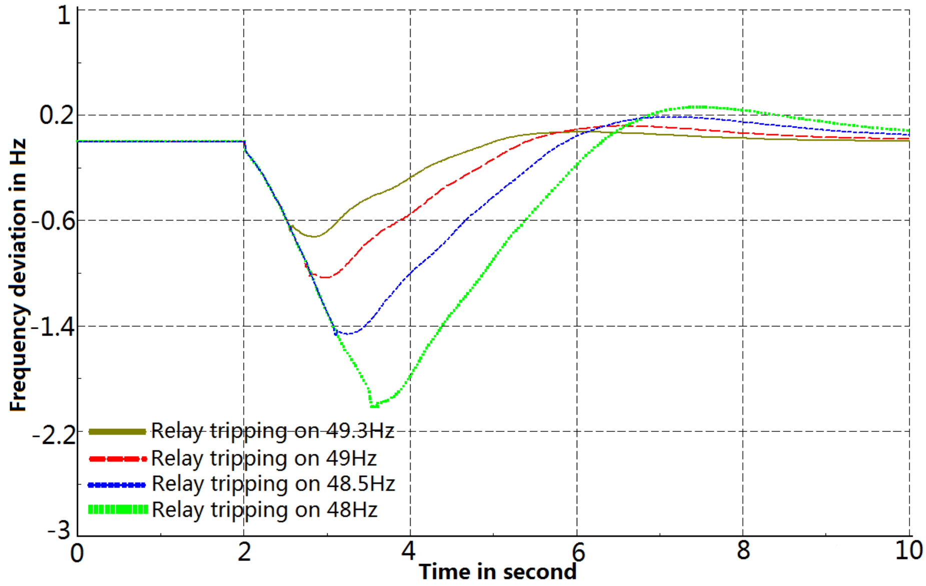


Fig. 5.10 One step load shedding for 40% when relays set to 48Hz, 48.5Hz, 49Hz and 49.3Hz

The control delays which are demonstrated in Section IV C are initially studied in this case in terms of the lowest frequency deviation and restoration speed. It is obvious from Fig. 5.11 that the lower the LLS control delays are, the better performance can be resulted.

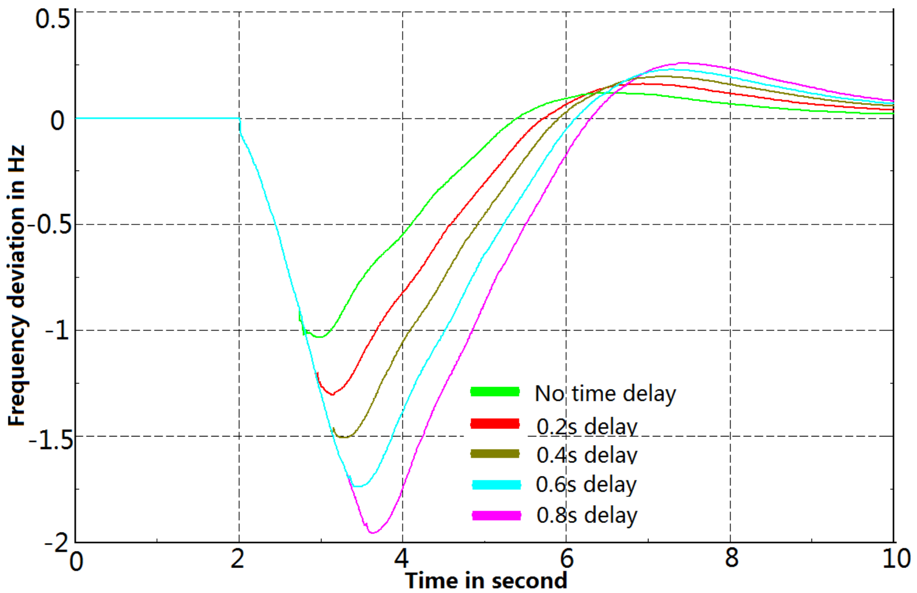


Fig. 5.11 Frequency deviation with different time delay when one step load shed is tripped at 49 Hz

As the amount of loads to be shed cannot be determined at the initial drop of the system frequency, the discrete loads have to be disconnected by the scheme one after another in order to give appropriate system support. Four scenarios on load disconnection sequences are designed as shown in Table. 5.3 for the proposed LLS in a way as demonstrated above. Due to the fault, the frequency begins to drop to a level which is below the top threshold of 49 Hz to trigger the load shedding action for specific load(s) which is designated to be first disconnected (e.g. L11 and L24 for Scenario I). Shortly the frequency drops to a new lower threshold of 48.8 Hz to trigger the second load (e.g. L25 for Scenario I) and 48.6 Hz to trigger the third (e.g. L32 for Scenario I) and so on. The simulation results as presented in Fig. 5.11 examine the optimal scenarios for disconnecting specific loads in the load shedding steps performed in different time intervals. The frequency to be covered by the proposed LLS ranges from 48Hz to 49Hz with 0.2Hz discrimination between two adjacent steps. This is to investigate whether the best performance is resulted by smaller load disconnection and then higher load disconnection or in a reversed manner.

Tripping threshold	**Scenario I**	**Scenario II**	**Scenario III**	**Scenario IV**
49 Hz	0.48 MW (L11 & L24)	0.09 MW (L23)	0.48 MW (L11 & L24)	0.1 MW (L2)
48.8 Hz	0.42 MW (L25)	0.1 MW (L2)	0.21 MW (L32)	0.21 MW (L32)
48.6 Hz	0.21 MW (L32)	0.2 MW (L30)	0.1 MW (L2)	0.48 MW (L11 & L24)
48.4 Hz	0.2 MW (L30)	0.21 MW (L32)	0.09 MW (L23)	0.42 MW (L25)
48.2 Hz	0.1 MW (L2)	0.42 MW (L25)	0.2 MW (L30)	0.2 MW (L30)
48 Hz	0.09 MW (L23)	0.48 MW (L11 & L24)	0.42 MW (L25)	0.09 MW (L23)

Table. 5.3 4 scenarios for the load selection

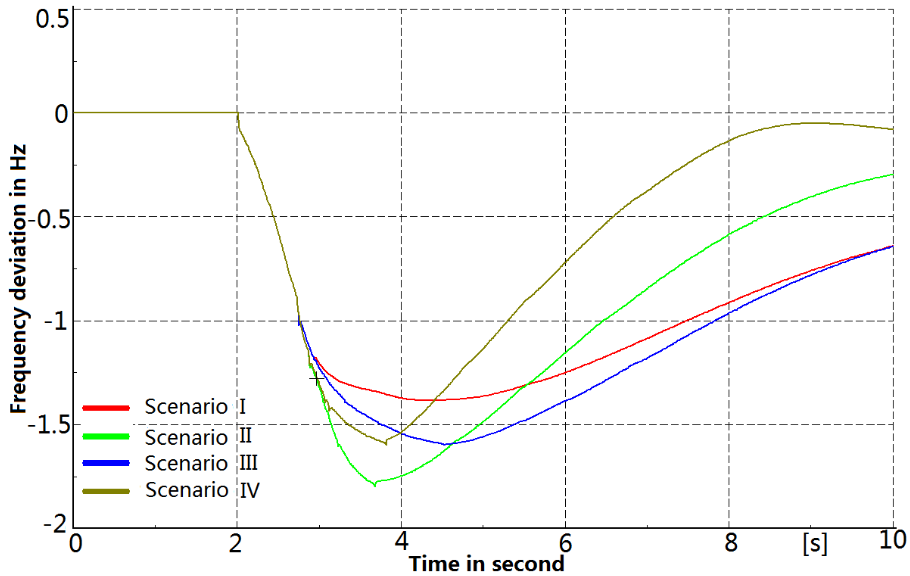


Fig. 5.12 Frequency derivation under 4 sequences

As it can be observed in Fig. 5.12, Scenario I which trigger the load amount from largest to smallest results in the lowest frequency drop, whereas Scenarios IV which disconnects the largest load in the middle range of the frequency 48.6Hz and 48.4Hz gives the fastest frequency restoration speed. Scenarios II and III do not have outstanding advantages compared to Scenarios I and IV.

5.4 Conclusion

The chapter gives a brief event sequence of the disturbance that occurred on 30th and 31st of July 2012 in the India power grid. Reasons for the disturbance have been discussed. Grid infrastructure, which is applying both AC and DC transmission lines to connect regions, is one of the main problems for these disturbances. The generation production is dependent too much on the weather condition, and the power cannot be restored within a short time. Some sensitivity analysis has been done to investigate the level of the disturbance affected the grid when power generated in the North and wind penetration level in the Western Region grid is increased. Increasing the power output in the Northern Region is a simple solution when the load is increased in the Northern Region grid as then the transmission line linking the regions is not overloaded. Wind generation in the Western Region grid cannot supply enough energy from the Western-Eastern-Northern area when the lines between Northern Region and Western Region are out of service. It can be foreseen that a coordinated dispatch schedule is essential for a secure electricity supply. From the blackout, it also suggests that increasing rate of generation capacity is lacking behind the economy development rate. It is important to plan the electricity infrastructures at least few years in advance.

In addition, this chapter proposes a distribution load shedding (LLS) scheme for system stability improvement. The proposed LLS scheme computes the amount of load to be connected in real time based on the system frequency deviation and the characteristic of the system effective inertia. The discrete loads available in the distribution network are then disconnected by the real-time commands of the LLS scheme. The LLS scheme is validated in an IEEE 33-bus distribution network model and its system advantages in terms of reducing frequency deviations and promoting frequency storage speed are verified in three case studies. It can be proved from the simulation that the proposed LLS is able to prevent the system frequency from falling too low and quickly restore the frequency to the nominal value. In the meanwhile, it is interesting to find that shedding the largest loads in the first stage of load shedding actions results in a lowest frequency deviation whereas shedding the largest loads in the middle range of covered frequency results in a fastest frequency recovery speed. Various control delays of the proposed LLS scheme and different tripping thresholds for the LLS scheme are also studied in the simulation in terms of the impact on the performance of the proposed LLS scheme.

It can be concluded that the proposed LLS scheme is an effective automatic load shedding measure to survive the distribution network at transient system power imbalances and provides economic and reliability advantages to distribution network operators with an uninterruptable solution for system operations.

Chapter 6

Decision Support Systems for Smart Grid Implementation

6.1 Introduction

Decision Support System (DSS) is an information system, which is based on interactive computer to support decision making in planning, management, operations for power utility, business and organizations. The rapid changes on decision making, which cannot be easily identified, can be assisted by communication technologies and computer-based system compiling information gathered from a wide range of resources like raw data, documents, experts' experience and knowledge, and business models [85]. Originally, decision support concept came from the theoretical studies of decision making for organizations by Carnegie Institute of Technology and technical practice on interactive computer systems by Massachusetts Institute of Technology in the 60s [85]. In 70s, 'decision support' began to grow among academia, and the first paper appeared in the conference and journal at that time. The DSSs have been introduced to China in 80s. In the earlier 1990s, DSS applications are spread into different areas through data warehousing and on-line analytical processes. Since middle 1990s, DSS starts to apply web-based analytical process [86]. Recently, with the development of cloud computing technology, DSS based on cloud computing technology has been proposed [87-89]. Throughout the development of DSS in the recent 30 years, there are more than 20 methods to implement the DSS. It is difficult to distinguish the best principle to solve decision making problems from others since proposed DSS systems are usually project-oriented. DSS has been involved in a plenty of technical areas which include transportation, electricity and resource dispatch and so on.

In 2004, IEEE published a guide for electric power distribution reliability indices, which is used for power system planning and operation. In realistic project, a decision support system is required for assisting governments or network planners to make critical decisions. In power system planning, reliability and security are the essential input for a decision support system.

6.2 Decision Support System Requirements

A DSS involves a number of scientific areas such as computer science, simulation technology, software programming and cognitive science and so on. Basically, there are three types of problems for decision making, namely structured, unstructured and semi-structured. Structured problems can be solved by standard solution techniques with clearly specified procedures to make a decision. Whereas the procedures of unstructured problems are unspecified in advance, and most of the decisions procedures are followed only once. In semi-structured problems, procedures for decision making can be specified but the optimal decision making cannot be verified. For different levels in organizations and business companies, the objectives of the DSSs are not the same. There are three different levels in companies and organizations. Firstly, strategic planning, including long term policies planning, is used for governing resource acquisition, utilization and disposition. Secondly, management control ensures the resources can be obtained and used effectively and efficiently to achieve the organization objectives. Finally, operation control ensures effective progress.

6.2.1 DSS Functionalities

In general, the DSS is project-oriented and the functionality is always determined by system architecture. With different architectures, DSS functionalities can be summarized as follows:

- Collecting, managing and providing the organization external information related to decision questions in domains like policy, economy, society, environment, market and technology.
- Collecting, managing and providing the organization internal information

related to decision questions in domains like order request, storage status, production capability and finance.

- Collecting, managing and providing the feedback of each alternative decision execution such as contract processing, material supply plan, and production implementation.
- Having a certain capability of data storage and managing mathematical models which are closely linked with decision making.
- Having a certain capability of storing and providing frequently-used mathematical methodology and algorithm, such as regression analysis, linear programming, and computational intelligence models.
- Having a certain capability of easily adding and modifying data, model and algorithm.
- Having a certain capability of flexibly processing, collecting, analyzing and forecasting data through models and methodology, thereby generating general message and projections.
- Providing a friendly interface to communicate between man and machine, and functionality of graphic output. Also, there is a capability to meet the request of stochastic data query to answer some "what…if…" questions and so on.
- Providing favourable functionality of data communication in order to ensure that the required data can be collected, processed and delivered to the user in time.

To include all the functionalities above, a typical DSS architecture should have an optimization toolbox, an on-line analytical processing toolbox, a data mining toolbox, a transaction processing system and a database as illustrated in Fig. 6.1. Users can generate problems to the DSS and obtain the analyzed answers from the user interface. And a data mining toolbox can find the required data in large database where data related to the problem are located.

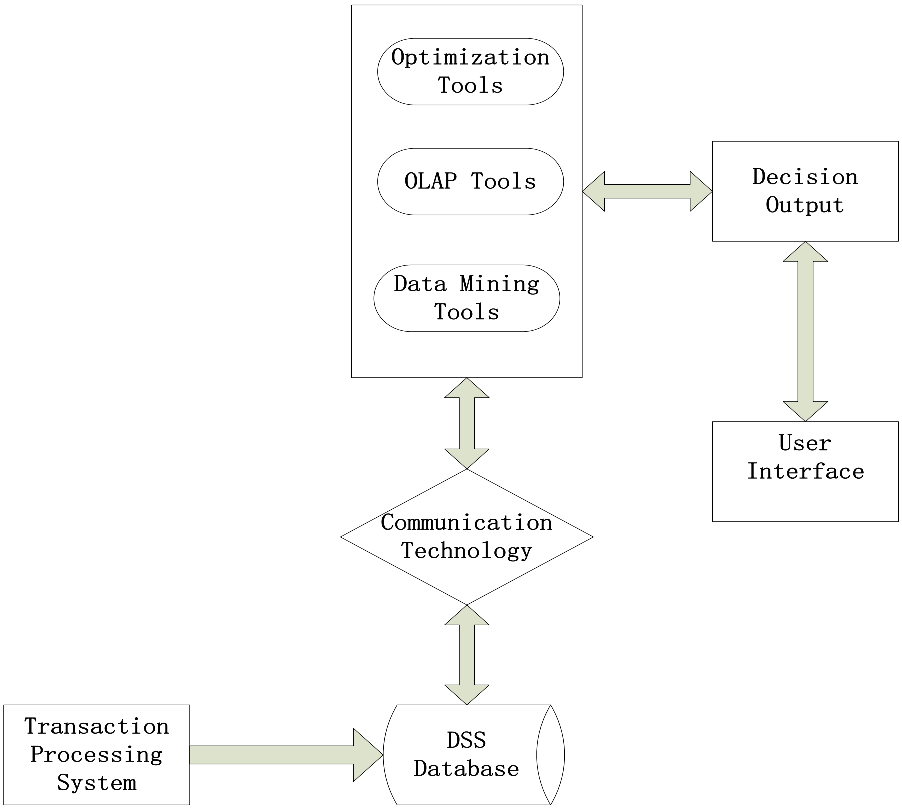


Fig. 6.1 A typical structure of DSS

6.2.2 Requirements for DSS

In general, there are five types of DSSs to achieve a decision making, namely, communication-driven DSS, data-driven DSS, document-driven DSS, knowledge-driven DSS and model-driven DSS [90]. No matter what kind of DSS is applied to a certain project, there are some generic requirements which are listed as follows:

- Be compatible with as many decision processes and structures as possible.
- Should have an interactive interface and friendly to users.
- Can be accessed and controlled by users.
- Allow end users to develop DSS without difficult.
- Support modeling, data access and analysis.
- Have an ability to work in both standalone and web-based environment.

DSS has been widely used in many areas, such as port planning, planning of the workload, oil refineries, traffic control and driver safety, even a small case for helicopter landing have been involved with DSS[144].

6.3 Past, Present and Future

This section will give critical discussions about the development of Decision Support Systems. Also the promoting trend for future DSS system will be investigated.

6.3.1 Past

From 1970s to 1980s, comprehensive framework had been proposed to integrate with knowledge-based systems. The proposed DSS usually concentrates on the structure improvement during that time.

More domain-independent and user-friendly systems were developed by exploiting expert systems design in reference [150]. The proposed DSS structure as shown in Fig. 6.2 was called XDSS. The knowledge base consisted of 5 areas, namely, domain, data dictionary, model, report generator and graphics knowledge. Each component in the architecture was maintained by experts. The domain knowledge would comprehend the issue that was defined by users and presented in the XDSS software. Then, the issue would be separated into sub-issues so that the relative knowledge base component could be adopted. Finally, a solution would come out through all sub-issues integrated with XDSS software.

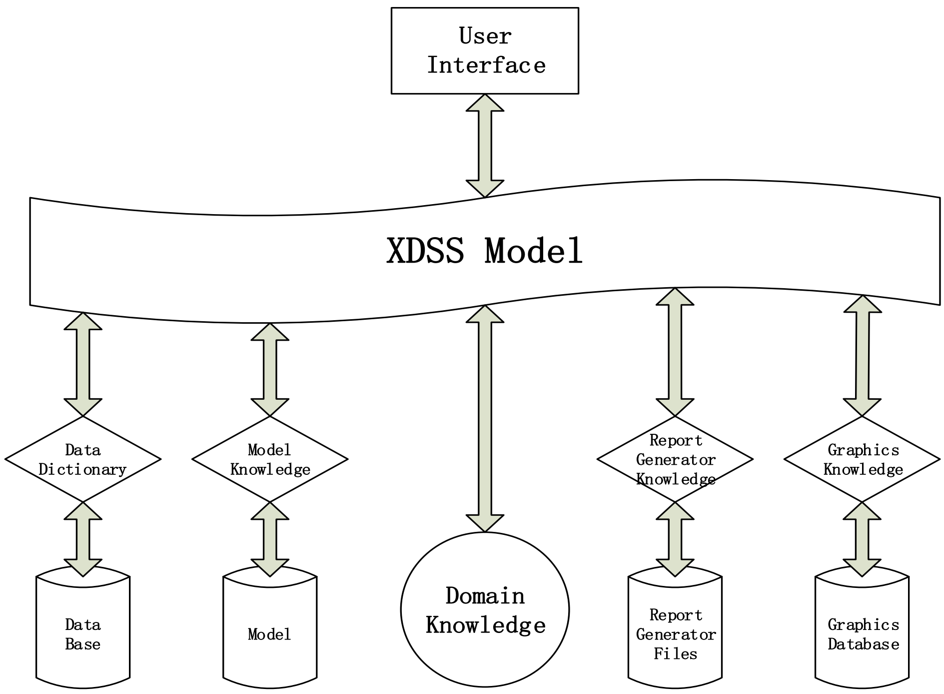


Fig. 6.2 An XDSS approach [150]

A flexible logic-based DSS was proposed in reference [151]. The model developed by the authors adopts intentional database (IDB) for logic-based system. It means that the user could store a number of rules. However, there is another extensional database (EDB) for storing the actual data. Two kinds of models, namely, coded models and defined models, had been applied to the DSS system in order to reduce workload. The author believed that the DSS model achieved considerable development, and was used for design architectures based on IBM's top down approach so on.

Model management evolution was divided into 4 generations and has been described in [152]. Fig. 6.3 demonstrated these 4 generations for DSS development. The author pointed out the advantages of the last generation models are:

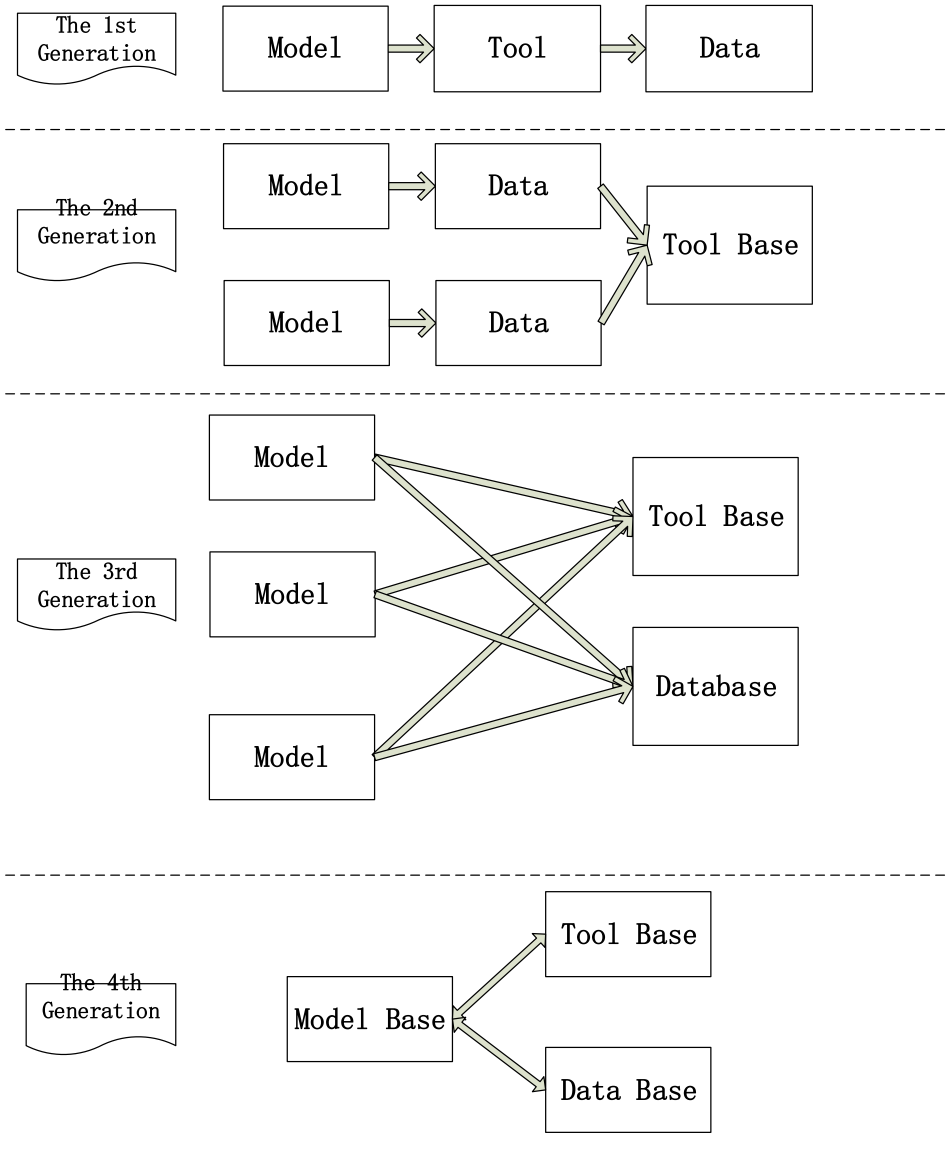


Fig. 6.3 4 Generations for DSS development [152]

1. The system could automatically integrate the model with data in order to reduce the programming redundancy.
2. Authorized user can access the model without many problems since many DSS systems were built in a distributed environment.
3. High compatibility enables the model management system to achieve more flexibility for DSS. Accommodating new database management system, model management system can reduce the impact of changing database models.

In reference [153], the framework of DSS for distributed computer system has been provided. Optional solutions were explored systematically by this methodology when objectives conflict with each other.

Three conceptual steps were developed to assess the DSS impact on organizational elements in reference [154]. The first step is to establish the DSS to identify the real consequence, at least in principle. The second step tries to recognize the subsets of the real consequence. And the last step is to evaluate both the recognized consequence and predicted consequence. The authors also discovered that the DSS could serve more when linking to an information network with all organizational centers connected together. Integrating with personal and organizational knowledge based systems is the trend pointed out by the authors.

A framework of DSS for Computer-Integrated manufacturing has been discussed in reference [155]. In this survey, an information processing approach has been adopted to study the manufacturing environment. Some possible factors for designing the DSS system, such as the role of problem formulation and specification (involving goal setting), have been discussed in reference [156]. In 1985, a DSS system for global decision-making was reported. It summarized that the DSS would achieve more alternatives and better co-ordination [157]. Inquiry systems can be implemented for ill-structured organizational problems and developing information systems. Strategies for creating a cooperative communication between expert system database and deduction have been outlined in reference [158]. There were many research papers debating on the appropriate mechanisms for coupling deduction and data component for an expert system. In reference [144], the authors proposed a new perspective in decision support system for port planning. A 2-layer information management system architecture was shown in Fig. 6.4 to illustrate a conceptual distance from the logical to physical data structure.

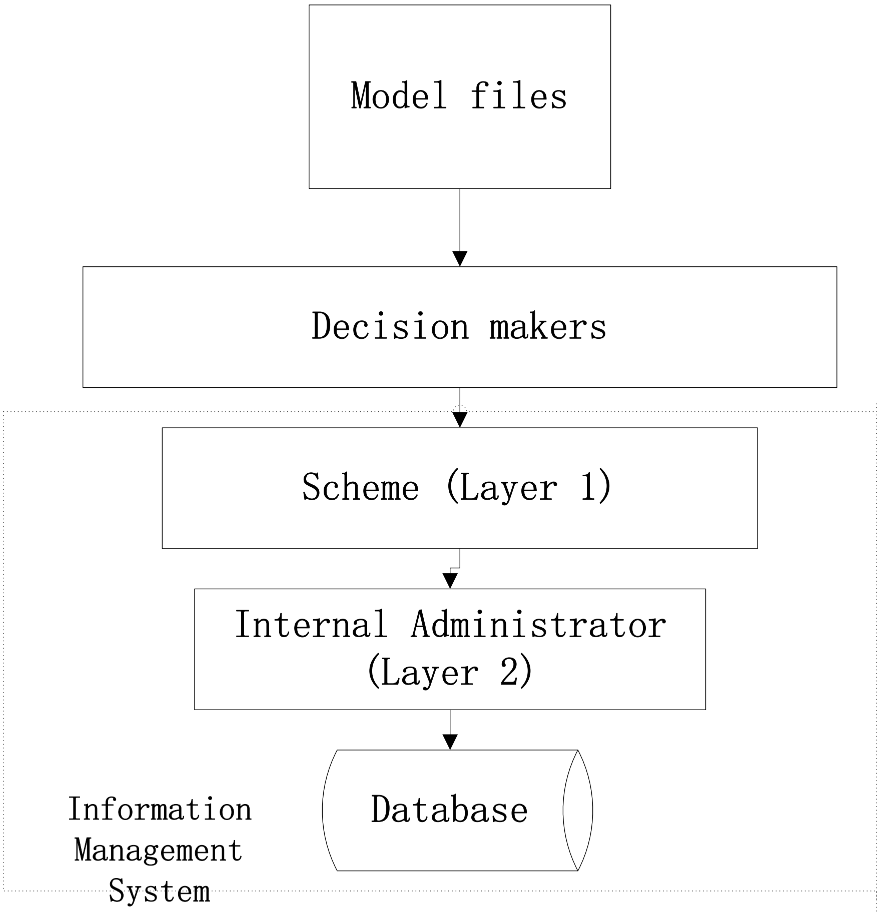


Fig. 6.4 DSS with 2-layer information management system [144]

6.3.2 Present

Around 2010s, DSS researchers began to pay attention to the multi-criteria decision making and dynamic interaction within a DSS. An increasing number of people realized that classical DSS cannot afford the dynamic changes in decision making of the real world. Besides, DSS frameworks proposed during that period also tried to minimize project risk.

Reference [146] proposed a new framework for dynamic multi-criteria decision support system. Classical multi-criteria decision making model would be used to find all available options. The proposed one introduced a dynamic environment where real world decision is taking place. It is worth noting that the versatile framework chooses a retention policy for historical options and can be widely used in many applications. For example helicopter landing was provided to illustrate the dynamic DSS system behaviour.

In project management field there are uncertainties & constraints, risks in projects and risk interaction need to be managed. A risk network model for decision support system in managing project risk was shown in Fig. 6.5 [159]. The innovation of this framework is that the managerial suggestions can be modified, completed and refined, and also the managers can provide their knowledge to analyze the propagation behaviour in the network.

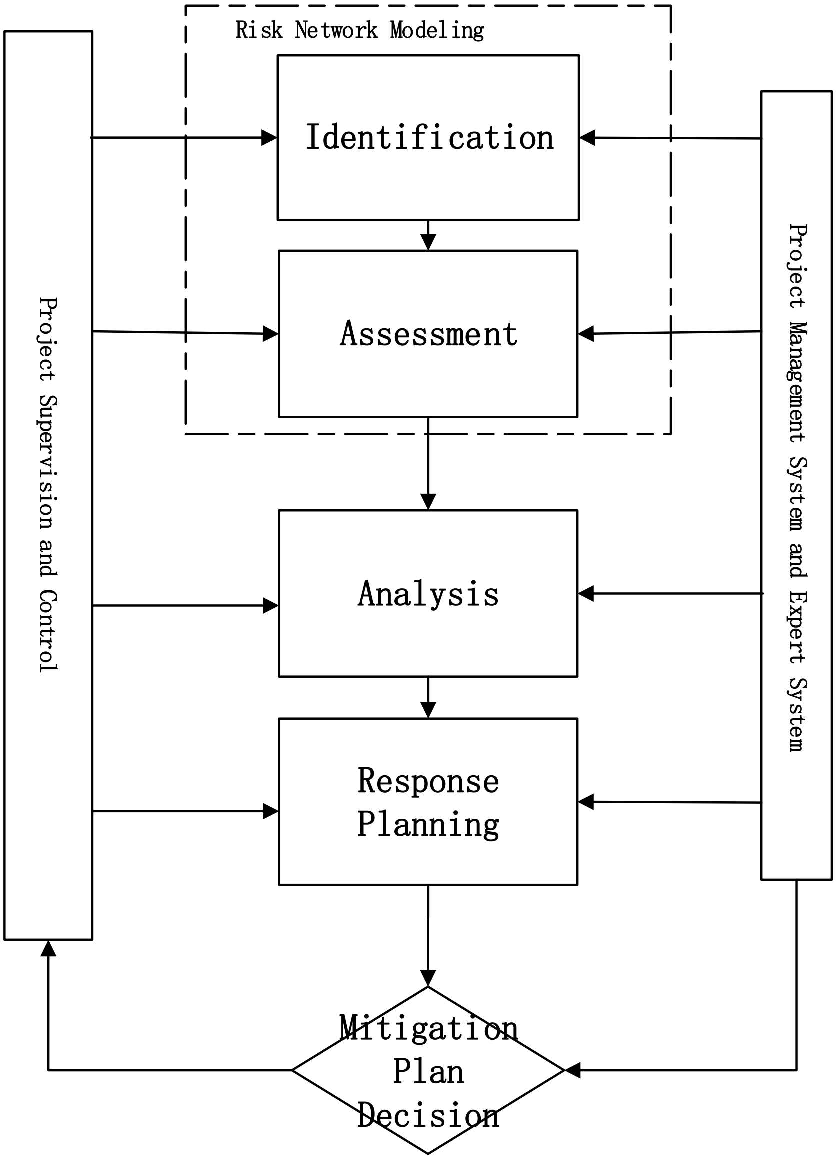


Fig. 6.5 DSS architecture for project risk management [159]

A collaborative pattern mining for distributed information systems was described in reference [160]. Three frameworks have been compared with each other, and the advantage of the collaborative pattern (CLAP) has been listed. Self-contained mining framework is not efficient and feasible for fulfilling many objectives. CLAP was proposed to solve these problems by using communication network to exchange messages and database for information mining.

The authors in reference [147] added a dashboard between the decisions models and decision makers as illustrated in Fig. 6.6 to consider both business and engineering decision variables, which are sometimes conflict with each other. To carry out sub-optimization for decision making, 2-stage decision based on optimization and agent-based models had been proposed. The first stage is to solve a multi-objective robust optimization problem by simulating integrated business and engineer models. The variables obtained in stage one would transfer to the next stage and process iterates until set criteria reached.

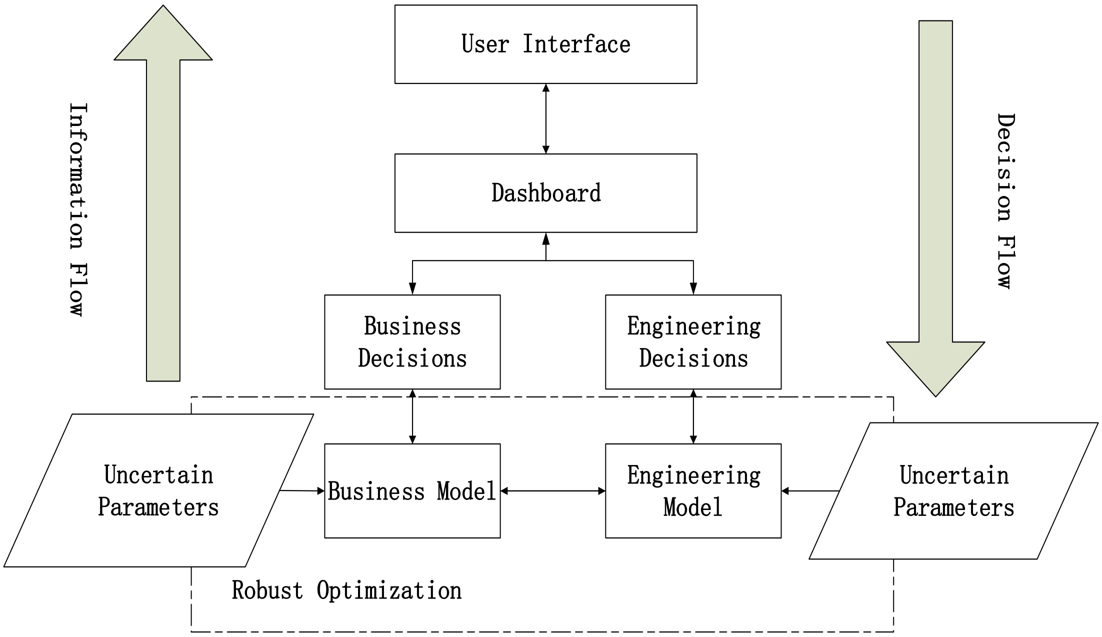


Fig. 6.6 Business and engineering decision model with dashboard [147]

A measurement approach was derived to quantify dynamic interaction in knowledge based systems (KBS) based on control theory to examine the improvements [161]. The authors believed that the decision maker's initial attitude might affect the actual dynamic interaction.

Neural networks were proposed in reference [162] for decision making. To improve the decision making accuracy and reduce the misclassification, the authors have made comparisons among different cost index to investigate the best convergence. The final results made a clear picture that increasing number of cost index may lead to slower converging for related cost-sensitive decision.

A text-based decision support system was proposed for financial sequence prediction in reference [163]. In this system, event sequences can be extracted from shallow text patterns and a classifier-based inference engine was applied for predicting the possibility of events occurring.

A shallow language model was provided to delete the incorrectly information. Also, the DSS system could verify the priority of event occurrence with both explicit and implicit knowledge participation during predicting. The other contribution was the inference engine, which provided a robust and efficient means to predict financial texts. These contributions made the prediction accuracy of the model improved by 7% for un-seen data.

6.3.3 Future

Cloud computing was proposed for some future DSS systems for database and service sharing. Services like computation, data access, software applications and so on need to be delivered to the client. There are three service models comprising together to form a cloud computation environment, namely software as a service (SaaS), platform as a service (PaaS) and infrastructure as a service (IaaS). Fig. 6.7 shows the DSS architecture with cloud computing technology.

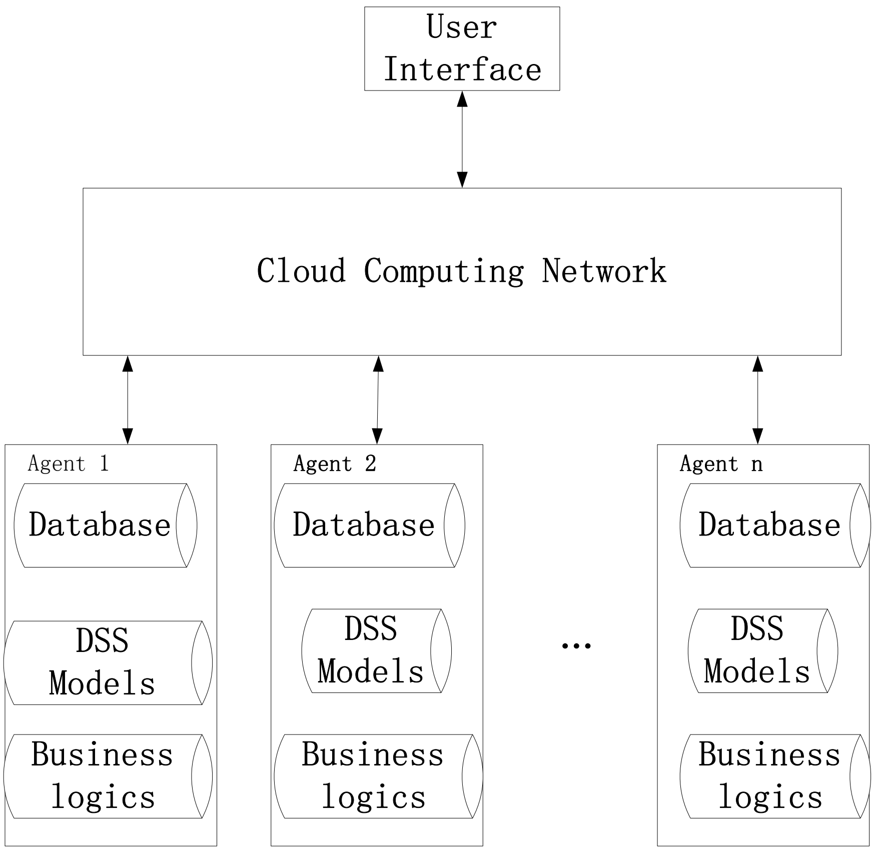


Fig. 6.7 DSS structure with cloud-computing technology

A management system for traffic control applied agent-base was described in reference [148]. 4-layer framework, namely, platform, application, unified and fabric layers have been proposed in cloud computing.

In reference [164], authors proposed a DSS architecture based upon cloud computing in order to meet the requirement of increasing demands of the information. Cloud is classified into three types: private cloud, public cloud and internal cloud. The aim of the cloud computation application in DSS is to reduce the complexity of managing the technology. Comparing with previous DSS systems, another benefit for applying cloud computing is that the demand can be scaled, the data centre can be streamlined, business processes can be improved and starting cost can be minimized. The authors in reference [149] demonstrated the requirements for cloud-based DSS system. 6 activities and proposed DSS framework and design clusters for traffic control has been described.

To implement DSS in a better way, communication technologies become more and more important to achieve data mining. As an important trend for communication development, cloud computing technologies will be involved for decision making. The past to the future trend has been discussed in Table.6.1.

Past	**Present**	**Future**
Concentrating on architecture development: 1. Applying XDSS framework 2. Integrating model management with data management 3. Employing distributed computer system 4. Data inference for DSS 5. Aggregating data 6. Expert system for accessing specific declaration knowledge	Concentrating on dynamic interaction and multi-criteria decisions: 1. Risk network model for project risk management 2. Data mining methodology such as SQLP, PALP and CLAP 3. Agent-based approach 4. Optimization methodology 5. Textual information data	Concentrating on data sharing and information acquisition: 1. Cloud computing technology 2. Agent-based systems 3. Security 4. Integration with intelligent methods, such as SVM, swarm optimization and evolutionary computing

Table. 6.1 DSS approaches and architectures from the past to the future

As mention in 6.2, Smart Grid Decision support systems need to establish a database for system estimation and further evaluation. To achieve the implementation of smart grid, plenty of models and scenarios are necessary to consist in the knowledge database. Here a stability scenarios and indices to evaluate the system reliability are talked.

6.4 Power System Stability Scenarios

Variability and uncertainty are the inherent characteristics of the power system. Many countries' national laboratories have studied wind and solar penetration to achieve large percentage generation capacity to reduce carbon emission and air pollution. There could be a stability problem when many wind turbines and PV farms integrated into power grid. The penetration level of a power system is closely linked with how much flexible generation capacities installation in the network. To deal with intermittence of wind and solar energy generation, these generators must have the capability of fast response. Various scenarios will be investigated to demonstrate the potential in maximizing the use of variable renewables. Naturally, for a full scale project to be established, it is also required to carry out a cost-benefit analysis. But in terms of technology, it shows that there are many challenges and our fellow engineers will have a huge opportunity to make contributions.

In addition to renewable connection scenario, load shedding strategy, which is talked in the previous chapter, is preventing power systems from suffering frequency instability based on the real-time data frequency relays. As power system loads are varying all the time, Load shedding strategies are facing a challenge to adequately and accurately take shedding actions. On the generation side, increasingly non-dispatchable and inflexible renewable power generations being integrated to the system complicates generation predictions and results in frequent power imbalance. If the load shedding is not operating properly, the whole grid is exposed to a dangerous situation, as the frequency will drop to a low level which may destroy the generators, especially the steam turbine. And it may be followed by serious blackout. Here a network model with renewable penetration is considered to evaluate the stability scenarios.

6.4.1 Renewable and Solar Penetration Investigation

Renewable energy sources such as wind, solar and hydro are regarded as one of the best solutions to reduce carbon emission under the increase in power demand. Climate change which is mainly caused by those power plants burning fossil fuels such as coal, oil and gas, naturally, it is a trend to develop renewable energies to substitute fossil fuels. However, renewable energies are intermittent, and difficult to forecast precisely. Countries around the world have concentrated in renewable energy generation for

decades. Renewable energies are growing rapidly and still increasing dramatically in the near future. A target has been set by European Wind Energy Association (EWEA) to generate 23%electric power from wind by 2030 [94]. Wind generation penetration in Denmark has met the target around 20% in2006, and there is a suggestion on that to set the target to 35%in 2015, and 50% in 2030. Spain set wind penetration target to
15% in 2011, which equals to 20GW installation capacity. And will reach the target around 20% in wind and 4% in Solar PV in 2020, however, the penetration in the year of 2004 in Spain is only about 6.5% [95, 96].

How much renewable energy can be penetrated into the power system network depends on the generation structure. Power system network with large conventional generation power plant such as coal and nuclear cannot response do not work very well with energy with intermittent characteristics. Network with hydro power generation and pumped hydro energy storage can respond quickly to varied wind energy [97]. A penetration study on wind and solar integration was made by GE Energy through the U.S. National Renewable Energy Laboratory (NREL) in May 2010. The survey is made to discuss different scenarios on wind and solar penetration from10%-30% and 1%-5% respectively [98]. Research is presenting from large time scale for one day long for unit commitment and minimum time scale from minute to minute for regulation. Because weather is changing all the time and forecasting error exists, renewable energy have variability and uncertainty. Actually, every element in power system such as loads, power lines, and generator availability has variability and uncertainty [99]. Even conventional power plant like coal fire plant and nuclear cannot avoid from uncertainty and variability. From the case study by Ernest Orlando Lawrence Berkeley National Laboratory in reference [99], the output power can be smoothed via large wind farms integration though there is uncertainty and variability in renewable energy, same happened when the load aggregating could smooth the load curve. Power quality including dynamic study caused by variability and uncertainty is a very important part for stability study.

6.4.2 Wind Energy Conversion

In general, there are two ways to represent the power performance of the wind turbine in dimensionless form. For fixed wind speed, it will use the power coefficient C_p and the tip speed ratio λ. For fixed rotor angular speed, the advance ratio J and the rotor speed power coefficient K_p are used [100].For simplicity, the first approach will be adopted in this paper. For a wind turbine of performance coefficient C_p, air density ρ, turbine swept area A and wind speed v_{wind}, the output power could be demonstrated in Equation 6.1 below:

$$P_m = C_p(\lambda, \beta)\frac{\rho \cdot A}{2} v_{wind}^3 \tag{6.1}$$

To achieve the maximum value of the output power, the wind turbine needs to be operated under maximum power coefficient C_p, which is determined by tip speed ratio λ and blade pitch angle β. Maximum C_p is achieved when the blade pitch angle β is 0. The relationship between power coefficient C_p and tip speed ratio λ when β equals to 0 is shown in Fig. 6.8 below, and the parameters are from Matlab Help, Distributed Resources (DR), and wind turbine:

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - C_3\beta - c_4\right)e^{\frac{-C_5}{\lambda_i}} + c_6\lambda \tag{6.2}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{6.3}$$

Where the coefficients are:

$$c_1 = 0.5176; c_2 = 116; c_3 = 0.4$$
$$c_4 = 5; c_5 = 21; c_6 = 0.0068$$

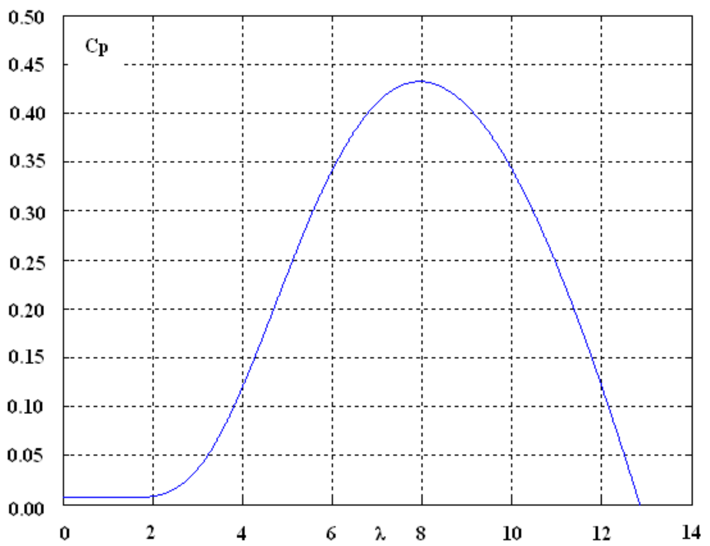


Fig. 6.8 Rotor power coefficient performance C_p against tip speed ratio λ

Basically, there is a cut-in wind speed when wind turbine is starting. When wind speed is less than 5m/s, there is no electric power generated from wind. During operation, the power generated from wind turbine has relationship with wind speed cubed. After generator reaching its rated power, output power keep constant even though wind speed is increasing. Wind generators will be shut down when wind speed exceeds25 m/s as the wind is too strong, and damage will be caused [95]. Fig. 6.9 illustrates the wind output power changes with wind speed variation.

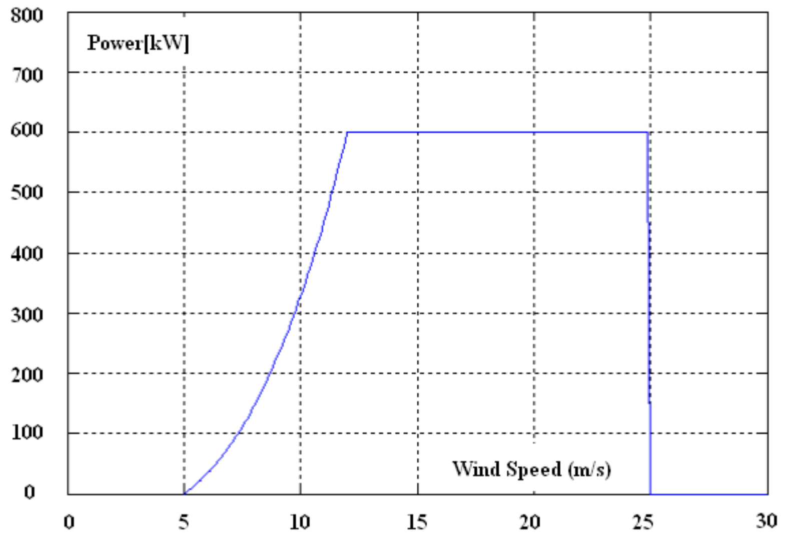


Fig. 6.9 Wind speed VS output power curve

6.4.3 Solar Energy Conversion

Output power from the solar array depends on how much radiation injecting to solar array from the sun. Not only affecting by 'height' of the sun, the radiation fluctuates all the time because of quick passing clouds. Fig. 6.10 shows the radiation of Westminster, London within 24 hours. As can be seen in the figure, the solar radiation changes dramatically within a short period. However, as mentioned above, the solar output power will be smoothed by aggregation. The more solar power distributed in different area, the more smooth total output power from solar could be achieved.

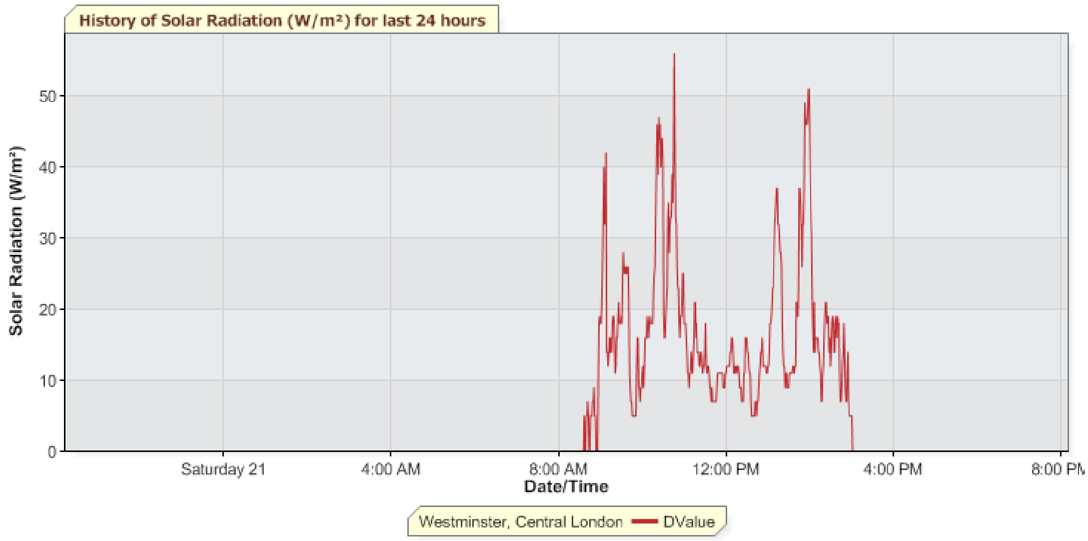


Fig. 6.10 Solar radiation for day-time with cloud impact [165]

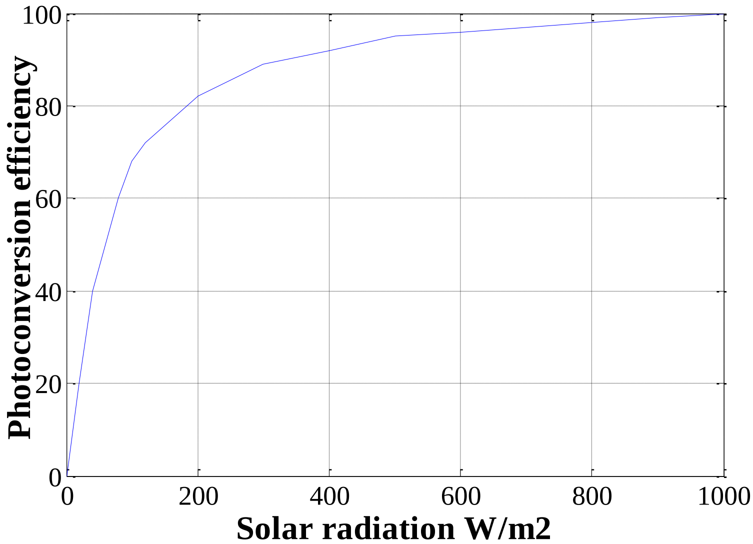


Fig. 6.11 Photo conversion efficiency VS solar radiation [101]

Fig. 6.11 gives information on the PV characteristics about conversion efficiency when the solar radiation is changing. The solar radiation in cloudy weather is represented by500w/m^2, and in brilliant weather by 1000w/m^2, however, the efficiency of the photovoltaic conversion does not change too much [101].

6.4.4 DIgSILENT Models for Stability Analysis

A modified WSCC 9-bus model in Fig. 6.12 is represented a power system network, parameters of the model can be found in reference [102]. The wind and PV models are represented by a wind Doubly-Fed Induction Generator and a PV array static generator in DIgSILENT template respectively. Capacity of the Generator 3 which is connected to Bus 3, has been reduced from 128MVA to 65.5MVA. The rest of the capacities are complemented by PV, wind and Battery, which are 60MVA, 40MVA and 60MVA respectively.

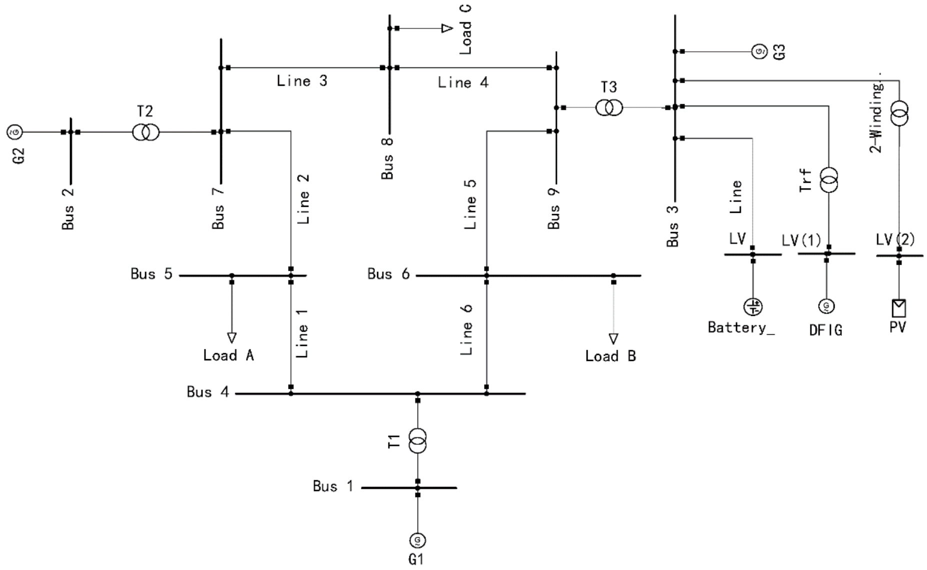


Fig. 6.12 Modified WSCC 9-bus model

Because the wind speed varies stochastically and there is no accurate wind speed data for such short time, wind speed has been assumed as average value of each 5 seconds. The wind variation details is illustrated in Table 6.2. And at the same time, with a cloud passing by the solar array, solar radiation dropped from 1233 W/m^2 to 100 W/m^2, and then recovered back to 1233 W/m^2 within 40 seconds in this study. Wind speed pattern and solar radiation pattern is introduced in this case. The wind speed pattern and solar radiation pattern are drawn in Fig. 6.13 and 6.14.

Time	Wind speed (m/s)
1-5s	11
5-10s	8
10-15s	10
15-20s	12
20-25s	8
25-30s	15
30-35s	12
35-40s	9
40-50s	11

Table. 6.2 Wind speed variation from 0-50s

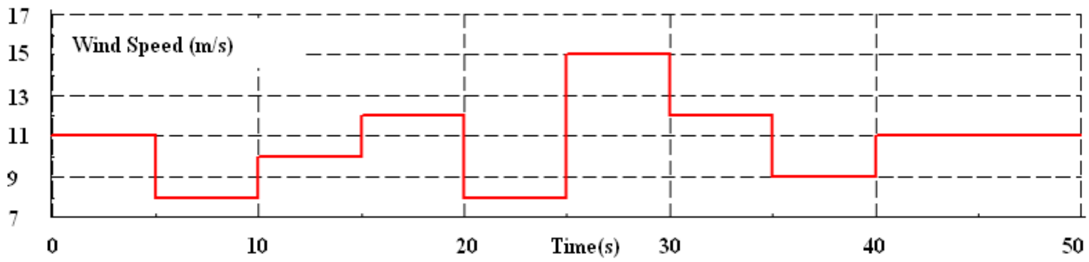


Fig. 6.13 Wind speed pattern

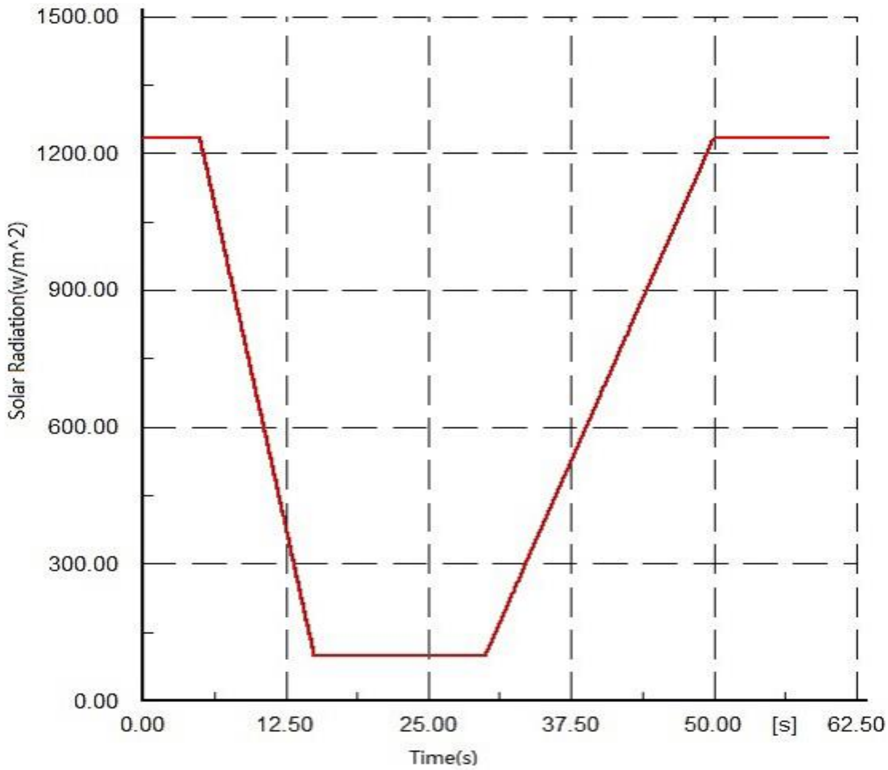


Fig. 6.14 Solar radiation pattern

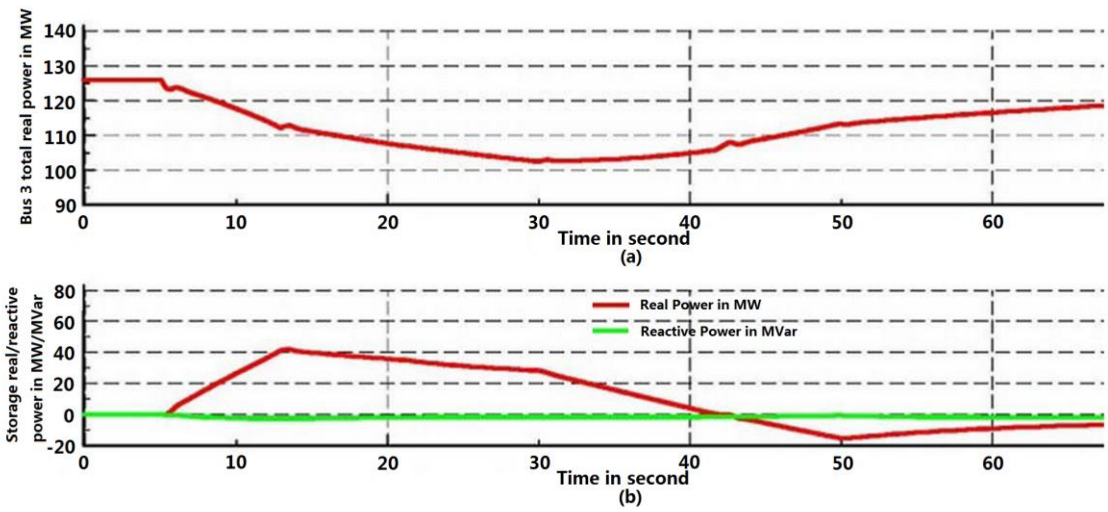


Fig. 6.15 Total active power and battery storage variation in Bus 3 when solar radiation is changing

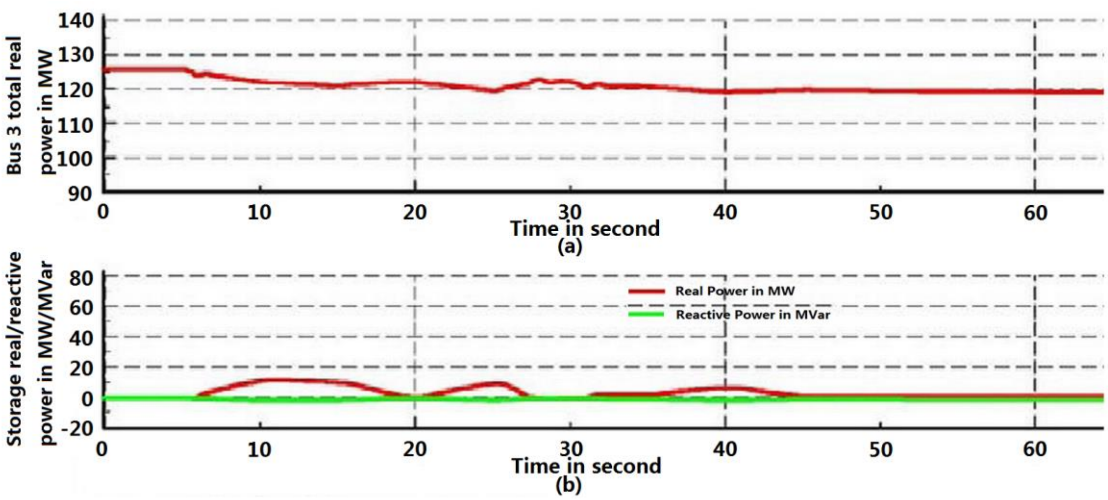


Fig. 6.16 Total active power and battery storage variation in Bus 3 when wind speed is changing

Fig. 6.15 shows the result of total active power and battery storage variation in bus 3 when PV radiation is changing, and wind speed is 11m/s. Fig. 6.16 illustrates the result of active power and battery storage variation when wind speed is changing by following the previous wind speed pattern. While Fig. 6.17 gives the information about the result when wind speed and PV radiation are changing at the same time. In the meantime, system frequency is dropped from rate frequency by 0.2Hz, which is shown in Fig. 6.18.

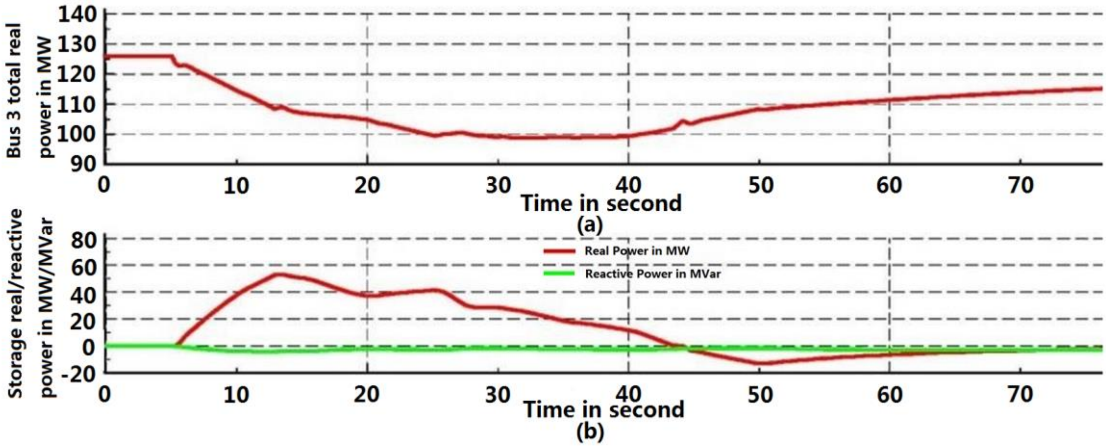


Fig. 6.17 Total active power and battery storage variation in Bus 3 when wind speed and PV radiation are changing at the same time

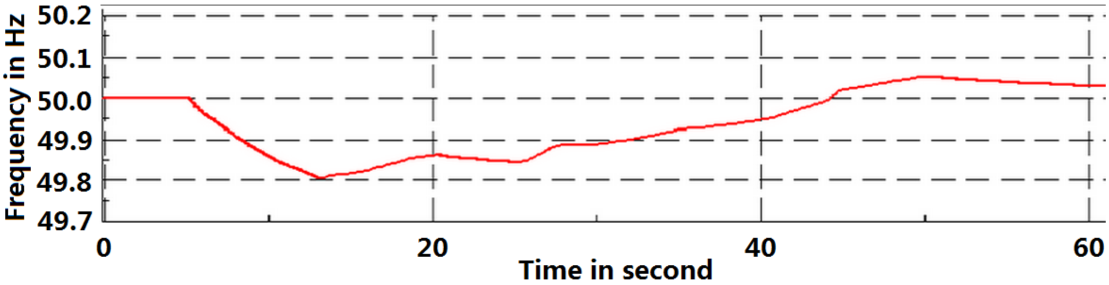


Fig. 6.18 System frequency which is measured in Bus 5

Sensitivity analysis is divided into two parts in this section. In Part 1, wind generation capacity was changed from 40MWto 84MW. The capacity of generator G2 and G3 is reduced by the same level to test the system frequency when renewable penetration was increased. In Part 2, the system state was kept the same except reducing the battery storage from 60MW to30MW. In this case, solar capacity, Load A, Load B and Load C were kept constant.

G1 (MW)	G2 (MW)	G3 (MW)	Battery (MVA)	Wind (MW)	Maximum System frequency variation(Hz)
32.88	163	29	60	40	0.1946
46.81	163	0	60	54	0.2291
75.42	123	0	60	64	0.2869
85.16	103	0	60	74	0.3513
75.62	103	0	60	84	0.4162
75.62	103	0	50	84	0.5599
75.62	103	0	40	84	0.6835
75.62	103	0	30	84	0.7929

Table. 6.3 Maximum system frequency change with penetration level and battery storage level changing

In Table. 6.3, frequency will be dropped by increasing the penetration level when battery storage was stayed the same. With the decreasing of the battery storage capacity, the maximum system frequency is getting larger. With the same level of battery storage capacity injecting to the grid, the increased penetration level of the wind and solar could decrease the frequency stability of the grid. The reason is that the traditional power plants cannot respond to the sudden variation of the wind generated power. Output power from wind turbine is un-continuous due to the wind speed is varied all the time. Large battery array could improve stability. When the battery storage capacity is getting smaller, demand cannot be feed adequately, thus caused system frequency dropping.

When fix the penetration level to 40 MW and Wind speed pattern was moved downwards from 0 unit to 5 units with the level each time by 1m/s, the results of maximum frequency drop is shown in Table. 6.4. After the sensitivity analysis, the penetration level is changed to 84MW and procedures are repeated. The results of the maximum frequency deviation are shown in Table. 6.5.

Wind Pattern dropping Times	**Time for Δf reaching maximum (s)**	**f (Hz)**	**Δf max(Hz)**
0	13.1482	49.8054	0.1946
1	13.1932	49.7913	0.2087
2	14.0112	49.7464	0.2536
3	14.1642	49.6948	0.3052
4	14.1742	49.6569	0.3431
5	14.1942	49.6323	0.3677

Table. 6.4 Maximum frequency error with wind speed pattern dropping when wind penetration is 40 MW

Wind Pattern dropping Times	**Time for Δf reaching maximum(s)**	**f (Hz)**	**Δf max(Hz)**
0	13.6842s	49.5853	0.4147
1	13.6912s	49.4088	0.5912
2	13.6772s	49.2803	0.7197
3	13.7002s	49.1865	0.8135
4	13.7442s	49.1179	0.8821
5	13.7812s	49.0718	0.9282

Table. 6.5 Maximum frequency error with wind speed pattern dropping when wind penetration is 84MW

As compared with Table. 6.5, the maximum frequency errors in Table.6.5 are much larger than that in Table.6.4. With the increase in the wind and solar penetration level, system frequency is susceptible to the wind speed and solar radiation variation. As can be seen in the Table. 6.5, when Δf max is getting large protection will start operation.

6.5 Reliability Indices

There are three major factors driving the changes for developing electric industry and increasing renewable energies, including government policies, rapidly developing economies and energy security. Wind energy is under deployment stage, and more mature than any other technologies such as concentrating photovoltaic and wave energy in renewable energies, which are under developing stage [166].

Distribution network reliability and generation adequacy attract an increasing number of countries' attention in both technical and economic area such as investment in power systems. Investments on renewable energies and any other components of power systems require to be considered when carrying out policy making or cost-benefit analysis. A decision support tool in restructured electricity systems has been overviewed in [167]. Reliability assessment has been considered in a framework for creating a common spatial picture to include renewable energy investment [168]. Factors for long-term balancing the national energy requirement, ensuring energy security and promoting sustainable development for renewable energy resources investment have been discussed [169].In brief, system reliability assessment always aims at single technical area, which could not lead investors or operators to make a clear decision on network planning, rather than considering all the technology areas on system reliability assessment as a whole. Also, for wind energy planning, distributed generation and centralized generation have not been compared with each other on system reliability so far. This section will illustrate the difference between the centralized wind farm and distributed wind generation on reliability and investment aspects.

6.5.1 Generation Investment

There are some interactive effects between reliability and investment, because the distribution network operators need to increase reliability of the network or maintain reliability level of the network by increasing investment [170]. With the increasing loads in distribution network, operators have to lay out money on grid expending. Substations, cables, and other electric equipment need to update to deal with high loading. Fig. 6.19 gives typical characteristic on relationship between cost and investment. Moreover, roles of distributed generation for increasing network reliability has been widely recognized [171]. With distributed generation installed, network expanding will be deferred in a certain degree, and distribution capacity will be reduced by small capacity of DG assisting. According to Table. 6.6 [172], onshore wind generation is much more competitive among the DG technologies since the investment cost is lower than any others, plus the application range is very flexible. This section applies wind generation to the system for reliability assessment, comparisons between network reliability indices on applying centralized large wind generation and small DG wind turbines are addressed.

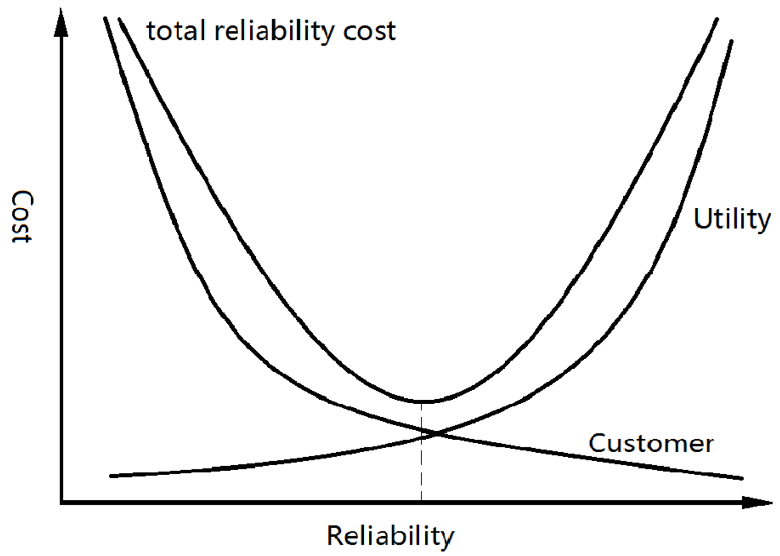


Fig. 6.19 Relationship between reliability and cost

DG Technologies	**Investment Cost per kW**	**Application Range**
Reciprocating Engines	€ 1500-2500	5kW-10MW
Gas Turbines	€ 1000-1250	1-20MW
Micro Turbines	€ 1500-2000	30kW-200kW
Fuel Cells	€ 4500-20000	1kW-5MW
Photovoltaic	€ 5000-7000	Depending on number of cells, 1-20kW
Wind Onshore	€ 800-1000	200W-3MW
Wind Offshore	€2000	

Table. 6.6 Distributed generation investment cost and application ranges

Mean Installed and Operation and Maintenance Costs			
Unit ($/kW, $/kW-yr)		**Installed Cost**	**O&M**
Utility Scale	Wind Offshore	2900	70
	Wind Onshore	1600	30
Distributed Generation	Wind 1~19kW	7500	175
	Wind 20~100kW	5100	50
	Wind 100~1000kW	2500	50

Table. 6.7 Mean installed cost of utility scale wind farms and DGs

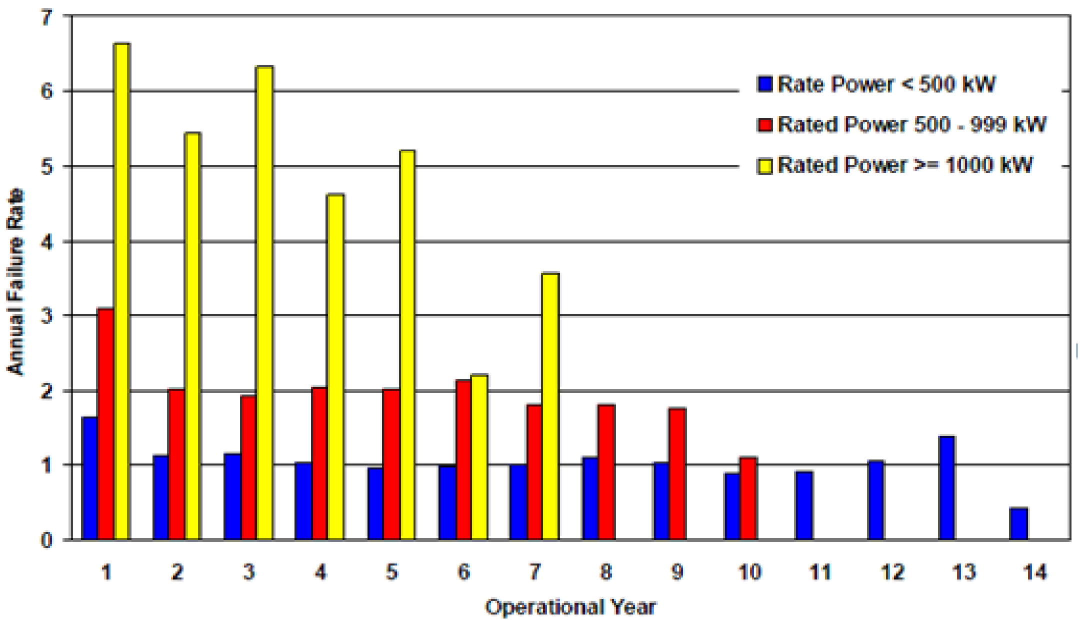


Fig. 6.20 Frequency of failure rate with increasing operational age [173]

From the perspective of investment, the capital cost, operation and maintenance fees are required to estimate the regular costs and non-regular costs. National Renewable

Energy Laboratory (NREL) indicates the range of recent capital cost estimates for both large-scale renewable energy generations and distributed generations [174]. The national-level cost data is provided in dollars per installed kilowatts of generating capacity in 2006, United States. Table. 6.7 shows the mean installed and operation and maintenance (O&M) cost of the utility scale onshore and offshore wind farms and distributed wind generations with different capacities. As can be seen in the table, the mean capital cost and O&M cost of the onshore wind farm are much less than that of offshore one by 1300$/kW and 40$/kW-yr respectively. However, in distributed wind generation, the high capacity the distributed wind generator is, the cheaper the installed cost and O&M cost per kW will be.

6.5.2 Reliability Indices

To evaluate the reliability of a distribution network, three basic reliability data are required to apply to the system:

1. Average failure rate λ_S

$$\lambda_S = \sum_k \lambda_k \tag{6.4}$$

2. Average outage time r_S

$$r_S = \frac{U_S}{\lambda_S} \tag{6.5}$$

3. Average annual outage time U_S

$$U_S = \sum_k \lambda_k r_k \tag{6.6}$$

According to IEEE guide, there are 12 indices (7 in the sustained interruption indices, 2 in the load based indices and 3 in the other momentary indices) to apply to distribution systems, substations, circuits and defined regions. Sustained interruption indices are related to customers affected, including system average interrupt frequency index (SAIFI), system average interruption duration index (SAIDI), customer average interruption duration index (CAIDI), customer total average interruption duration index (CTAIDI), customer average interruption frequency index (CAIFI), average service availability index (ASAI) and customer experiencing multiple interruption (CEMIn). Load based indices which are involving average system interruption frequency index (ASIFI) and average system interruption duration index (ASIDI) are closely linked with connected served load and interrupted load. Other momentary indices namely momentary average interruption frequency index (MAIFI), momentary average interruption event frequency index (MAIFIE) and customers experiencing multiple sustained interruption and momentary interruption events (CEMSMIn) are addressed for momentary average interruption events [92]. However, usually generation adequacy indices such as Total energy not supplied (ENS), loss of load probability (LOLP), loss of load expectancy (LOLE), loss of energy expectancy (LOEE), and expected demand not supplied (EDNS) are also placed into the reliability indices.

For distribution and transmission system planning, investors need to consider the benefit and costs in order to obtain profits from the project. Three pieces of information need to be considered carefully when estimating the expected or observed changes in these reliability indicators to justify the costs of the investments required to achieve smart grid: the utility costs required to achieve given levels of reliability such as investment, maintenance and operation costs; the changes in CAIDI, SAIFI and MAIFI which may result from a given smart grid investment or set of investment, and the average economic losses resulting from the units of unreliability such as CAIDI, SAIFI and so on [93]. The equations of SAIDI, SAIFI, CAIDI, CAIFI and ENS are shown below:

$$SAIDI = \frac{\sum Customer\ Interruption\ Durations}{Total\ Number\ of\ Coustomers\ Served}$$
$$= \frac{\sum r_i N_i}{N_T} = \frac{CMI}{N_T} \quad (6.7)$$

$$SAIFI = \frac{\sum Total\ Number\ of\ Customers\ Interrupted}{Total\ Number\ of\ Coustomers\ Served}$$
$$= \frac{\sum N_i}{N_T} = \frac{CI}{N_T} \quad (6.8)$$

$$CAIDI = \frac{\sum Customer\ Interruption\ Duration}{Total\ Number\ of\ Coustomers\ Interrupted}$$
$$= \frac{\sum r_i N_i}{N_i} = \frac{SAIDI}{SAIFI} \quad (6.9)$$

$$CAIFI = \frac{\sum Total\ Number\ of\ Coustomers\ Interrupted}{Total\ Number\ of\ Coustomers\ Interrupted}$$
$$= \frac{\sum N_i}{CN} \quad (6.10)$$

Where r_i is the restoration time for each interruption event, *CI* is customer interrupted, *CMI* is customer minutes interrupted, N_i is number of interrupted customers for each sustained interruption event during the reporting period, *NT* is total number of customers served for the areas, *CN* is total number of customers who have experienced a sustained interruptions and momentary interruption events during the reporting period [92].

Basically, there are two types of failures in wind energy generation. Firstly, mechanical component failures that are occupy 79% of total number of failures. These include failures due to the blades, gearbox, hydraulic unit, yaw unit and brake pad. Secondly, electrical and electronic components failures that occupy 21% and this includes control panel, capacitor panel and generator failures [175]. Fig. 6.20 illustrates the frequency of failure rate of the wind generation with increasing operational age. It can be seen that the failure rates of wind generators with different capacities are declined with the increasing operational age. At the beginning of the operational years, the failure rate of the wind generators with 500-999kW rated power, which was 3.1 in the first year, is twice as much as that of wind generators with under 500kW rated power. Failure rates colored in yellow representing wind generators with over 1000kW are dramatically higher than any other wind generators [173].Here three basic reliability assessment scenarios will be produced to study the effects of wind generation to the main power grid. Some of the important reliability indices will be discussed. Investments between distributed generation and large-scale wind farms will be compared with each other in order to give decision making to develop renewables. An IEEE 39-bus 10-generator system is modelled and shown in Fig. 6.21 for reliability assessment. A simple distribution network for planning distributed generation shown in Fig. 6.22 is considered in the study.

In order to simplify the system, common stochastic failure rate and time are applied to same components. Only one customer in each load, failure rates and durations in each component are given in Table. 6.8.

Power system elements	**Failure frequency**	**Repair duration**	**Additional fault frequency per connection**
100kV 30kV busbar	0.0002	72 hours	0.0002
11kV 10kV busbar	0.002	14hours	0.005
3.3kV busbar	0.002	14hours	0.005
Line type	0.025	212hours	-
Transformer	0.02	343hours	-

Table. 6.8 system component reliability parameter

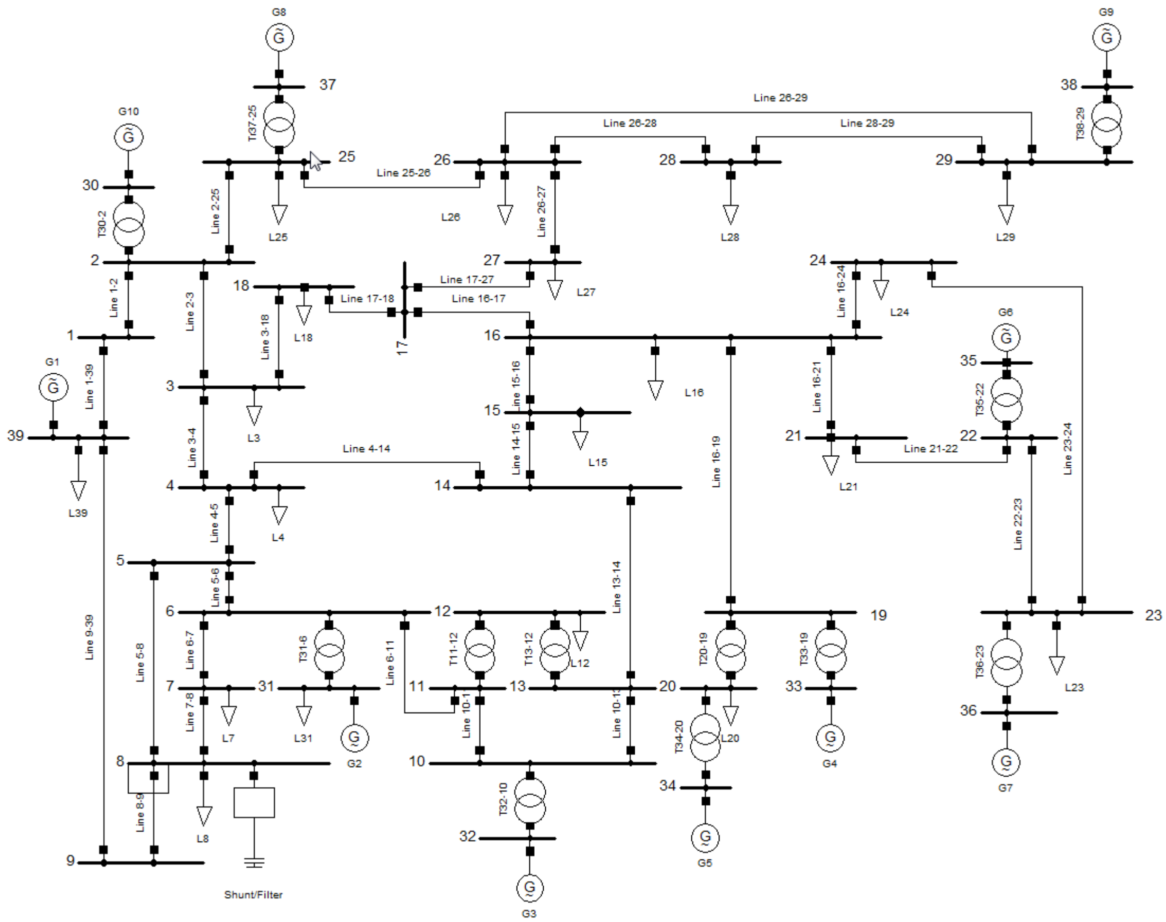


Fig. 6.21 New England 39-bus 10-gnerator systems

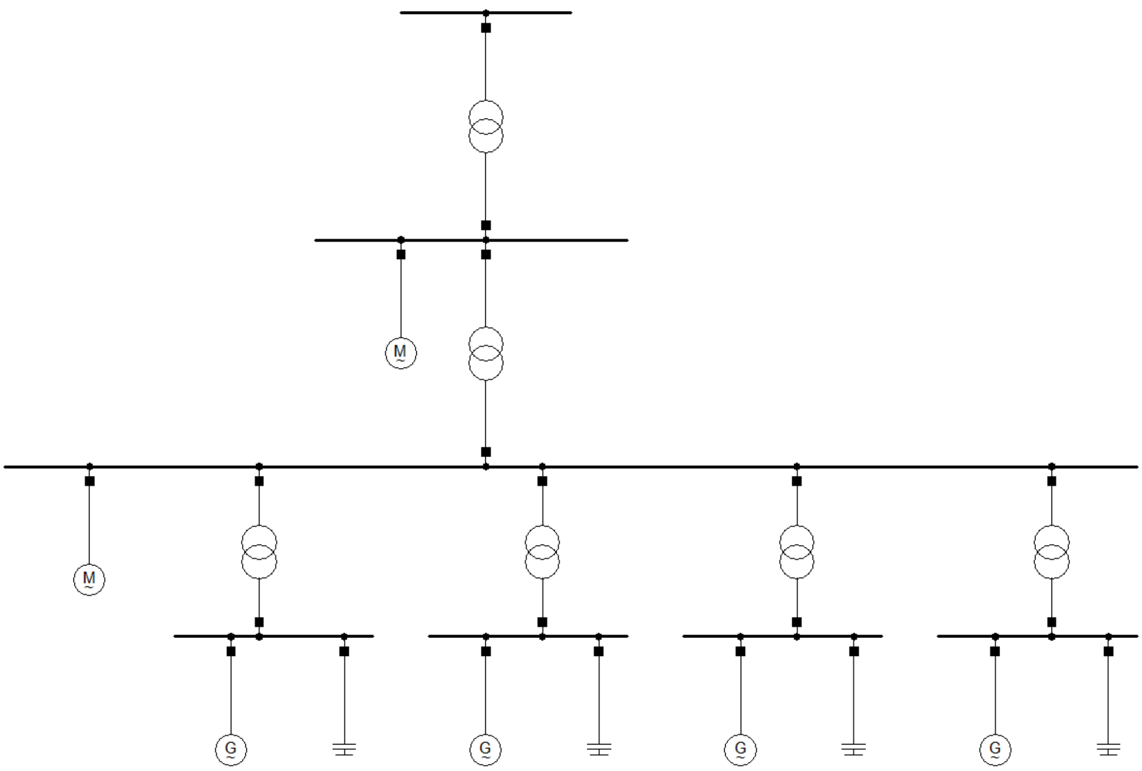


Fig. 6.22 Distribution system for DG planning

Case 1 Distributed generations (DGs) at different busbars

Case 1 illustrates the difference in reliability indices when DGs dep1loyed at different busbars. In this case, the distribution system with 4 distributed generators is deployed into the 39-bus system. The results of reliability index in each bus are shown in Table. 6.9. As can be seen in the Table, CAIDI when the DGs are in the busbar 6 is much less than in any other bus. However, CAIFI in bus 6 is the greatest with DG deployed. CAIDI without any distributed generation deployment in the system is the worst, while the CAIFI at that moment is the best.

BUS Number	SAIFI	CAIFI	SAIDI	CAIDI
No DGs	0.066822	0.066822	13.337	199.592
1	0.066839	0.066839	13.338	199.560
2	0.066822	0.066822	13.337	199.592
3	0.066832	0.066832	13.338	199.573
4	0.066838	0.066838	13.338	199.562
5	0.066822	0.066822	13.337	199.592
6	0.067021	0.067021	13.351	199.212
7	0.066832	0.066832	13.338	199.572
8	0.066838	0.066838	13.338	199.560
9	0.066822	0.066822	13.337	199.592
10	0.066822	0.066822	13.337	199.592
11	0.066822	0.066822	13.337	199.592
12	0.066822	0.066822	13.337	199.592
13	0.066822	0.066822	13.337	199.592
14	0.066822	0.066822	13.337	199.592
15	0.066832	0.066832	13.338	199.573
16	0.066879	0.066879	13.341	199.482
17	0.066822	0.066822	13.337	199.592
18	0.066827	0.066827	13.337	199.583
19	0.066842	0.066842	13.339	199.554
20	0.066842	0.066842	13.339	199.554
21	0.066830	0.066830	13.338	199.576
22	0.066822	0.066822	13.337	199.592
23	0.066830	0.066830	13.338	199.577
24	0.066831	0.066831	13.338	199.573
25	0.066829	0.066829	13.338	199.579
26	0.066842	0.066842	13.339	199.554
27	0.066831	0.066831	13.338	199.575
28	0.066828	0.066828	13.338	199.580
29	0.066839	0.066839	13.338	199.560
39	0.066857	0.066857	13.340	199.524

Table. 6.9 Results of reliability index in each bus when deploying DG

Case 2: Multi-centralized wind generation in selected busbars

This case aims to investigate the reliability variations with different number of centralized wind generation connected into the system. System reliability indices with zero up to 3 wind generators connected into the system are demonstrated in Table. 6.10. With the increasing number of wind generators, the system reliability index is getting lower and lower. That is because some additional bus rated failure and duration has been accounted for the reliability indices.

BUS Number	SAIFI	CAIFI	SAIDI	CAIDI
NULL	0.066822	0.066822	13.337	199.592
23	0.066830	0.066830	13.338	199.577
23, 29	0.066839	0.066839	13.337	199.560
23,29,39	0.066874	0.066874	13.341	199.492

Table. 6.10 Reliability result for different number of wind generation connected to the grid

Case 3: Comparison between large-scale wind generation and distributed wind generation

Large scale wind generation is compared with the same capacity distributed wind generations in Case 3 which is shown in Table. 6.11 According to Fig. 6.20, the large-scale wind generation failure rate is 6.8 in the first year and distributed generation failure rate is 3 times in the first year. These failure rates for large scale wind generation and distributed generation is applied to Case 3 to observe the differences for these two kinds of energy generation. Although the failure rate of distributed generation is less than that of large-scale wind generator, CAIDI of DGs is larger than that of large scale wind generator. The rest of reliability indices of DGs are better than that of the large-scale cases.

	Large-scale wind generation	Distributed wind generation
SAIFI	0.066893	0.066857
CAIFI	0.066893	0.066857
SAIDI	13.342	13.340
CAIDI	199.456	199.524

Table. 6.11 Reliability result for large-scale& DG wind generation

6.6 Conclusion

First of all, there is an overview on the structure and projects in DSS development. The current survey gives a brief investigation in decision support system from the very beginning to the future. As a project-oriented structure, DSS cannot be compatible with every project. However, researchers devote themselves to make contributions to the

DSS in order to design a general structure which can be applied into as many applications as possible. General DSS functionality and requirement have been discussed. Some classical DSS frameworks with graphical illustration have also been demonstrated. Cloud computing technology could make a real positive difference in the future, however, security could be a major issue and full attention should be given to this.

Secondly, the chapter talks about index and scenarios of a smart grid DSS system inputs requirement. Two main aspects like power system reliability and stability is given as examples. 8. Reliability indices of the system with large scale wind generations are compared to that with distributed generations, investment and cost were considered with power utilities' benefits for decision making.

In stability scenarios, a tutorial value is given for the integration of renewables to power grid. Some simulations have been carried out to demonstrate the physical insight of such a system. This work demonstrates the physical insight of the system, and also provides stability indices for cost-benefit analysis and decision making.

Naturally, for a full scale project to be established, it is also required to carry out a cost-benefit analysis. But in terms of technology, it shows that there are many challenges and our fellow engineers will have a huge opportunity to make contributions.

Wind energy and Photovoltaic have some degree of compensation ability to each other. Solar panel can generate electric power during the day when the wind speed is not so high; during the night, the solar panel cannot generate electricity while the wind generates electricity as wind speed much higher than day-time. There is a common view by countries around the world that developing renewable energy is a sustainable way to deal with the carbon emission and air pollution.

The penetration level of a power system is closely linked with how much flexible generation capacities installation in the network. To deal with variations of wind and solar energy generation, these generators should have the capability of fast response.

In the future work, a more complex network will be studied, and more accurate aerodynamic model will be built for dynamic stability study.

In reliability section, the reliability indices are compared between the use of large-scale wind generators and distributed generators, and between different busbars. The failure rates of different size of wind generators have been considered during simulations. Utility scale wind generation is much cheaper than distributed generation wind energy. With the increasing of generator capacity, the capital cost is getting much cheaper and cheaper. However, the reliability indices such as SAIFI, CAIFI and SAIDI indicate that system large-scale generation reliability is worse than that with distributed generation. Reliability indices such as SAIFI, CAIFI, and SAIDI indicate different meanings in system reliability. The more wind generators connected to the system, the worse the system reliability index achieved when only considering the failure duration and frequency.

Chapter 7
Conclusions and Future Work

7.1 Overall Conclusion

Plenty of advanced technologies, creative architectures, and novel algorithms will be deployed into the existed power system to improve energy efficiency and achieve resource allocation optimization and make the grid "smart".

Bi-communication channel deployment is one of the distinct marking of the smart grid. With smart grid monitoring system, smart grid can collect and transmit the data monitored from power system components to the system operators and form a bi-communication channel through the grid from power plant to electricity consumers.

Accurate short-term load forecasting may contribute to the power economic dispatch and design an appropriate demand response or further load shedding plan to prevent the loads from over-withdrawing energy from the grid. Long-term load forecasting can offer a consultative reference to further planning for optimizing energy resource allocation.

Accurate load forecasting gives further information of the load trend in advance to the network operators for providing steady energy supply to the consumers. However, contingency like supply deficit and fault may occur to the power system and impact on energy consumption. As a key technical solution of self-healing technology, Load shedding mechanism is the final step to prevent the power system from collapsing and trying to maintain the integrity of the grid.

The implementation of a smart grid is a step-by-step procedure to replace the old power system components or planning to build facilities based on existing grid instead of establishing a brand new grid. For further smart grid planning, it may not only consider the effect from the creative technologies, but also respecting for all stakeholder's interest. Decision making may need to execute to analysis each smart grid component investment and cost before deploying to the real grid.

Regarding to the issues mentioned above, this thesis reveals the overall structure of the deigned communication and monitoring system. Fully utilization of the information is one of the main strategies to take the full benefit of smart grid and promote its acceptance. A case of information from weather forecasting system utilized for load forecasting is talked in Chapter 4.

This thesis integrates Artificial Neural Network into load forecasting system for Macro grid load forecast. Details of system architecture and simulation are revealed. Different training algorithms such as gradient descent, Levemberg-Marquadt and Quasi-Newton are applied to a 3-layer network for data training. Historical weather and demand data from Ontario, Canada are applied for load prediction.

In addition, a common contingency of power system, load shedding strategy, is proposed in this thesis. Lessons learned from India blackout in July 2012 are analyzed. Some sensitivity analysis has been done to investigate the level of disturbance affected the grid. A coordinated dispatch schedule is essential for a secure electricity supply. Otherwise, a load shedding strategy may need to act properly to rescue the entire grid from collapsing.

Last but not least, the architecture of decision support systems is reviewed and new trend for decision support system was pointed out for further research. With large penetration of new technologies such as renewable energies and communication technologies integrated in power system, problems to power system such as power stability, reliability, security are appearing or even becoming more critical than in traditional power grid. Stability scenarios and reliability indices, which demonstrate the physical insight of the system, are provided for cost-benefit analysis and decision making.

7.2 Trends and Further Work

As a brand new concept and with plenty creative technologies implementation, smart grid is facing multiple challenges in many diverse aspects such as safety and security, reliability, power quality, interactivity between grid and customers, market, efficiency, and so on.

Because of the complexity of the electrical network, especially in distribution systems, the necessity of intelligent device installation in the system demands evaluation. Different groups of stakeholders may divide in benefit orientations. Well-balancing between stakeholders may bring rapid development in smart grid, while how to balance the interests is one of the ticklers in smart grid development. Since the communication technology is still experiencing evolution, the communication devices might update much more rapidly than that of electrotechnical devices which could mislead the investment evaluation for long-term planning. Other open challenges like what the system issues of integrating alternative energy sources are, where we place energy storage devices to improve structural stability of the network, how we integrate micro-grids are still existing and will be debated between smart grid researchers for long time in the near future.

With increasing number of communication technologies deployment into power grid, cyber security is becoming an issue. The impact of cyber-attack to power systems needs to be simulated according to the real system business and operation scenarios. Data package missing and modification by criminals may lead to mal-operation in power systems which may further result in system collapse. Also, reliability of the whole system and investment on communication may need to be re-evaluated. When the non-dispatchable energies penetration level is increased, more accurate load forecasting is required to balance between generation and demand. Thereby, more accurate data is required for data mining and prediction. To achieve these scenarios, a co-simulation engine between power system simulator and communication network simulators needs to be established in the future. Models and Scenarios which are discussed above can be built and simulated as core part of a decision support system for further evaluation.

Optimal planning and coordination are required to take into account for the new services and technologies deployment. In addition to this, decision support system for smart grid implementation is extremely necessary for decision makers to take as a reference. Plenty of advanced technologies, creative architectures, novel algorithms will be deployed into the existing power systems to improve energy efficiency and achieve optimization of resource allocation. However, there is no mature tools for observing all impact of deploying a certain new technology to date. From the decision making perspective, developing tools for implementation smart grid is extremely urgent for determination of installing smart device throughout the entire system. A co-simulation framework has been established during the research, the implementation of co-simulation between two software need to be take action in the future.

There are numerous technologies applying into the power systems hardware and software so that the power network could be called “smart grid”. It is not a simple job to achieve smart grid. To date, the definitions of smart grid published by different organizations and institutions are not unique. To develop a smart grid, not only technical aspect need to be considered, but also the economical aspect has to be take into account. This may need more precise models and accurate data for analyzing the contribution of a certain new technology. Thus, more research work needs to be done for data mining and modelling in the future.

Another future task is finding a proper way to integrate the electrical market and services. Demand response is one of the critical aspects for consumers participating into a grid activation in the further. New pricing policies such as dynamic pricing and network operation strategies, for instance, real-time voltage control, need to be considered in co-simulation and more scenarios need to be generated and compared with each other for further decision making.

As the last step to prevent the whole grid from collapse, the load shedding scheme will not only consider the technical aspect, the impact to the system reliability may also need to be considered in the future work. More complex scenarios will be considered such as the distributed generation with intended islanding, and new reliability indices for assessing smart grid reliability and so on. Intelligent systems for reliability improvement also need to be addressed in the future work. Better decision making tools for system designing and planning will be needed to study for improved security of electricity supply system with higher reliability. Besides, new indices for smart grid assessment will be generated. Considering the communication network, signal generating and reception impacts on electricity delivery will be added to smart grid reliability assessment.

Investment needs to be considered on smart grid planning in the further study. The economic benefits and costs to the decision for each year of its life need to be quantified and calculated.

List of Publications

[1]. Hao-Tian Zhang, Fang Yuan Xu and Long Zhou, *'Artificial neural network for load forecasting in smart grid',* 2010 International Conference on Machine Learning and Cybernetics, IEEE, Vol. 6, pp. 3200-3205.

[2]. Hao-Tian Zhang and Loi Lei Lai, *'An overview on smart grid simulator',* 2012 IEEE General Meeting on Power and Energy Society, Page 1-6.

[3]. Hao-Tian Zhang, Qian Yang, Chun Sing Lai and Loi Lei Lai, *'New trends for decision support systems',* 2012 IEEE International Conference on Systems, Man, and Cybernetics, pp. 1373-1378.

[4]. Hao-Tian Zhang and Loi Lei Lai, *'Research on wind and solar penetration in a 9-bus network',* 2012 IEEE General Meeting on Power and Energy Society, pp. 1-6.

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Appendix I
Biological Neural Networks

Biological neuron which is contained in our brain pallium, is a special cell that can process information received from other neurons and transmit the signals generated by its cell body. These signals are transmitted via axon and branches into strands and sub-strands, whose terminals are so called "synapses". A synapse is an elementary structure and functional unit between two neurons. The signals passing through a synapse can adjust the effectiveness of the synapse, and makes synapse be able to learn from the activities they participate [75].

A simplified biological neuron model is shown in Fig. A.I. As can be seen in the figure, a neuron includes:

1. a cell body or so called "Soma" with a nucleus inside
2. a number of dendrites which is the receiver connecting to other neurons
3. an axon which is the transmitter and eventually split into a number of strands to link to other neurons
4. A single neuron may connect with 100,000 other neurons via dendrites and axons [76].

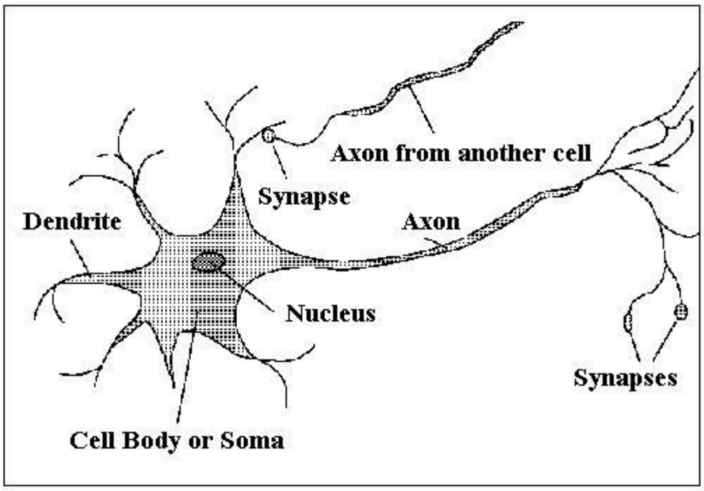

Fig. A.I.Biological Neuron [76]

Appendix II
Network Data for IEEE 33-bus Test System in Chapter 5

1. 33-bus System Network Data

Line Number	Sending Bus	Receiving Bus	Load at receiving end bus	
			Impedance (Ohm)	**Power (kVA)**
1	1	2	0.0922+j0.0477	100+j60
2	2	3	0.493+j0.2511	90+j40
3	3	4	0.366+j0.1864	120+j80
4	4	5	0.3811+j0.1941	60+j30
5	5	6	0.819+j0.707	60+j20
6	6	7	0.1872+j0.6188	200+j100
7	7	8	1.7114+j1.2351	200+j100
8	8	9	1.03+j0.74	60+j20
9	9	10	1.04+j0.74	60+j20
10	10	11	0.1966+j0.065	45+j30
11	11	12	0.3744+j0.1238	60+j35
12	12	13	1.468+j1.155	60+j35
13	13	14	0.5416+j0.7129	120+j80
14	14	15	0.591+j0.526	60+j10
15	15	16	0.7463+j0.545	60+j20
16	16	17	1.289+j1.721	60+j20
17	17	18	0.732+j0.574	90+j40
18	2	19	0.164+j0.1565	90+j40
19	19	20	1.5042+j1.3554	90+j40
20	20	21	0.4095+j0.4784	90+j40
21	21	22	0.7089+j0.9373	90+j40
22	3	23	0.4512+j0.3083	90+j50
23	23	24	0.898+j0.7091	420+j200
24	24	25	0.896+j0.7011	420+j200
25	6	26	0.203+j0.1034	60+j25
26	26	27	0.2842+j0.1447	60+j25
27	27	28	1.059+j0.9337	60+j20
28	28	29	0.8042+j0.7006	120+j70
29	29	30	0.5075+j0.2585	200+j600
30	30	31	0.9744+j0.963	150+j70
31	31	32	0.3105+j0.3619	210+j l00
32	32	33	0.341+j0.5302	60+j40
33a	21	8	2+j2	

34a	9	15	2+j2
35a	12	22	2+j2
36a	18	33	0.5+j0.5
37a	25	29	0.5+j0.5

Substation voltage = 12.66 kV, MVA base = 10 MVA

2. Generator Governors parameters

Hydro Generator	**Parameter**
Power MVA	3 MVA
Terminal voltage	12.66 kV
Permanent droop *R*	0.04
Temporary droop *r*	0.5
Governor Time Constant T_r	8.408
Filter Time Constant T_f	0.05 s
Servo time constant T_g	0.5 s
Water starting time T_w	0.496 s
Turbine Gain A_t	1.15
Gate Velocity Limit V_{elm}	0.2 p.u.
Maximum Gate Limit G_{max}	1

Gas Generator	**Parameter**
Power MVA	0.8 MVA
Terminal voltage	12.66 kV
Speed droop *R*	0.02
Controller Time Constant T_1	0.4 s
Actuator Time Constant T_2	0.1 s
Compressor Time Constant T_3	3 s
Ambient Temperature Load limit	1
Turbine Factor K_t	2
Controller Minimum Output V_{min}	0
Controller Maximum Output V_{max}	1 p.u.

Diesel Generator	**Parameter**
Power MVA	0.8 MVA
Terminal voltage	12.66 kV
Actuator Gain *K*	10
T_1	0.2
T_2	0.3
T_3	0.3
T_4	1
T_5	0.1
T_6	0.2
Droop	0.03
Combustion Delay	0.01
Time constant power feedback	0.5
Minimum Throttle	0
Maximum Throttle	1

DFIG Wind Generator	**Parameter**
Power MVA	1 MVA
Terminal voltage	0.69/12.66 kV