Policy Partnership on Science, Technology
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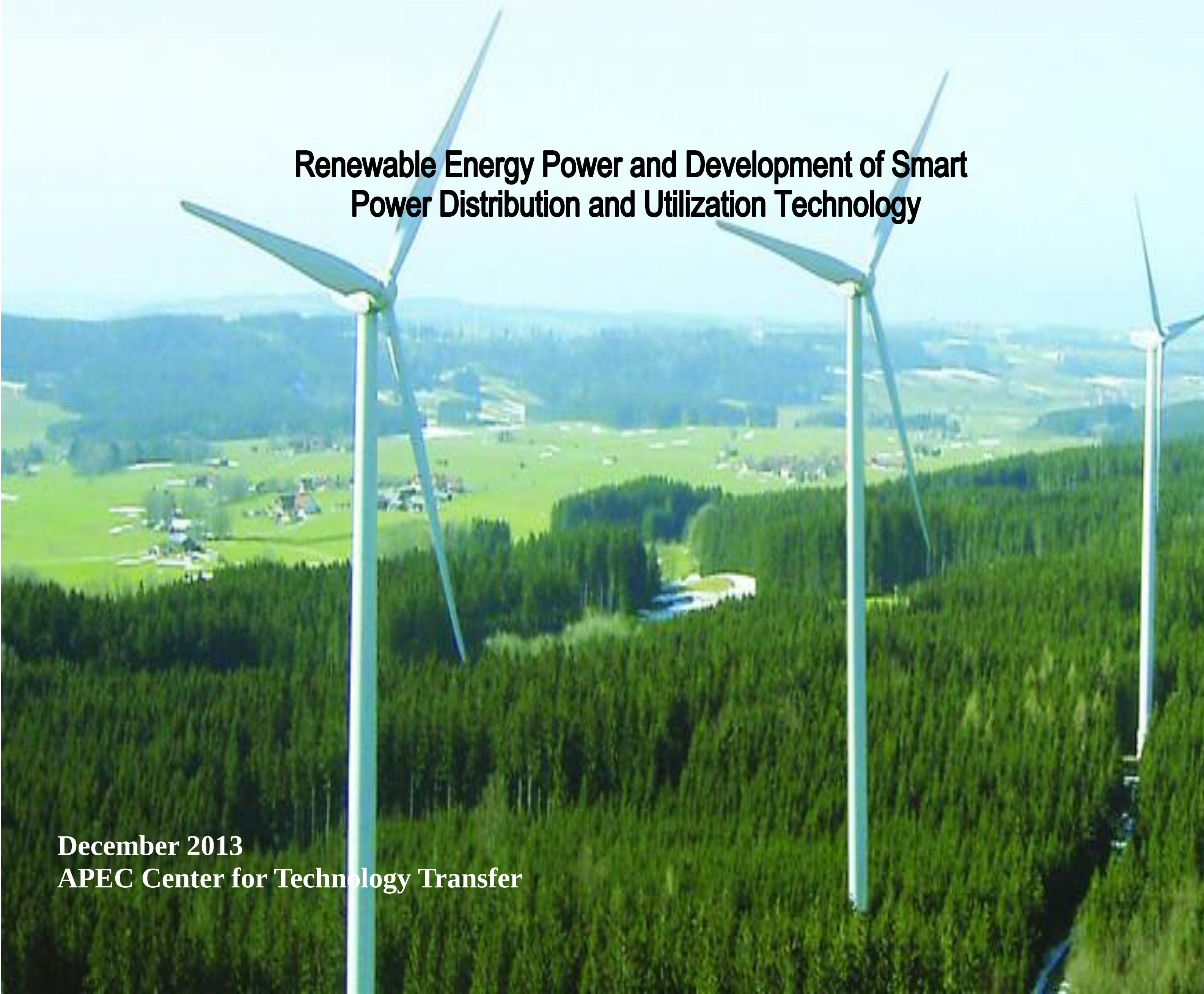
Asia-Pacific
Economic Cooperation

Cooperative Study on Efficient Renewable Resources Integration and Distribution Technologies for Smart Grid Construction

(No.: IST 01 2011A)



Renewable Energy Power and Development of Smart Power Distribution and Utilization Technology

December 2013
APEC Center for Technology Transfer

Asia-Pacific
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The Final Report of APEC Funded Project:

"Cooperative Study on Efficient Renewable Resources Integration and Distribution Technologies for Smart Grid Construction"

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Foreword

As was recorded in 2009 Leaders' Declaration, citizens of the Asia-Pacific region shall advance work on sharing best practices in energy efficiency with a view to deploying cleaner and more efficient technologies...recognize the role of renewable energy in reducing emissions and encourage its development in the APEC region. In accordance with the aim to strengthen economic and technical cooperation emphasized in the Declaration, APEC Center for Technology Transfer proposed the project "Cooperative Study on Efficient Renewable Resources Integration and Distribution Technologies for Smart Grid Construction", which obtained approval from and support of the APEC Secretariat and the APEC Policy Partnership on Science, Technology and Innovation (PPSTI), named as APEC Industrial Science and Technology Working Group (ISTWG) at that time, on the 39th APEC Industrial Science and Technology Working Group Meeting held in Japan in September 2010.

Given that many APEC member economies are currently still relying on an outdated planned power grid infrastructure which limits its flexibility and at the same time puts citizens at risk, nowadays there is a growing agreement among policy-makers, business leaders and other key stakeholders on the idea that the application and promotion of a smart grid is high on the list of technological development.

Not only researchers but also stakeholders of the smart grid field have gradually come to realize that smart grid is closely related to a series of industries. Its construction involves advanced technologies of many fields, ranging from renewable resources integration into the grid, distribution circuit and metering infrastructure to energy storage, peak demand control and instantaneous monitoring and management, etc.

The smart grid project was initially aimed to analyze technologies on integration of renewable energy resources into smart grid, facilitate the reduction of energy wastage by encouraging projects with recommended technologies in this project to help achieve a low carbon society and safeguard the quality of life through sustainable growth.

In this research project, not only the latest efficient renewable resources integration and distribution technologies have been studied and analyzed, the recommended technologies of renewable resources integration and customer-end management have also been expected to be utilized by prosperous enterprises to achieve the potential cooperation and technology transfer. Focused on the technologies directly related to small and medium enterprises (SMEs) of smart grid industry, this project selected and studied technologies on Intelligent Electric Meter, Intelligent Distribution Box Design and Grid Networks Management System Development. Realizing that seamless integration of renewable energy resources like wind and solar power into the grid is one of the breakthroughs to address problems resulting from energy shortage, we have placed energy integration and storage as well as instantaneous monitoring as the primary focus of this project. We hope that instantaneous

management devices which enable more customer choices and better experiences will, encouraged by the project, be developed with huge market potential.

This concluding report is to be disseminated in the Asia-Pacific region with the help of consultants and researchers. It summarizes the recent development of distributed power supply and community with smart power distribution and utilization system, analyzes the operating principle and control model of typical distributed power supply such as wind power, solar power, gas turbine, fuel cell, energy-storage system, and introduces the development of distributed power supply and smart power distribution system in Japan, Australia and the UK and describes the development of distributed power generation system and operating experience of micro-grid demonstration community in China.

Technologies with application potential, especially energy integration and customer-end management technologies will be promoted and introduced to relevant enterprises. Continuous efforts will be made to facilitate the recommended technologies to be applied in more economies. APEC Center for Technology Transfer has managed to collect feedbacks from the active participants in the project. Upon the completion of an analysis of the feedbacks, we will disseminate and circulate the report to research institutes and department of industry in the Asia-Pacific region so as to enhance their capabilities in this field. Chances are higher that more citizens of the Asia-Pacific region may enjoy better power grid operation experience, as more outputs of the projects are coming into existence.

Acknowledgement

This project could not have been successfully completed if it had not been the help and support of many organizations and people. First, we would like to express our gratitude to Asia-Pacific Economic Cooperation (APEC) and the APEC Policy Partnership on Science, Technology and Innovation (PPSTI), including Japan, Republic of Korea, Russia, Chinese Taipei and Thailand, for having provided funding for the project.

In the meantime, we would like to give our heartfelt thanks to Ministry of Science and Technology of the People's Republic of China, Ministry of Foreign Affairs of the People's Republic of China, China Science and Technology Exchange Center, People's Government of Suzhou Municipality, Suzhou Science and Technology Bureau for their continuous support of the project.

We also would like to acknowledge North China Electric Power University, Jiangsu Smart Grid Industry Alliance and Zhangjiagang Smart Grid Research Institute for providing professional suggestions and technological advice in the process of the project.

Special gratitudes must be given to the speakers for their contributions to the project. They are: Prof. Sun Jiaping from China Association of Mechanical and Electrical Engineering, Prof. Zhang Jianhua and Mr. Wu Kehe from North China Electric Power University, Dr. Zhaoyang Dong from University of Sydney, Dr. Jin Zhong from University of Hong Kong, Dr. Miles Alexander Redfern from University of Bath, Mr. Nakayama Hajime from Japan Electric Information Center, Inc. and Dr. Charles Robert Simpson Jr. from General Electric Company.

Apart from our gratitudes to speakers from Australia, People's Republic of China, Hong Kong, China, Japan, the United States and the United Kingdom, we also would like to give our sincere thanks to Indonesia, Republic of Korea, Malaysia, Mexico, Russia and Viet Nam for having respectively nominated one or two participants for this project. These international participants have received a two-day training on frontier knowledge of smart grid and are expected to disseminate and circulate the outputs of the project when they returned in order to enhance the capacity building of APEC developing economies.

In addition, it is also highly appreciated that more than 100 representatives from Chinese enterprises in the smart grid field have actively participated in the project. They have entertained a heated discussion with each speaker after an introduction of the recommended project in the promotion meeting. These corporate representatives have developed an interest in the emerging innovative technologies and their applications in the newly-developing smart grid industry, and may bring them into full market potential in the future, so that more citizens will have the possibility to enjoy smart grid products or experiences when the recommended technologies are applied

Acknowledgement

to practical projects.

Special thanks should be given to Suzhou Taigu Electrics Co., Ltd for having provided facilities and enabled a field trip. The participants have acquired a more profound knowledge of its operation mode and business value as well as China Power Services after an introduction to its functions and the sharing of some successful cases.

All in all, we would like to acknowledge, with much appreciation, all the participants for the time and efforts they have invested in and the contributions they have made to this project. The successful completion of the project was the result of a combined effort of everyone involved.

APEC Center for Technology Transfer

Executive Summary

Project Implementation

APEC project - “Cooperative Study on Efficient Renewable Resources Integration and Distribution Technologies for Smart Grid Construction” (IST 01 2011A) was endorsed in 2013 for implementation, funded by the APEC Policy Partnership on Science, Technology and Innovation (PPSTI) and co-sponsored by Japan, Korea, Russia, Chinese Taipei and Thailand, with speakers and participants from Australia, China, Hong Kong, China, Indonesia, Japan, Korea, Malaysia, Mexico, Russia, the United States, Viet Nam and the United Kingdom. Held on 22-25 October 2013 in Suzhou, China, this project was further divided into a two-day training session and a two-day promotion meeting.

The project conducts the following principal activities:

1. Collecting data and research observations from various channels, including prints, official websites, media, etc.
2. Defining research topics of the project and locating suitable researchers
3. Exchanging ideas among the researchers and consultants on current research
4. Organizing and implementing the smart grid project
5. Collecting feedbacks and conducting an analysis
6. Drawing up a final report and disseminating the report in APEC member economies

In the process of the implementation of the smart grid project, a training session and a promotion meeting were held on 22-25 October 2013 in Suzhou, China.

During the training session, experts in smart grid field were invited to analyze technologies on integration of renewable energy resources into smart grid. Approximately 30 attendees from APEC member economies have participated in the training session, along with a field trip to Suzhou Taigu Electrics Co., Ltd.

During the promotion meeting, successful experiences of applying the technologies on renewable energies integration to the grid network were shared among representatives from APEC economies. More than 100 Chinese corporate representatives have taken part in the promotion meeting.

This final report will be circulated and disseminated in APEC member economies to facilitate the development of society and safeguard the quality of life through sustainable growth.

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Chapter 1: Smart Grid – the Way for Renewable Energy Integration to Power Grid

Chapter 1 provides an overview of the issues that need to be addressed and the application of smart grid technologies in power systems.

Energy efficiency can be improved by renewable energy generation and clean energy based distributed generation, whereas mitigate the environmental problem. The other method to improve energy efficiency is two-way demand side management (DSM). Energy storage is necessary to a grid with a high penetration of wind and solar generation. The real time control on distributed generation and demand side response requires fast, two-way modern information and communication technologies (ICTs).

The international trend in smart grid development is to start from distribution network and demand side by installing advanced metering infrastructure (AMI), ICT, distributed renewable generation, and distributed storages. Smart grid technologies provide the platform for renewable energy integration to power grid.

Chapter 2: Mode of New Energy Power Connection into Power Network

Chapter 2 introduces centralized exploitation of renewable energy power in large scale and directly connecting to power network as well as distributed exploitation and entering power system by micro-grid.

Mainly adopted in China up till now, the mode of centralized wind power and solar energy development in a large scale and directly connecting to the network requires the network not only to have large capacity, but also to have a strong real-time flexible dispatching capability, which can effectively reduce investment in a project and accelerate the speed of exploitation of wind and solar power.

Considering that the centralized large-scale development of wind power in China will become saturated in 2020, China will promote distributed development and local utilization in the future, as the western European countries have done. With the development of smart grid and smart power distribution and utilization technique, the engineering application of distributed generation accessing to the network by micro-grid is just around the corner, which will effectively improve the quality of local voltage and the reliability of power supply.

Chapter 3: Status and Trends of Distributed Power Source and Smart Power Distribution and Utilization Technology

Chapter 3 firstly provides the survey report of some typical pilot projects of intelligent power distribution and utilization system constructed by actual micro-grids in the

world.

In North America, two Canadian hydropower companies, BC and Quebec, have begun to carry out the construction of the micro-grid demonstration projects. Jointly funded by the US Department of Energy and California Energy Commission, formal studies of micro-grid in America began in 2003.

In Japan, renewable energy and new energy have been the focus of the Japanese power industry in recent years, and the application of renewable and distributed generation technologies in micro-grid has been greatly encouraged. The New Energy and Industrial Technology Development Organization respectively established micro-grid demonstration areas in Aomori Prefecture, Aichi Prefecture, Kyoto Prefecture and in Sendai.

In Europe, test point of micro-grid and intelligent power distribution and utilization system has been respectively established in Netherlands, Germany, Denmark, Italy, Portugal and Spain to study micro-grid and intelligent power distribution and utilization system.

In China, the two most representative demonstration projects include the souther Combined Cooling Heating and Power (CCHP) micro-grid intelligent power distribution and utilization system constructed by China Southern Power Grid Company in Shenzhen and Distributed CCHP System of MW-level Integrated Technology and Demonstration Area in the Northern Region established by China Power Investment Corporation in Hohhot, Inner Mongolia.

This chapter also provides an overview of the application status of smart power distribution and utilization technologies overseas and in China, having primarily selected Beijing, Tianjin, Shanghai and Jiangxi.

It also discusses micro-grid running, smart electricity distribution and use system control, the relay protection and economy of micro-grid, advanced technology of distribution automation, electric vehicle charging and discharging technology and electricity information collection technology and advanced metering infrastructure.

Chapter 4: New Generation Technology as Distributed Power Source

Chapter 4 introduces the basic principle, mathematical model, advantages and disadvantages of distributed power sources adopted in micro-grid system, including wind power, micro gas turbine, fuel cells and solar-photovoltaic power.

In addition, this chapter also compares various power system energy storage elements, including pumped storage, compressed air energy storage (CAES), flywheel energy storage, the Superconducting Magnetic Energy Storage (SMES), super capacitor energy storage, lead-acid battery energy storage (BESS) and so on.

It also provides a brief description of the control model of the distributed power converter.

Chapter 5: Distributed Power Generation Technology and Micro-Grid Demonstration Community in China

Chapter 5 introduces the Hohhot City Micro-Grid Demonstration Community and Chengde City Project of Distributed Power Generation/Energy Storage and Technique Connecting into Power Network which have reflected the great progress made in the field of distributed power generation and micro-grid technology in China during the last 10 years.

This chapter describes the system design and operation simulation analysis of Da Shengkui Creative Industry Park of Hohhot City in terms of voltage stability and frequency stability.

It also provides a brief introduction to Chengde City Project of Distributed Power Generation/Energy Storage and Control Technique of Micro-Grid Connecting into Power Network and analyzes the negative influences to the grid power quality, system protection and the system operation reliability to reduce the impact to power grids and users due to the lot of distributed power generation simple on-grid.

Moreover, this chapter discusses the main functions, features and application of environment-friendly wind-photovoltaic power/energy storage distributed power generation system.

Chapter 6: Distributed Power Electricity in Japan and Development of Intelligent Power Distribution and Utilization Technique

Chapter 6 specifically introduces the distributed power electricity and development of intelligent power distribution and utilization technique in Japan. Since power system in Japan has basically realized automation in the transmission and distribution system apart from meters, the purpose of the current grid building is to solve the access problem of distributed renewable energy in order to improve the reliabitlity of power supply.

Japan’s smart grid is centered on research and development of new power, load and coordination of the use of the existing power system and looks forward to increasing revenue while promoting the sound development of the environment.

Chapter 7: Smart Grid and Future Grid Research and Development Opportunities and Challenges

Chapter 7 firstly provides a general overview of the School of Electrical and Information Engineering, the University of Sydney, Australia and its association with the Australian federal government and then introduces Ausgrid's $600million Smart Grid, Smart City project.

Smart Grid, Smart City was a demonstration project funded by the Australian federal government, led by Ausgrid and supported by its consortium partners. Under the Smart Grid Smart City project, there are a number of trials expected to complete by early 2014, including Active Volt Var Control, Fault Detection Isolation & Restoration (FDIR), Wide Area Measurement (WAM), Network Customer Trials and EnergyAustralia Trial.

This chapter also introduces several selected projects, including Solve PV Project, PV Coating Technology, Feeder Load Modeling, Feeder Loss Minimisation with Capacitor Banks, Demand Side Management for Network Stability Support, Smart Grid Cyber Security and Future Grid.

Chapter 8: Smart DC Micro-Grids

Chapter 8 points out that the power industry must provide an acceptable return for investors to finance the sector and fund future investment and that there is an urgent need for an economically sustainable industry.

Apart from the discussion about the definitions of "smart grid" and "micro-grid", the war of DC-AC supplies, this section also introduces two projects in the UK: Project Edison and Project Sola BRISTOL. The opportunities and challenges offered by smart DC micro-grids have been outlined in this part.

Project Edison is a demonstration project involving a DC micro-grid operating in the library at the University of Bath. The library includes local storage and offers options for DC lighting and easy access for local generation using renewable energy sources. The micro-grid was designed to demonstrate the feasibility and potential benefits of local DC Networks in terms of system efficiency, financial and environmental benefits together with flexibility gains.

Project SoLa BRISTOL is funded by OFGEM, the Office of Gas and Electricity Markets in the UK, as part of their Low Carbon Network Fund project investigating the implications of using in DC micro-grids for homes, schools and offices. Project Sola Bristol considers Buildings, Renewables and Integrated Storage with Tariffs to Overcome network Limitations.

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Both Projects Edison and Project SoLa BRISTOL have highlighted the value and importance of storage in the DC micro-grid. Both projects have involved battery storage as a key element in the demand management.

Generally, the conclusions are: “The future is bright.” “The future is electric.”

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Chapter 1 Smart Grid–the Way for Renewable Energy Integration to Power Grid

1.1 Introduction

Power industry has been developed for more than one century. Nowadays, electricity is a necessity of daily life. Power system automation technologies have been developed and applied in power grid operation and control since 1960s. The existing power system automation techniques support automatic generation control, automatic fault clearance, automatic voltage regulation, large system inter-connection, etc. The reliability of power supply has been improved significantly due to the application of automation and control techniques in the past decades. Since the beginning of the 20th century, large-scale electric power plants have been developed as the major generation techniques due to the economy of scale of power industry. Thermal power plants that burn fossil fuels, mainly coals, have been used as the major generation sources. In 2009, around 66% of electricity all over the world is generated by fossil fuel power plants. The efficiency of traditional fossil-fuel thermal power plants for converting energy of fuels to electrical energy is usually around 1/3, which is not high. The CO2 and sulfur emissions from fossil-fuel power plants exert pressures on environment.

Nowadays, power industry is facing many challenges from various aspects. With the development of economy, there is an increasing demand for electricity. However, we are facing energy issues caused by energy crisis and environmental problem. The modern society has higher requirement on reliability, security and quality of power supply, but many transmission and distribution facilities currently on operation were built decades ago. Infrastructures for power generation and delivery need to be upgraded.

Smart power grid has been raised recent years as a solution of energy and environmental issues. In traditional power systems, power flows from generation units to transmission and distribution (T&D) grid then to consumers. With the installation of distributed generation (DG) at customer sides, power could also flow from customer side to T&D grid. Generators, grid companies and customers all have information exchange with control center through communication networks. Smart grid technologies apply to all sections of power system, generation, T&D grid and consumer, as well as control center. Customers' role in smart grid is mainly demand response. Smart meters and advanced metering infrastructure (AMI) provide hardware support of demand response.

The role of generation section in smart grid is renewable energy integration. For transmission and distribution systems, smart substations and installations of phasor measurement units (PMU) and wide area management system (WMS) provide the possibility of forecasting fault events in advance. As the brain of the power system, control center play an important role in smart grid. A smart control center requires integrated communication, advanced control and improved interfaces for decision making support. On the other hand, a mature electricity market as well as regulations and policies are needed to facilitate the functions of smart grids.

1.2 Customers Demand Response in Smart Grid

In the U.S. and some European countries, the implementation of smart grid starts from customer sides. Electricity consumers, in the past, are passive users. By installing smart meters and AMI, a customer could adjust his energy consumption pattern according to real-time electricity price. If the customer has his own distributed renewable energy generation, e.g. solar panels and small wind turbines, he can sell surplus electricity to the grid during the peak-load hours. In this case, smart meters will be the smart agent with optimization functions as well as two way communication functions. The AMI system installed over a distribution system will enable consumers to participate in demand response programs. With a well designed economic incentive mechanism, electricity users' energy consumption patterns could be adjusted to an optimum way. For example, some appliances are scheduled to run during the hours of low electricity prices, which are usually non-peaking periods. The surplus electricity generated by customer owned distributed generators are storage in batteries for selling to the grid during the peaking load hours at higher electricity prices. Customer demand response can help shaving peak load, hence reduce the capacity reserve requirement of increasing demand. The implementation of demand response requires 1) AMI and smart meters to measure electricity consumption and response to the electricity prices and commands sent by the system operators; 2) real-time (RT) or time of use (TOU) pricing mechanisms to encourage consumers to participate in the program.

The AMI mentioned in smart grid is different from the automatic metering reading that has been applied in some utilities. AMI has more two-way communication functions. For an AMI system, all smart meters at a home (electricity, gas, heat and water meters) communicate with the data concentrator through local area network (LAN). Through the wide area network (WAN), the concentrator exchange data with AMI host server, which is managed by the meter data management system (MDMS). Installing smart meter is the first step of implementing smart grid. In some countries, electricity utilities have started to install smart meters to their customers. In Italy, smart meters have been installed in over 30 million homes, which lead to 5% energy saving per year. In the U.S. 13 million smart meters have been installed by 2010, more will be installed later. Tokyo Electric Power plans to install smart meters to their 27 million customers free of charge. Some other countries are also planning to start smart meter and AMI projects.

1.3 Renewable Energy Integration to Grid and Energy Storage

Renewable energy generation is an effective solution to environmental and energy crisis issues. However, there are some technical concerns of connecting renewable energy generation. Smart grid provides a technical platform for renewable energy grid Integration.

Renewable energy generation could be installed either at the generation side, such as large wind farms and solar farms, or at the customer side as distributed generation (DG). Distributed generations refer to those small-scaled generators installed close to customers. DGs are usually clean energy or renewable energy based generators, such as, combined head and power (CHP), micro turbine, fuel cell, wind turbine and photovoltaic panel, etc. To a traditional power grid, the concern of connecting DGs to the distribution network is the reverse power flow from DGs to the grid when a local micro-grid generates more power than it consumes. Traditional protection schemes need to be re-designed to accommodate bi-directional power flow.

Large-scale renewable energy generation connecting to power grid is constrained by the security and reliability operation requirements of power systems. Renewable energy, e.g. wind and solar, has intermittent characteristics. The generations of wind farm and solar farm are unstable and uncontrollable. Although power system automatic generation control (AGC) and spinning reserve capacity can compensate some load deviations in short term, the sudden changes of power outputs due to intermittent wind power and solar energy require a much higher amount of compensation in a short time. The traditional AGC and reserve criteria may not be enough. More ancillary services and fast generation compensations are needed. Large capacity of wind turbines will also cause voltage problems and harmonic issues. Until these technical issues are solved, the total capacity of wind farm connecting to a power grid will be limited under certain penetration levels.

Energy storage is the solution to compensate intermittent renewable energy generation once practical and inexpensive energy storage methods are developed maturely. Electric energy could be stored mechanically through pump storage, compressed air, and fly wheel; or stored electro-magnetically through superconducting magnetic storage, and super-capacitor; or stored electron-chemically through lead-acid battery, flow battery and other advanced battery technologies.

Large-scale energy storage system could be installed at the generation side coordinating with wind and solar generation. For example, a combined renewable energy system with wind farms, solar panels and storage system (e.g. pump storage station) will provide a stable output profile of renewable energy to the power grid. A well-developed storage system could also be used to provide ancillary services to power grid. The optimization and coordination of renewable energy generation and storage charging and discharging is a key issue of improving energy efficiency of the combined renewable energy system. The other challenge is developing mature storage techniques that are practical and inexpensive for large-scale storage usage.

Distributed energy storage as well as distributed renewable energy generation are the key components in customer demand response in additional to consumption pattern adjustments using smart meters. Battery is a popular storage method for distributed energy storage. The combination of small renewable energy generators and batteries could be used as stand-alone system or used for grid-connected micro-grid system.

Electric Vehicle (EV), especially EV to Grid (V2G) technique, is a very important issue in smart grid. EV could perform as generation as well as storage with a V2G control system. EV could be used for leveling peak load, and as a backup for power failure. EV is an effective means of street CO2 reduction. V2G is a promising technique for the future. However, to use EV in a wide range, some issues need to be considered 1) A high penetration of EVs may affect the existing power system operation, a smart power grid will have the capability of accommodating high penetration of EVs; 2) Standards need to be set to solve the problem of reverse power from EVs; 3) More charging spots and replacing stations are needed for drained batteries, so it is convenient for customers to use EVs.

Renewable energy and storage integration to power grid will provide a solution to energy and environmental issues. The coordination of renewable, storage and EV will significantly reduce the fluctuation of renewable energy generation. However, there are some barriers of accommodating all generation and storage options in power grid. The cost of owning these generation sources and storages are high. Consumers and investors are not motivated to invest. The techniques of grid-connection with high penetrations are not mature. To break the barriers, the smart grid needs to have 1) applications and standards that support Plug and Play functionality; 2) operational and planning tools; 3) smart sensors and smart controllers; 4) real-time pricing mechanisms.

1.4 Future Control Center and ICT applications

Information and communication technologies (ICT) are the fundamental of power system automation. The existing automation consists of: supervisory control and data acquisition (SCADA), energy management system (EMS), distribution management system (DMS), distribution automation (DA), substation automation (SA), and feeder automation (FA), etc. Most utility companies started to construct their automation systems since 1980s. The automation techniques significantly improved system reliability and service of power supply.

In the past decade, the information revolution has changed human's living style. Applying the latest ICT to power system automation will significantly improve efficiency of energy usage, improve power quality and reduce total cost. According to DOE, the capabilities of smart grid include: self healing, consumer participation, high quality of power, resist attack, accommodate diversified generation options, enable power market, optimize asset, and enable high penetration of intermittent generation sources [1]. ICT will be the fundamental and necessary techniques to implement these functions of smart grids.

Substations are important nodes in a power grid that assemble all monitoring, protection and control devices. Substation also plays a role as collecting data from feeders and consumers, and communicating information with upper level control centers. Smart substations widely dispersed in the grid are key elements of a smart grid. A smart substation should be equipped with accurate data measurement units and data analysis tools for online network analysis. The standard communication and processes inside the station and among stations are also important for information exchange. Phasor measurement unit (PMU) will increase the accuracy of data measurement in power grid. The data measured by traditional remote terminal unit (RTU) is not synchronized. PMU data is synchronized by a global positioning system (GPS). A phasor data concentrator (PDC) collects data from PMUs and sends data to SCADA and wide area management system (WAMS). Using data from PMUs and applying wide area control, power system operating conditions can be accurately monitored and simulated; hence it is possible to forecast fault events before events occur. That will significantly increase the system security and reliability.

The future control center, by applying smart grid technologies, will be able to monitor operation conditions of primary devices, diagnose fault events, clear faults before they occur, support demand response, support intermittent renewable generations using realtime on-line data analysis and system control.

1.5 Conclusions

Renewable energy and customer demand responses are the major solutions of energy and environmental issues. Smart grid provides the platform for renewable energy integration to grid and customer participation. Latest information and communication technologies will improve power system operation though online data analysis and real-time control, hence improve power system security and reliability, and the quality of power supply. Various smart grid technologies applied in power generation, transmission, distribution and consumption will change customers' life styles, improve energy consumption pattern and the environment of the earth.

Chapter 2 Mode of Renewable Energy Power Connection into Power Network

2.1 Centralized Exploitation of Renewable Energy Power in Large Scale and Directly Connecting to Power Network

The mode of centralized wind power and solar energy development in a large scale and directly connecting to the network requires the large electric network to have good ability to absorb the new energy power. Because of the intermittent and time-varying characteristics of wind and solar energy, it requires the network not only to have large capacity, but also to have a strong real-time flexible dispatching capability. Centralized large-scale development of wind and solar energy in the resource-rich region can effectively reduce investment in a project, and accelerate the speed of exploitation of wind and solar power, which mode is mainly adopted in China till now.

According to the Chinese wind power planning, as of 2020, China's goal of total wind power installed capacity is 200 million kW. Eight wind power bases of ten million kW will be built in the northern and eastern coastal areas of China, thus the total installed capacity reaching 150 million kW and the annual generating capacity being more than 300 billion kWh. The eight bases are: Xinjiang, Gansu, western Inner Mongolia, eastern Inner Mongolia, Hebei, Jilin, Jiangsu and Shandong.

Despite the advantage of fast development and low cost using the mode of centralized wind power development in a large scale and directly accessing to the network, wind abandonment is common because the wind changes can't be accurately predicted in real time and thus lacking timely regulation on the grid, rendering it impossible to make full use of the resources have been developed. As of the end of 2011, the northeast, north and northwest regions (the "Three North" for short) access 39.52 million kW of wind power to the grid, generating capacity of 63.537 billion kWh in 2011, and abandoning 12.3 billion kWh of wind power, abandoned wind rate of about 16%.

Table 2.1 The eight wind power bases of ten million kW as of 2020

Wind power base	Planning installed capacity (million kW)	Detailed description of the wind site
Gansu	12.7	Nine wind sites in Jiuquan
Xinjiang	12.0	Focus on Hami Prefecture

Hebei	14.0	Zhangjiakou, Chengde and the offshore area in the east
Jilin	27.0	Songyuan and Baicheng in the west part of Jilin
western Inner Mongolia	38.3	Hohhot, Baotou and Ordos
eastern Inner Mongolia	24.0	Chifeng, Tongliao and Hulunbeier
Jiangsu	10.0	Eastern coastal and offshore wind site
Shandong	12.0	Mainly the coastal and offshore wind site

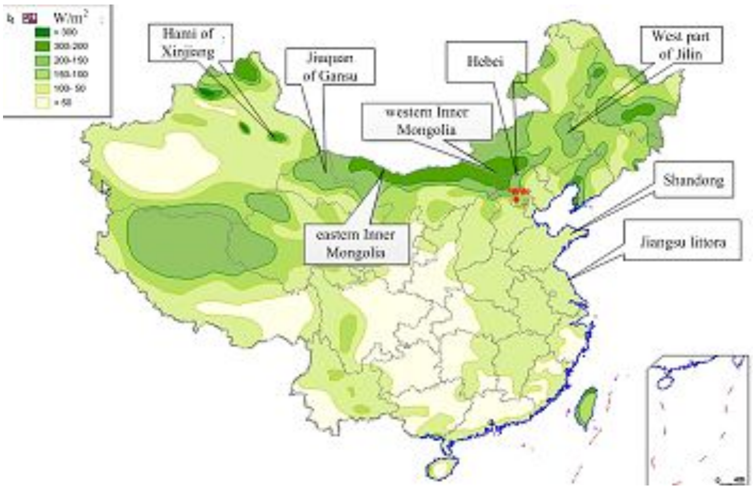


Fig.2. 1 Distribution of Large Wind Power Bases in China

Fig.2. 2 Sketch Map of Wind Power Flows

2.2 Distributed Exploitation and Entering Power System by Micro-grid

The Western European countries that develop wind power early adopt the mode of "distributed development and local utilization". The mode has been adopted by countries all over the world. The centralized large-scale development of wind power in China will become saturated in 2020, and China will promote distributed development in the future, developing 6-8 m / s low-speed wind power projects. As to photovoltaic power generation, distributed generation project will be prioritized, as well as the market. By 2015, the installed capacity of solar power in China will reach 21 million kW, and it will be 50 million by 2020.

With the development of smart grid and smart power distribution & utilization technique, distributed generation accessing to the network by micro-grid has make a major breakthrough in theoretically and demonstration applications, and engineering applications is just around the corner. The pilot project of hybrid wind and photovoltaic distributed power generation and micro-grid accessing to the power system, built by NARI Technology Development Company Limited and Jibei Electric Company Limited of the State Grid in Chengde, Hebei, has run incessantly nearly 7000 hours since the end of November 2011 to the end of September 2012, generating about 65,000 kwh, effectively improving the quality of local voltage and the reliability of power supply.

The micro-grid is composed with power source, power load, energy-storage device as well as control & protection system. The intermittent and time-varying new energy accesses to the micro-grid and stable and controllable electricity can be got; what's more, according to the need of large electric system, micro-grid can also provide reactive power and function of harmonic control, making full and effective use of the resources that have been developed.

Chapter 3 Status and Trends of Distributed Power Source and Smart Power Distribution & Utilization Technology

3.1 Research Status of Distributed Power Source and Smart Micro-grid

Many developed countries and regions such as in Europe, United States and Japan have completed the basic theoretical research of the micro-grid and intelligent power distribution and utilization system, initially established the distributed generation and micro-grid model and simulation analysis tools, completed the control and protection strategies, communication protocols of the micro-grid and intelligent power distribution and utilization system, solved the basic theoretical issues of operation, protection and economic analysis through laboratory tests and verification of demonstration community with intelligent power distribution and utilization system. The goal of future research is to develop advanced control strategies, integrate the interactions of multiple micro-grids and intelligent power distribution management system (DMS), carry on standardized design and field test to further verify the running effect of control strategy in the intelligent power distribution and utilization system constructed by the actual micro-grid, estimate the impact of micro-grid on power system operation and planning.

Here is the survey result of some typical pilot projects of intelligent power distribution & utilization system constructed by actual micro-grids in the world.

3.1.1 Research of Smart Power Distribution & Utilization System Based on Micro-grid in North America

First of all, the concept of micro-grid first proposed by The Consortium for Electric Reliability Technology Solutions (CERTS) is one of the most representative concepts of micro-grid. In its report of micro-grid concept, American CERTS provided a detailed overview of the main idea of micro-grid as well as critical technical problems, and explained the two major components of micro-grid—static switch and autonomous micro power supply, systematically expounded the structure, control mode, relay protection and economic evaluation and other related issues of micro-grid. At present, the American CERTS's preliminary theory and method about micro-grid has been successfully validated in Walnut micro-grid test facility of American Electric Power Company. Mad River micro-grid connected the northern United States power system is the first American micro-grid demonstration project. It examined the model, simulation methods, protection and control strategies as well as economic benefits of micro-grid and explored the formulation of the management rules and regulations of the micro-grid. Therefore it is a successful example of micro-grid projects in the United States. At the same time, the USA Department of Energy proposed a phased plan about the placement and utilization of micro-distributed power generation system in the form of micro grid, and gave a more detailed description of the future development and programming of micro-grid in the “Grid 2030” development strategy. In addition, two Canadian hydropower companies, BC and Quebec, have begun to carry out the construction of the "micro-grid" demonstration projects and especially a running test of micro-grid’s converting to isolated operation initiatively, in order to improve the power supply reliability in the user side by reasonable placement of IPP (Independent Power Producer).

Micro-grid in America is jointly funded by the U.S. Department of Energy (DOE) and the California Energy Commission (CEC), and formal studies began in 2003. The Consortium for Electric Reliability Technology Solutions (CERTS) is the most famous micro-grid research institutions which first proposed the concept of micro-grid in the “The concept of micro grid” white paper written for the U.S. Department of Energy and the California Energy Commission in 2003. This concept has been a successfully tested on the test platform in the laboratory of University of Wisconsin. In order to further validate the preparatory and rationality of the concept, CERTS started to build micro-grid demonstration area in November, 2006 and established an experimental platform of intelligent power distribution & utilization system, constructed by micro-grids in the American Electric Power Company Dolan Technology Center, shown in Fig.3.1.

Fig.3. 1 Layout micro-grid test platforms in Dolan Technology Center

3.1.2 Research of Distributed Generation and Micro-grid in Japan

Japan carried out the study of micro-grid on account of went short of energy sources increasingly and rapid growth of load demand. At present, Japan has established several micro-grid projects. Renewable energy and new energy has been the focus of the Japanese power industry, in recent years, so the New Energy and Industrial Technology Development Organization (NEDO) strongly supported a series of micro-grid demonstration projects and encouraged the application of renewable and distributed generation technologies in micro-grid. Series of studies carried out by

Japan about micro-grid technic and micro-grid integration control, combining use of heat and power, which provide a broad development space for the application of the distributed generation system and large-scale independent system that is based on renewable power.

NEDO launched a regional distribution network project containing renewable energy in 2003 and established three micro-grid demonstration areas in Aomori Prefecture, Aichi Prefecture and Kyoto Prefecture. The demonstration area located in Hachinohe City of Aomori Prefecture is shown in Fig.3.2. That project supply electricity and heat by the only use of renewable energy (wind, solar and biomass). The power includes biomass gas generation 3*170kW, lead-acid battery 2*50kW, photovoltaic power generation 80kW, wind power generation 20kW, thus a total of 710kW. Load includes: the City Hall 360kW, four schools 205kW, 8 Water Supply Administration Bureaus 38kW, thus a total of 603kW. The micro-grid system accesses to the external power grid through the point of common coupling (PCC). During the nine months' running, the power system has reduced electricity use purchased from the grid and CO2 emissions have significantly reduced as well, since the establishment of micro-grid elevated the utilization factor of renewable energy. During one week's isolated running, the system has maintained the frequency at the range of 50±0.5Hz, properly keeping the stability of the system.

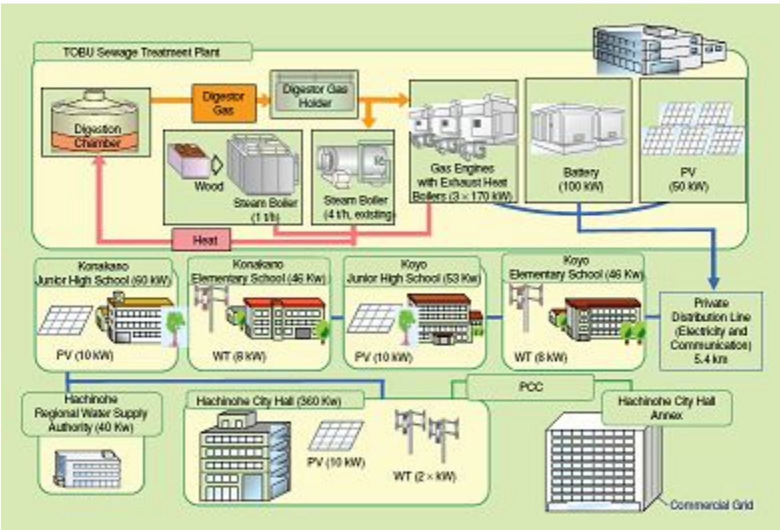


Fig.3. 2 Demonstration community with intelligent power distribution and utilization system constructed by micro-grids in Aomori Prefecture

Kyoto Economic and Energy Engineering in Kyoto Prefecture was built and began running in December 2005. The project power consists of photovoltaic power generation 50kW, wind power generation 50kW, biomass generation5× 80kW, molten carbonate fuel cells 250kW and a battery pack 100kW. The energy control center communicates with the distributed generation through telecommunications network so as to balance the energy supply and demand. Once the balance break, the system can be adjusted within 5 minutes, and is planned further shortening in the future.

In Sendai, the New Energy and Industrial Technology Development Organization (NEDO) also establish a demonstration community with intelligent power distribution and utilization system offering power quality reliability services which had been completed in 2006. The purpose of this project is to study if multiple reliability of power quality can meet the needs of a range of users at the same time. In addition, private enterprises and departments also studied micro-grid. For example, Shimizu Corporation and the University of Tokyo jointly developed the control system of micro-grid, and have already established a pilot project in the Research Center in Tokyo. In Japan, the micro-grid technology system mainly focuses on how to take advantage of new energy generation and how to provide multiple reliability of power quality when maintaining the power supply of traditional power grid. Now the studies of micro-grid in many fields examine the feasibility of micro-grid, but clean economy and environmental benefits are not taken into account. The micro-grid still faces many challenges in economic evaluation.

3.1.3 Research of Micro-grid in Europe

Taking the electricity market demand, security of power supply, environmental protection, and other factors into comprehensive consideration, Europe proposed the goal of the “smart grid” in 2005, and made the introduction of technology realization scheme of the plan in 2006. As the European power development goal for 2020 and the further future, the plan indicates that European electricity grid will be flexible, accessible, reliable and economic in the future. Based on these characteristics, Europe proposed to make full use of distributed power generation systems, smart technology, advanced power electronics technology to achieve the efficient integration of centralized power supply and distributed generation, and actively encourage the independent operators and power producers to participate in the electricity market transactions, and promote the development of grid technology. Because the micro-grid is smart, clean and efficient and has the feature of multistage diversified application of power, it will be an important part of European future development in the grid.

Currently, EU mainly funds and promotes two micro-grid projects, “Micro-grids” and “More Micro-grids”, and attempts to expand and develop the concept of micro-grid to increase the penetration of micro-generation devices. They have initially formed the basic theory of running, controlling, protection, security, and communication in the field of intelligent power distribution and utilization system constructed by micro-grid, and successively established various scale of micro-grid experimental platform in Greece, Germany, and Spain. The German Institute for Solar Energy (ISET) built the largest micro-grid laboratory with capacity of 200 kVA and designed and installed a simple energy management system in the experimental platform. In the future, EU will focus on the control strategies of renewable micro-generation system, micro-grid planning, research of multi-micro-grid management operation optimization tool, formulation of technical and commercial specifications, promotion of exemplary micro-grid test platform, and comprehensive assessment of power system operation performance. These measures will pave the way to make the large-scale distributed power generation systems and renewable energy systems connected to micro-grid and make the transformation of the traditional power grid to the smart grid.

EU Framework program is one of the largest official technology plans in the world today, which has the characteristics of high level of research, wide field of research, huge investment and many countries to participate in. EU Fifth Framework Programme (from 1998 to 2002) funded the pioneering studies of micro-grid, and formed a huge research team headed by Athens National University of Science and Technology, including 14 organizations from 7 EU member states. The achievement of research included: (1) Completed the distributed generation modeling and the steady-state dynamic analysis software; (2) Formed principles, control algorithms, local black start strategy for micro-grid isolated and grid connected operating (3) Defined the necessary conditions of response of distributed generation interface and its intelligence as well as the quantitative method of reliability (4) Complete the micro-grid grounding and protection method as well as the laboratory-scale micro-grid with a variety of functions. Subsequently, under the funding of EU Sixth Framework Programme (from 2002 to 2006), the research team further expanded the scale, recruiting some manufacturers such as Siemens and ABB and some power enterprises and research teams from EU member states. The object of the study also developed to parallel operation of multiple micro-grids in order to achieve the technical and commercial access of multiple micro-grids in the electricity market environment. At the same time, EU has also established several demonstration community with intelligent power distribution and utilization system constructed by micro-grid. The Kythnos micro-grid project built by Greece CRES Company is shown in Fig.3.3.

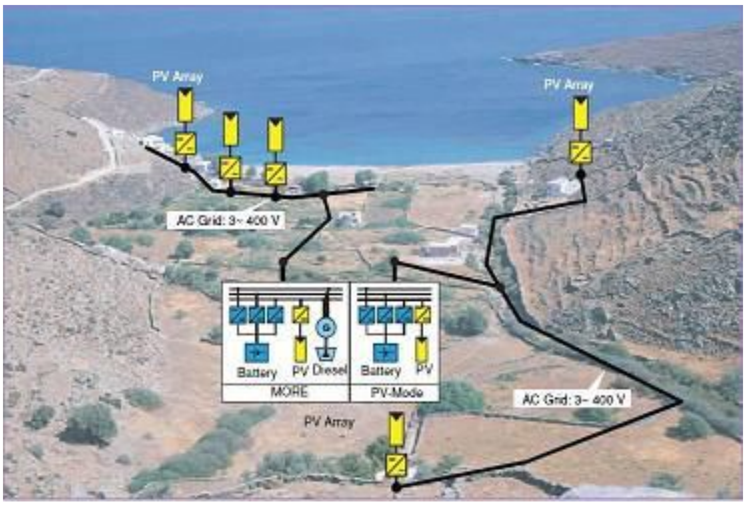


Fig.3. 3 Kythnos micro-grid demonstration project

The micro-grid is located in Cyclades, the southern Aegean, and supply power for 12 residents. The power consists of photovoltaic cells of 10kW, battery group of 53kWh and a diesel engine group of 5kW. Wha's more, the photovoltaic cells of 2kW were installed on the roof of the control building, providing power for monitoring and communication through SMA inverter and a battery pack of 32kWh. The power supply of the residential area depends on a reliable unidirectional circuit composed of three parallel SMA battery inverters group. The battery inverters group can work in the mode of frequency droop: when the battery pack power is low, it allows information to flow switch load controller; when the battery pack is in saturated condition, it restricts the power output of photovoltaic inverters group.

Netherland's Continuon Company set up a micro-grid project in the holiday park in Bronsbergen. There are more than 200 households and the photovoltaic power generation of 315kW in this area. The households are connected to the low voltage transformer through 4 feeders of about 400 m. When the load is relatively low in the day, most of the power generated by the PV injects the medium voltage network. At night, the network outputs the power to meet the needs. In the photovoltaic power generation, the high voltage and large voltage distortion of the feeder end have been taken into account. Additionally, when the micro-grid runs in isolated operation, the improvement of power quality can be done by the power electronic devices and energy storage.

German company MVV Energie in Mannheim-Wallstadt, an ecological zone containing approximately 1200 residents, established multiple long-term test points of micro-grid and intelligent power distribution and utilization system. Photovoltaic power generation is 30kW, and more distributed generation is planned to put in use in the future. The first goal of the test is the load management in the user-side. Within two months in the summer of 2006, more than 20 residents and a kindergarten will join in a project called "bath with the sun". As the information of photovoltaic power generation can be acquired by users, when users generate electricity directly by photovoltaic cells, the load will be transferred according to the situation. The result shows that users significantly transferred the load: the load was transferred from the peak period at night to the period of strong solar radiation in the day, from the cloudy periods to the sunny periods.

In addition, Denmark's OESTKRAFT, Italy's CESI, Portugal's EDP and Spain's LABEIN each established the test point of Micro-grid and intelligent power distribution and utilization system in their respective countries and studied micro-grid and intelligent power distribution and utilization system.

Those results of research have become an important part of the EU "smart grid—outlook and strategy of European future grid". The plan of smart grid launched in 2005, aiming at completing the vision and strategy of the grid development in Europe after 2020. As the programmatic goals of the Europe's future power grid development, in the plan of smart grid, main frame structure of the future power system is the combination of the centralized power generation, long-distance power transmission backbone network, regional transmission and distribution network and distributed generation systems with core of micro-grid. It can reduce investment and energy consumption, improve energy efficiency, improve reliability, flexibility and quality of power supply and make European grid meet the challenges and opportunities of the 21st century as well as energy demands from the society, environment and politics.

3.1.4 Research Status of Micro grid in China

At present, the studies of the micro grid technology and renewable energy power generation system in China is still in its infancy in China but the micro-grid technology has been included in the Ministry of Science and Technology “863 Program 2007 annual thematic topics in the field of advanced energy technologies”. And the micro-grid studies have been carried out in Tsinghua University, North China Electric Power University, Institute of Electrical Engineering, Academia Sinica, Tianjin University, Hohai University, Southeast University and other units. Cooperating with Liaoning Hi-Tech Energy Group Company, Tsinghua University first applied the micro-grid to the practical engineering in the country and accumulated a wealth of practical experience and academic achievements. Tianjin University’s research “Related basic research of distributed generation energy supply system” won the national 973 project fund. Hohai University has close academic cooperation and exchange with Glasgow Caledonian University and studied the micro grid together. At the same time, Hohai University also carried out a lot of research in the field of micro-grid with Hiroshima University. The National High Technology Research and Development Program (863 Program) established two distributed generation supply and intelligent power distribution and utilization system demonstration project in northern and southern China in 2007. Currently, the southern Combined Cooling Heating and Power (CCHP) micro-grid intelligent power distribution and utilization system demonstration project is under construction by China Southern Power Grid Company in Shenzhen. The project is Shenzhen Science and Technology Park micro-grid intelligent power distribution and utilization system demonstration area based on three gas turbines CCHP. Another project is northern CCHP demonstration project established by China Power Investment Corporation in Hohhot, Inner Mongolia, called “Distributed CCHP System of MW-level Integrated Technology and Demonstration Area in the Northern Region”. The project is a demonstration area with micro-grid intelligent power distribution and utilization system based on two gas turbines Da Shengkui CCHP. Therefore, the characteristics of micro-grid and intelligent power distribution and utilization system constructed by the micro-grid fit overall the demand and direction of China’s Electric Power Development and there will be a broad prospect in our country. So, the micro-grid parallel operation control theory is the key technical problem of the application and promotion of micro-grid and intelligent power distribution and utilization system.

3.2 Application Status and Future Prospect of Smart Power Distribution & Utilization Technique

3.2.1 Overseas status

The earliest city in the world to fully use the application of the “Smart Grid” is Boulder City, built by Xcel Energy Corporation of American in Colorado in 2008. The Smart Grid in Boulder City is a high-speed, real-time and two-way communication system, including smart substation, user energy control system and sensors for rapid diagnosis and error correction of network failure. A new system of measurement has been established in the entire grid, all households in the city installing a Smart Meter. By supporting the access of distributed clean energy, citizens have a priority in using the clean energy such as solar power and wind power through the Meter. Meanwhile, the Substation after upgraded could collect the electricity consumption of every household, re-equipping with power if there are problems. In addition, the Spanish Power Company and local government are carrying out a Smart City pilot in cooperation in the southern city, Puerto Rea, launched in April 2009, which plans to be completed within four years. It involves 9,000 users, a substation and five medium voltage lines, 65 transmission line center, improving the existing power grid in several aspects, such as in the grid, the family, the metering infrastructure.

The oversea has had significant research of the intelligent power distribution and utilization system Technology, such as the research of “triple play” technology based on the power optical fiber, construction of communication network platform and discussion of operational mode, the integration of data acquisition, communication processing and control by distribution automation. Additional, many abroad enterprises also attach great importance to the research and development of intelligent power distribution and utilization technique, such as Germany’s Siemens, Schneider, U.S. COOPER company, Motorola, British ABB, Japan’s Toshiba Corp. and so on. They involve in electricity distribution automation and intelligent power distribution and utilization technique to varying degrees. Overall, it can be summed up several following characteristics of abroad intelligent power distribution and utilization technique: the combination of Intelligent power distribution and utilization technique pilot in one step and partial technology gradually popularity, especially the promotion of Smart Meters; promoting the micro-grid project pilot and considering the development of distributed generation and micro-grid depended on the local demands; guiding the user to participate in demand-side response through Smart Meters and related electrical tariff policy, economizing energy and easing grid pressure; actively carrying out cutting-edge research and discussion of Intelligent power distribution and utilization technique.

3.2.2 The domestic current situation and future prospect

Currently, intelligent power system in our country is in the primary pilot construction phase. Until the end of 2011, China had has some intelligent electricity distribution parks which are under construction or about to be completed. To introduce the development status of intelligent power distribution and utilization parks in our country, this section primarily selected Beijing, Tianjin, Shanghai and Jiangxi four representative demonstration projects.

In May 2009, the State Grid Information and Communications Limited Company set up two smart grid pilot user services in Beijing Lianxiang Park community and Fucheng Road No. 95. Through the use of optical fiber composite low voltage cable, the smart grid user service system of Lianxiang Park project achieve the fiber while the power line reached to the home, as a result achieving a two-way, real-time interaction of grid and users. The key features realized include three table (water, electricity, and gas), collecting information, two-way real-time communication, management of home appliances, responding to the power peaking requirement, providing community services and security services, realizing the “triple play” of power network, information network and communication network. The roof also installs eight solar panels, not only to meet the demands for electricity in the home, but also to be fed into the network when the power surplus and earn the power generation cost. Meanwhile, it also has functions remote control which can control switch on-off remotely and easy to interrupt connection with distributed sources to ensure the maintenance of security. The micro-grid could to be connected with network in appropriate time by tracking the frequency, amplitude and phase of the power grid, while the grid has electricity surplus.

In September 19, 2011, the most popular coverage area and the most complete function of smart grid demonstration area at present in the international-Zhongxin Tianjin Eco-city smart grid demonstration project-have put into operation successfully, which is the first smart grid demonstration project in our country. Zhongxin Tianjin Eco-city intelligent power distribution and use park located in Tianjin Binhai New Area, adjacent to the Tianjin Economic and Technological Development Zone, Tianjin Port, waterfront leisure tourist area, between the Tanggu District and Hangu District. It has a total area of about 31 square kilometers, planning to live a population of 350,000. The demonstration project constructs a small micro-grid system by six kilowatts of wind power and 30kW photovoltaic, and 60kWh of energy storage devices. It cover six links about generation, transmission, transformation, distribution, use, scheduling, including totally 12 sub-projects about distributed power access, energy storage systems, smart grid equipment condition monitoring system, intelligent substation, power distribution automation, power quality monitoring and control, information collection system, intelligent power district or building, electric vehicle charging facilities, communication and information networks, the grid platform of intelligence operation visualization and intelligent power supply operating room. After the project put into operation, it can meet the renewable energy utilization ratio not lower than 20%; smart meter coverage of 100%, power supply reliability rate of 99.999%, reaching the international advanced level. In addition, some frontier technologies of the current smart grid are fully reflected in the project, such as the national first integration of photovoltaic power generation, wind power generation and a relatively complete micro-grid system of advanced energy storage technology, which fill in the field blank of our micro-grid distributed power access technology and micro-grid control technology. Therefore it has important demonstration significance. By 2020, the eco-city will all adopt the clean energy and green building, and the alternatives of renewable energy, such as solar power, sea power, wind power will be about 24.62% of the electricity consumption of the entire eco-city; The Zhongxin eco-city smart grid select lithium-ion batteries as the main energy storage device, building a centralized storage station to ensure the power output of wind power and other new energy, as to improve energy efficiency by “load shifting”. To cooperate with the eco-city traffic planning, Eco-city will build 3 large-scale charging stations, 3 medium-sized charging stations and 300 alternative current charging piles by 2015. According to the eco-city planning scheme, smart grid community will achieve “three table combination” of water, gas, electricity and “four network integration” mode of cable, telephone, internet, electricity network; smart grid community provide a variety of intelligence services, realizing the information collection and control of sensitive load appliances, and at the same time establishing a home security system integrating emergency, gas leak, smoke detector and infrared detection. It also includes the meter inquiry, property distribution, and value-added services such as network, medical and so on.

In addition, the Shanghai World Expo is another representative intelligent electric distribution and use park demonstration project, also the first true sense of the Smart Grid Demonstration Garden in our country. This project totally includes nine demonstration projects of new energy access, energy storage systems, intelligent substation, distribution automation systems, fault repair management systems, power quality detection, information collection system, intelligent buildings or communities and electric vehicle charging and discharging station, and another four demonstration projects, including smart grid scheduling technology support systems, information platform, intelligent transmission and visualization display. The features of the project are listed as follow: First, built a new energy access comprehensive system, covering the wind farms, photovoltaic power plants, energy storage systems, electric vehicle charging and discharging stations and part of the comprehensive utilization of resources units in Shanghai, realizing an optimal complement of various forms of energy, improving the utilization ratio of resources; Additional, the full realization of automatic distribution enable the distribution network to have a self-healing function; Finally, the project also built a prototype system with function of bi-directional order electrical energy conversion mode (V2G), realizing the integration of grid scheduling and marketing systems, as well as the energy exchange between car battery pack and two-way grid, showing the broad application prospects of electric vehicles as mobile energy storage devices.

Aside from the intelligent electricity distribution park been put into operation above, another significant smart grid integration technology research and demonstration project of the State Grid Corporation — Jiangxi Gongqing city smart grid demonstration project—is under construction. The area of the pilot is approximately 6.5 square kilometers, and the first investment of the project is about 101 million Yuan, the implementation period from January 2012 to December 2014. The distinctive feature of the project is integrating the successful smart grid technologies piloted by the State Grid Corporation into a same platform to display and apply, promoting the systematization, utilization.

Another feature of the project is the introduction of international cooperation-combines China-Finland digital eco-city and China-Japan Smart Community-including the energy efficiency management of the micro-grid, factories and buildings. This project is planned to build 10 sub-projects about clean energy access and energy storage systems, distribution automation, power quality monitoring, the information collection, intelligent community, electric vehicle charging facilities, interactive business hall, the Emergency Command Center of Things applications and communication information network smart grid visualization platform. It will display the advanced features of smart grid information, automation, interactive. By embedding the advanced intelligent power system technology into cities, it will bring people a new low carbon way of life, having a remarkable demonstration effect to the replication, promotion of other cities and regions.

3.3 The Key Technology of Smart Power Distribution & Utilization System Based on Micro-grid

3.3.1 Micro-grid running

There are grid connected and isolated two kinds of micro-grid running mode.

Grid connected mode means that the micro-grid offers excess energy to the external main power grid or supplements the lack of its own generating capacity form the grid in normal condition. Micro-grid experimental platform proves that by reasonable control strategy, the micro-grid can run in grid connected or isolated mode and can convert smoothly between the two.

Isolated mode means that the micro-grid can break the connection with the external main grid and run by itself, and the DGS supplies power for the load in the micro-grid system when detects external grid failure or the power quality does not meet the requirements. It is the isolated mode that provides greater reliability and uninterrupted power supply.

After conducting a dynamic model of micro-grid by PSCAD/EMDTD or Matlab/Power Simulink, studying the feasibility of isolated running mode in the case of electromagnetic transient characteristics and intentional or unintentional isolation, it proves that the distributed generation system that is based on electronics interface as well as the energy storage can ensure the flatness of mode conversion and reduce the impact of isolated mode, ensure the angle stability and voltage quality.

3.3.2 Micro-grid and smart electricity distribution and use system control

Relative to the main network, the micro-grid can be used as a modular controllable unit, in the internal providing energy to meet the users' load needs. To achieve those functions, it must have a good control and management of the micro-grid, the main control devices including distributed power generation system controller, controllable load management, central energy management systems, and protection devices. Micro-grid should be done to make quick and independent response based on local information on the grid on the operating control facet. If the voltage drops, failure occurs or power outages, the micro-distributed power generation system should take advantage of the local information to automatically convert to independent operation, no longer accepting the unified control of the traditional way.

In general, the main objective of the micro-grid control:

1) Adjust feeders power flow of the micro-grid, reactive and active power independent decoupling control;

2) Be able to adjust each micro-power voltage at the interface, to guarantee the stability of the voltage;

3) When it operating along, ensure that each miniature power supply can respond quickly to share the user load;

4) Depends on the fault conditions or the system needs, smoothly and independently realizing separation with the main network, side, abreast or both the transitional conversion run;.

At present, the main micro-grid control methods:

1) Control based on power electronics technology Plug and Play (Plug and Play) and point-to-point (Point to Point):

Based on the micro-grid control objectives, the method chooses the similar droop characteristic curve to conventional generators (Droop Character) flexibly as micro-power control way, using the frequency active drooping curve of the system to assign dynamically the imbalance of power to each unit to assume, guaranteeing the isolated micro-grid power supply and demand balance and unified of the frequency. It has simple and reliable features. But at present, the method has not taken into account of the recovery of the system voltage and frequency—the secondary frequency problems of the conventional generator. Therefore, when the micro-grid suffered serious damage or interference, it is difficult for the system to ensure the quality of the frequency. In addition, the method is designed for control of power electronics technology, micro distributed generation system, never considering the coordination control between traditional generators such as small gas turbine or diesel engine and micro-grid.

2) Control based on the power management system:

The method uses different control modules to control active and reactive power respectively, meeting the requirements of the micro-grid P/Q, V/f and other control modes. Especially when adjusting the power balance, it adds the frequency recovery algorithm, which meets the requirements of frequency quality. In addition, to meet the different needs of the load in micro-grid for reactive power, the power management system takes a variety of control methods and adds VAR compensator, thereby increasing the flexibility of controlling and improving the performance. However, the method has not yet considered the coordination control between traditional generator with excitation system and speed control system, and distributed power generation system with power electronic interface.

3) Control based on multi-agent technology micro-grid:

The method applies multi-agent technology in the traditional power system to the micro-grid control system. Many features about autonomous, response capacity, spontaneous behavior of the agents justly meet the need for micro-grid distributed control system, providing an ability to embed various control without the managers often involves. For example, the typical AEN (Autonomous Electricity Networks) have three stairs control structures, the first stair ensuring the micro-grid reliability to meet the supply and demand balance, the secondary structure optimizing power quality and reduce the voltage and frequency fluctuations, the third structure realizing the economic optimization-the marginal cost equivalents optimize. However, multi-agent technology more focused on the level of control micro-grid frequency, voltage applying in micro-grid. To enable to the multi-agent technology to play a greater role in the control of the micro-grid, a lot of work research are needed.

U.S. General Electric Company (GE) funded to build a demonstration area of the micro-grid smart electricity distribution and use system by the U.S. Department of Energy. The purpose of this project is to develop and test micro-grid energy control management system framework for the wider application of the micro-grid to provide a unified control, protection and energy management standards, as shown in Fig.3.4. The project has been carried to the second stage. The same time, the United States actively carry out micro-grid applications in the military field research, establish energy assurance engineering (Energy Surety Project) in military bases to improve the reliability of the power supply of the national defense projects.

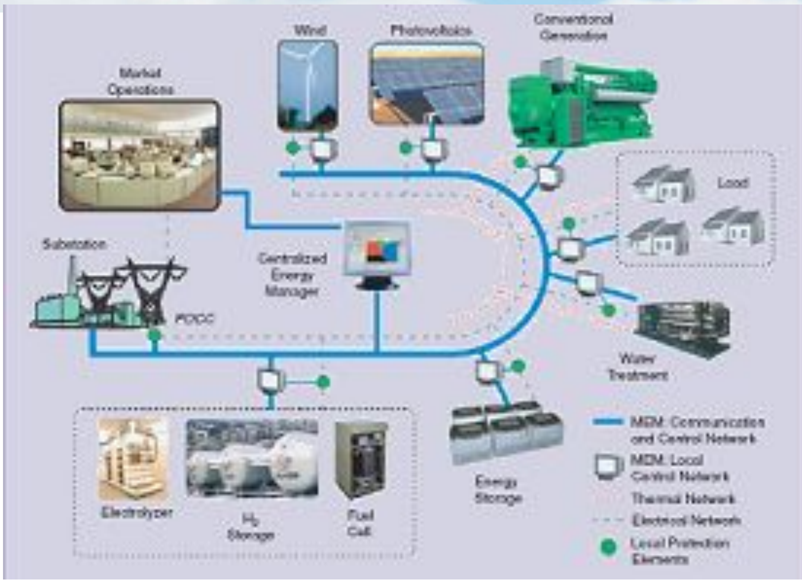


Fig.3. 4 Energy control and management framework of GE micro-grid intelligent electricity distribution and use system

U.S. Department of Energy considers micro-grid as one of the three basic technology of the future power system, and included in the plan of the United States "Grid 2030 - National Outlook about power in the next hundred years". The plan, presented in July 2003, is a programmatic document of the U.S. electricity reform and the main prospect of the United States in the future power system and to determine the various research and development milestones. The micro-grid will be the goal of future development in the United States.

The direction of future micro-grid and smart distribution of electricity control system should focus on the following aspects:

1) Different kinds of micro-distributed power generation system operation and control, including intermittent and controllable as well as the conventional model-based converter mode.

2) Micro-grid stand-alone mode and network operation mode, intelligent frequency, voltage control strategy of the feasibility study.

3) the micro-grid decentralized control method, and poly-dispense controller coordination optimization algorithm, independent voltage regulation and frequency control requirements for each distributed generation system according to their local information, and in accordance with the specific objective function to optimize multiple dispersed the performance of the controller, the overall system performance is optimal, and meet the requirements of voltage and frequency control under a variety of operating environments.

3.3.3 The relay protection of micro-grid

There is fundamental difference between the relay protection of micro-grid and that of traditional power system:

1) Bidirectional power flow

2) The short-circuit current in grid connected mode and that in isolated mode are greatly different because of the multiple distributed generation.

It is the key and difficulty of relay protection of micro-grid that how to response to the failure in the system whether in grid connected mode or isolated mode, and what is more, how to detect the failure of the external system in grid connected mode and ensure the selectivity, speedability, reliability and sensitivity of protection in the same time. In isolated mode, the short- circuit current is only twice as much as normal. As a result, the traditional current protection cannot response or response after dozens of seconds, which cannot meet the need of protection requirement. So more advanced fault diagnosis way is needed. Currently, some experts have proposed a symmetrical current component detection protection strategy aiming at single-phase ground fault and fault between conductors. That starting value of the primary protection can exceed a certain threshold of zero sequence and negative sequence components of current, combining traditional overcurrent protection and achieving good results. As for the micro-grid converting to isolated mode initiatively, the literature suggests a kind of initiative detection technology using three-phase voltage source converter. A disturbing signal is joined in for testing through the d-axis or q-axis of the current controller of voltage source. The amplitude of the voltage can be adjusted by an injection signal on the d-axis, but this method will deflect the frequency of the micro-grid system.

The profound impact of the generator and the type of load capacity on protection, and the impact of various types of distributed power generation systems (traditional small generators and micro inverter-based power), energy storage, as well as micro-grid in two different operation modes and different topology network structure on protection, are all the problems that are worth of studying in the future research of micro-grid protection strategies.

3.3.4 Economy of micro-grid

The economy of micro-grid is an important basis on its promoting and development. In the aspects of economic running, the micro-grid optimization can refer to the knowledge and experience of a large grid operation in the micro-grid scheduling principles, energy trading, and the optimal allocation of resources. More importantly, the micro-grid has many unique advantages, for example, provide different levels of power quality and reliability service for different users' requirements, and feedback electricity and even provide other auxiliary services such as black-start. Seen from the current study, the economy of micro-grid technology is mainly reflected in the following three aspects:

1) Optimization of the investment and running of micro-grid

Micro-grid optimization can be done on the energy management system, which meets the need of local heating, power and cooling, the requirements for the quality of power, the special need of the main grid, management requirement of the user side, and controls the configuration of micro-grid distributed generation system and the total capacity of energy provided by the power distribution system.

2) Assessment and quantization of the economic benefits of micro-grid

Assessment and quantification of the economic benefits of the micro-grid is the direct manifestation and measure for micro-grid investment and running. So far, there is no effective method for a fully quantification of the benefits to micro-grid users, the electricity sector and the whole society. With the development of micro-grid research, the uncertainty of micro-grid economic quantification will become an important research topic.

3) New economic characteristics of micro-grid

The micro-grid economic optimization is greatly different from that of traditional grid. The distributed generation unit, electrical and electronic control equipment and energy storage element in micro-grid have changed the grid structure of the distribution network as well as the characteristics of power flow, thus the micro-grid planning should not only follow the requirements of grid planning, but also take into account some of the new features of micro-grid itself.

3.3.5 Advanced technology of distribution automation

Intelligent power distribution system is an important part of intelligent power distribution and utilization community. Based on the flexible, reliable and efficient distribution network grid structure and high reliability, high security communication network, it can support flexible and adaptive fault processing and self-healing, and meet the access requirements of the high penetration of distributed power and energy storage device and user’s requirements of power quality. Advanced distribution automation is the critical supporting technologies to achieve those goals.

Advanced distribution automation includes running automation and management automation. The former includes distribution operation monitoring and control, automatic fault isolation and self-healing and so on, which is an effective combination of local automation, equipment remote monitoring, and the mature application of analysis software. The latter includes device management, outage management and so on. Advanced distribution automation mainly relying on the technical development of the following two aspects:

1) Construction of intelligent power distribution network structure based on SOA

The intelligent distribution network brings together a number of advanced technology and advanced equipment. During operation, the different types of operating systems, application software are intertwined, so managers have to face the complex operating environment. Therefore, it is very necessary to establish a programming interface and interoperability agreements with public property. The SOA, with its loosely coupled nature of the power grid, enables the grid enterprises to add new services or update existing services in modular way to meet new business needs, thereby providing a more flexible way of building unified intelligent distribution network platform for grid enterprises, which virtually eliminates islands of information, and information is shared.

2) Design of enterprise service bus

With traditional implementations, multiple interfaces must be developed for the complex multi-source information integration, so that not only system will become complex, but also the system maintenance will be very difficult. Therefore, it is necessary to propose a full range of solutions—enterprise service bus (ESB). The ESB provides the user centralized information management and the ability to obtain information, and also enables users to obtain real-time information from multiple data sources, providing a comprehensive solution for data management and content published. Its important core functions include:

Integrate a variety of formats such as database records, distributed applications and word processing documents from heterogeneous data sources;

Manage and process information intensively, organize information through a single view. Use XML to define relevant information and publish it to the staff or application;

Make full use of existing information base, including the existing database management system, real-time database, enterprise application system and distribution automation system.

3.3.6 Electric vehicle charging and discharging technology

As smart mobile energy storage units in the electricity Park, electric vehicles on the one hand transmit the car battery electricity to the grid during grid peak load hours, on the other hand the grid transmits electricity to car batteries of electric vehicles during grid low hours, which can effectively reduce the grid peak and valley difference, can reduce the traditional peaking spare capacity, and finally improve grid utilization efficiency. In the same time, electric vehicles can complete the grid ancillary services such as demand response, which can further improve the efficiency of grid distribution. Electric vehicles, on the other hand, can help the distribution network absorb the renewable energy distributed power generation capacity which is of volatility, and at the same time to get the direct economic benefits through lower electricity price charging during low hours and higher price discharging during peak times. The realization of the above objectives needs to get help from by electric vehicle charging and discharging equipment and development and research of management systems.

The main function of electric vehicle charging and discharging equipment and management systems is to provide real-time information exchange platform for the energy and information interaction by monitoring vehicle energy state, the state of the power grid operation, grid electricity and ancillary services billing information, and to provide information support for electricity to reasonably optimize the two-way flow according to the requirements of the grid or electric vehicles. Because of the dispersion of electric vehicles connected to the grid, it is hard to directly realize the charging and discharging operation controlled by correspondence with the smart grid two-way interactive service system and the electric vehicles. Therefore a electric vehicle discharge management system as a link needs to be built between the two-way interactive service system for smart grid and electric vehicles to achieve real-time information exchange between the electric vehicles and the power grid, and reasonable control of charge and discharge operations of electric vehicles according to the needs of both the electric vehicles and the grid.

From hardware perspective, parallel study of AC and DC charge and discharge pile is needed. The former is mainly used offer charging services for small electric passenger car with charge and discharge motors in the smart electricity park, and the latter mainly offer services for sanitation, public transport and other public service vehicles. Charge and discharge piles need to have the function of intelligent charging and discharging control can communicate with charge and discharge management systems and electric vehicles, is able to know the grid operating state and energy storage of electric vehicles in real time, and control the charge and discharge operations intelligently.

From software perspective, it is necessary to develop advanced electric vehicle charging and discharging management systems, on the one hand to be able to communicate through the charging and discharging equipment with electric vehicles; on the other hand, to be able to communicate with related systems of the smart, combine the real-time status of electric vehicles and the grid, and reasonably control the charge and discharge operations according to the demand of both sides. The system can be responsible for the unified control management of AC charge and discharge piles of the same parking area, and can also be in charge of the unified control management of DC charge and discharge motors of a centralized charging and discharging station.

3.3.7 Electricity information collection technology and advanced metering infrastructure

"Interactivity" is the biggest feature of the intelligent electricity distribution park, so the information collection and the construction of advanced metering system is the key technology to achieve smart electricity distribution. The information collection system is the foundation of building the advanced metering system, and advanced metering system is the expansion of the information collection system. The two are closely linked and mutually reinforcing.

The electricity information collection system is a system collecting, processing, and monitoring in real time electricity consumption information of power users, to achieve functions of collecting the electricity information automatically, monitoring abnormal measurement and power quality, analyzing and managing electricity consumption. The power consumption information collection system is mainly for electricity users and grid junctures to achieve real-time collecting, counting and analyzing of information of the three aspects which are electricity purchase, power supply and power sale, and finally to achieve the purpose of real-time monitoring of purchasing, supplying and selling. It is a technical support system of smart electricity management and service, and offer timely, complete, and accurate basic electricity data for the information management system. Seen from the architecture level, the electricity information collection system mainly includes data collection, data management, automatic meter reading management, fee control management, orderly power management, abnormal consumption analysis, line/variable analysis, security protection and other functions, covering the smart energy meter, terminal collection, master software, security encryption, local and remote correspondence and many other core technologies.

Advanced Metering Infrastructure (AMI) is a complete network and system which is used to measure, collect, store, and analyze users' electricity consumption information, mainly including smart meters, communication networks, as well as data management system. On the basis of two-way metering, two-way real-time communication, demand response, and users' electricity information collection technology, AMI utilizes smart meters to obtain the uses' a variety of measurement information (such as voltage, current, etc.) in time. It supports access and monitoring of user distributed power and electric vehicles access, and achieves a two-way interaction of the smart grid and power users. AMI consists of smart devices, communication networks and data management application software and related systems, establishes a communication network between the smart grid and power users, and integrates various business applications of the power grid and third-party enterprises. Smart meters and smart interactive terminals are the basic units of AMI, which plays an indispensable role, and its main functions are as follows:

- Bidirectional measurement of power, current, voltage, power, and its direction in different periods;

- To achieve two-way communication flexibly and reliably, support real-time communication with the power grid enterprises and support access and control for smart appliances.

- To achieve the remote power-off of arrears, power beyond the limit, of state of emergency and other functions.

- To summon meter reading function periodically, and support collecting metering information of photovoltaic power generation and electric vehicle charging and discharging motor distributed power equipment.

- To record and report abnormal electricity events, including data tampering, abnormal fluctuation and warning and reporting of unauthorized access.

- To monitor control machine to optimize and manage, to achieve real-time monitoring and controlling of user distributed power, electric vehicle power management and management of optimizing consumption of the micro grid.

Chapter 4 New Generation Technology as Distributed Power Source

Distributed Power Sources Adopted in Micro-Grid System Include Wind Power, Micro Gas Turbine, Fuel cells, Sola-Photovoltaic Power and Energy Storage Element.

4.1 Wind Power Technology

Doubly-fed asynchronous generator is mainly adopted as wind power generator in China till now.

4.1.1 Basic principle of doubly-fed asynchronous generator

The double-fed asynchronous generator can be seen as a traditional asynchronous generator which has an open wound rotor and is connected to the applied voltage source, the applied voltage source is introduced by inverter, and inverter can act as an excitation power source by modulating frequency, amplitude and phase of rotor loop current. Not only doubly-fed generator input power to system through the stator, but also exchange slip power with the system through the part of power inverter, and control all the active and reactive power of the doubly-fed generator by controlling the inverter.

Assume that the rotation speed of double-fed asynchronous generator is nr, and the excitation power supply of the rotor generates a rotating magnetic field, whose speed relative to rotor is ne, and the rotating speed of the stator synchronous magnetic field is ns, then the relationship between the nr, ne and the ns is:

$$n_r + n_e = n_s \qquad (4\text{-}1)$$

To guarantee that outputting the power frequency electrical energy when the rotor speed changes, we can regulate the frequency of the rotor excitation current; phase sequence of the rotor excitation current is the same with the stator current when the doubly-fed generator is subsynchronous operating; phase sequence of the rotor excitation current is opposite to the stator current when the doubly-fed generator is oversynchronous operating; rotor is for DC excitation when the doubly-fed generator is synchronous operating.

This AC excited VSCF doubly fed induction generator system has the following advantages:

(1) Allowing the prime mover variable-speed operation in a certain range, simplifying the adjustment device and reduce the mechanical stress when speed. At the same time, the unit control is more flexible, convenient, and improving the operating

efficiency of the unit.

(2) By regulating the amplitude and phase of the excitation current, we can regulate the active and reactive power. Regulate the active and reactive power independently by applying the vector control.

Because of these advantages, the AC excitation double-feedback generator has become mainstream generator in the VSCF wind power field.

4.1.2 The Structure Of The Doubly-fed Wind Generator System

Doubly fed induction generator is shown in Fig. 4.1. In the double-fed wind generator, The stator side of the generator is connected directly with the grid. Rotor side use symmetrical three-phase winding, and connect to the grid side through AC-DC-AC inverter, so it can provide AC excitation for generator, and the amplitude, phase and frequency of the excitation current can be changed, wherein the excitation frequency is the slip frequency. AC-DC-AC inverter is dual PWM inverter, and it can achieve four-quadrant operation. The grid side inverter's main task is to ensure that the current waveform and power factor meet requirements as well as to ensure the stability of the DC bus voltage. Rotor side inverter's main task is to regulate the active power, so it can capture maximum wind energy and provide rotor circuit exciter, and regulate the stator reactive power. The wind turbine use pitch control, when the wind speed is less than the rated wind speed, the pitch angle is 0º.Using maximum power point tracking strategy to capture the maximum wind energy. When the wind speed increases to greater than the rated wind speed, the variable pitch device operates, and the pitch angle gradually becomes larger to limit the output power of the generator near by the rated power. However, due to the rotation inertia of the wind turbine is larger, therefore, the variable pitch device moves with a certain delay.

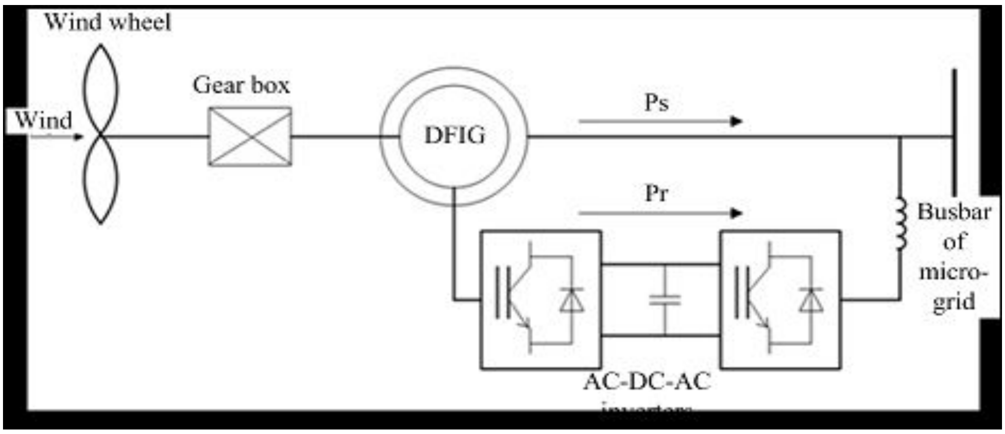


Fig.4. 1 Double-fed wind generator system

4.1.3 Mathematical Model of the Doubly-Fed Wind Generator and Control System

Aerodynamic model:

The output power of the wind generator can be drawn by the wind turbine aerodynamics knowledge:

$$P_w = \frac{1}{2}\rho \cdot \pi R_w^{\ 2} \cdot v^3 \cdot C_P \qquad (4\text{-}2)$$

Wherein, ρ is the air density, R_w is the radius of the wind turbine blade, $\pi R_w^{\ 2}$ is the swept area of the blades, V is the wind speed, C_P is the utilization factor of the wind energy. C_P is an important parameter to characterize the efficiency of the wind turbine and is a function of the wind turbine tip speed ratio and blade pitch angle. It can be expressed as $C_P(\lambda, \beta)$. According to Bates theory, the largest wind energy utilization coefficient of the wind turbine is 0.593. In addition, the tip speed ratio is the ratio of blade tip speed to wind speed, so it can be expressed as:

$$\lambda = \frac{\omega_w R_w}{v} \qquad (4\text{-}3)$$

Wherein, ω_w is the angular velocity of the blade rotation.

For a given tip speed ratio and blade pitch angle, we can calculate the wind energy utilization coefficient by the following formula:

$$C_p(\beta, \lambda) = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5.0\right)e^{\frac{-12.5}{\lambda_i}} \qquad (4\text{-}4)$$

Wherein $\lambda_i = \dfrac{1}{\dfrac{1}{\lambda + 0.08\beta} - \dfrac{0.035}{\beta^3 + 1}}$.

According to the above formula we can calculate C_P with different β 、 λ. The performance curve of the variable pitch wind turbine is shown in Fig.4.2.

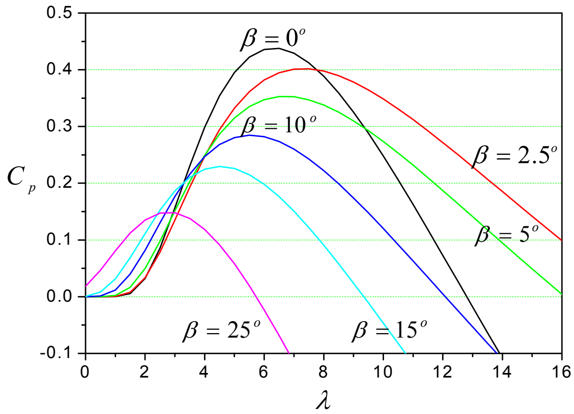


Fig.4. 2 Performance curve of variable pitch wind turbine

According to Fig.4.2 we can know, the size of C_P is related with λ when the pitch angle β to a constant value, and only one C_P that make tip speed ratio maximum, which is called with the optimal tip speed ratio λ_{opt}, and the angular velocity is the optimum rotation speed. Therefore, when β is constant, we can use any of a curve $C_P(\lambda)$ to describe the operating characteristics of the wind turbine fixed pitch.

In a fixed wind speed, along with the change in rotational speed of the wind turbine, blade rotating angular speed makes a big change, and C_P will change correspondingly, thus make the output mechanical power of the wind turbine change. By the formula (4-2) and (4-3) we can obtain the following formula between the output power of the wind turbine and the angular velocity.

$$P_w = \frac{1}{2}\rho \cdot \pi R_w{}^2 \cdot (\frac{R_w}{\lambda})^3 \cdot C_P \cdot \omega_w^3 = k\omega_w^3 \quad (4\text{-}5)$$

Wherein $k = \frac{1}{2}\rho \cdot \pi R_w{}^2 \cdot (\frac{R_W}{\lambda})^3 \cdot C_P$

In order to make the wind turbine maintain maximum power conversion efficiency, we must ensure that the tip speed ratio is always the optimal tip speed ratio, thus ω_w will change with the change in wind speed. By connecting the maximum power point in the different wind speed, we can obtain the optimal power curve P_{opt} of the wind turbine, the power expression is:

$$P_{opt} = \frac{1}{2}\rho \cdot \pi R_w{}^2 \cdot (\frac{R_w}{\lambda_{opt}})^3 \cdot C_{p\max} \cdot \omega_w^3 = k_{opt}\,\omega_w^3 \quad (4\text{-}6)$$

The pitch angle control model:

The pitch control system change the blade attack angle related to the wind speed by controlling the blade angle of the wind turbine, thus change the wind energy that wind turbine capture from the wind. Pitch control adopts different strategies in different cases:

(a) When the wind speed is below the rated wind speed, the pitch angle control is for optimization of the wind turbine power so that wind turbines generate as much electricity in a given wind speed. For variable speed wind turbines, the power optimization can be achieved through the speed change of the wind turbine, so when the wind speed is below the rated wind speed, the pitch angle is usually kept at around 0 º.As shown in the Fig. 4.2, C_P is maximum when β is 0.

(b) When the wind speed exceeds the rated wind speed, variable-pitch device operate and the pitch angle increases to limit the mechanical power of the wind turbine near the rated power, at the same time be able to protect the mechanical structure of the wind turbine from overload and avoid the danger of mechanical damage to the wind turbine.

The pitch control of doubly-fed turbine is wind turbine control model in power system simulation software PSACD, the transfer function shown in Fig. 4.3.

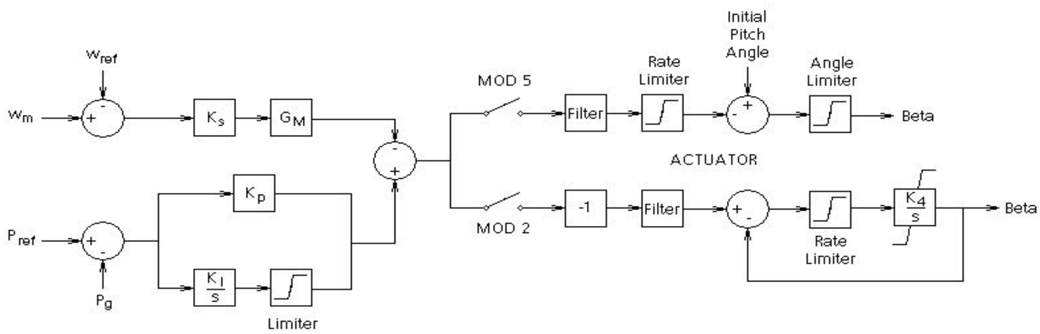
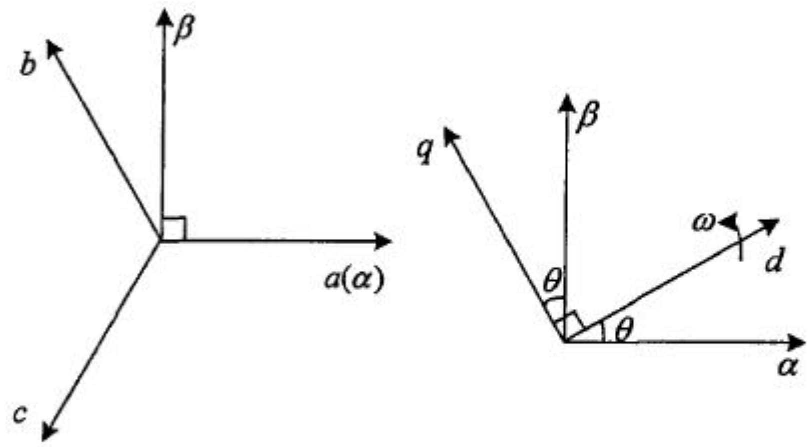


Fig.4. 3 the transfer function of the pitch control

Wherein, W_m is motor mechanical angular velocity, When the generator type is the asynchronous generator, there is no need to consider this variable. W_{ref} is speed reference value, P_{ref} is power reference value(p.u), P_g is output power per-unit value based on motor capacity, K_s is gain, K_p and K_1 is proportional gain and integral gain respectively, G_M is gain coefficient, K_4 is the blade controller gain integral. In addition, MOD2 applies to 3-bladed wind wheel rotating on the horizontal axis, while MOD5 applies to the 2-blade wind wheel rotating on the horizontal axis. The input signal is the measured values of the active power generated by the wind turbine. After comparing with the maximum power reference value we get the error signal. Then input the error signal to PI controller and get pitch angle reference value β_{REF} , at last compare β_{REF} with the actual pitch angle and input the pitch angle error signal to servo mechanism the pitch angle control system.

Dynamic mathematical model of the doubly-fed wind turbines

To simplify the analysis and be applied on vector control change, we simplify the mathematical model of the doubly-fed generator by using the coordinate transformation method. The coordinate transformation is shown in Fig.3.4.



(a) (b)

(a) Three-phase stationary coordinate system to system the two-phase stationary coordinate system rotating coordinate system

(b)Two-phase stationary coordinate to the two-phase

Fig.4. 4 coordinate transformation

In synchronous rotating dq coordinate system, the double-fed asynchronous generator equation is as follows.

Voltage equation:

$$u_{sd} = p\psi_{sd} - \omega_s\psi_{sq} + R_s i_{sd}$$
$$u_{sq} = p\psi_{sq} + \omega_s\psi_{sd} + R_s i_{sq}$$
$$u_{rd} = p\psi_{rd} - s\omega_s\psi_{rq} + R_r i_{rd}$$
$$u_{rq} = p\psi_{rq} + s\omega_s\psi_{rd} + R_r i_{rq} \quad (4\text{-}7)$$

Wherein whose subscript is s represent the stator volume, r represent the rotor volume, ω_s represent the synchronization angular velocity.

Flux equation:

$$\psi_{sd} = L_s i_{sd} + L_m i_{rd}$$
$$\psi_{sq} = L_s i_{sq} + L_m i_{rq}$$
$$\psi_{rd} = L_r i_{rd} + L_m i_{sd}$$
$$\psi_{rq} = L_r i_{rq} + L_m i_{sq} \quad (4\text{-}8)$$

Wherein $L_m = \frac{3}{2}L_{aA}$, L_{aA} is the mutual inductance peak between the stator and rotor.

Torque equation:

$$T_e = \frac{3}{2}(i_{sq}\psi_{sd} - i_{sd}\psi_{sq}) \quad (4\text{-}9)$$

The rotor motion equations:

$$-T_J\frac{ds}{dt} = Tm - Te - D\omega_r \quad (4\text{-}10)$$

Wherein T_J is the inertial time constant of the doubly-fed generator, D is the damping coefficient.

By simultaneously solving the above nine equations we can accurately describe all the dynamic behavior of the doubly-fed generator.

Vector control strategy of the doubly-fed wind turbines:

Since the stator of the doubly-fed generator connect to the constant frequency electric grid, stator resistance is smaller than the reactance, the voltage dropping across the stator resistance is far less than the terminal voltage of the stator, so stator winding resistance can usually be ignored. In synchronous rotating coordinate system, after ignoring the stator winding resistance, the phase difference between the generator stator flux and the stator terminal voltage vector is exactly 90º. If preferring the stator flux as the orientation and take the stator flux vector direction as the d-axis of the synchronous coordinate system, the stator voltage vector will fall on the shaft which is in advance 90º of the d axis, this can further simplify the mathematical model of the double-fed generator, thereby obtain the control equation required by the vector control.

$$P_S = \frac{3}{2} u_{sq} i_{sq} = -\frac{3}{2} u_s \frac{L_m}{L_s} i_{rq}$$

$$Q_S = \frac{3}{2} u_{sq} i_{sd} = \frac{3u_s}{2L_s} (\psi_s - L_m i_{rd}) \tag{4-11}$$

(4-11) constitute the mathematical model of the doubly-fed asynchronous generator rotor side inverter vector control. From the above formula, when the stator flux or the stator voltage keeps constant, stator active power is in direct ratio to the torque component of rotor current irq, while the stator reactive power is completely determined by excitation component ird of the rotor current. Rotor inverter vector control achieves the stator active and reactive power control decoupling, in other words, achieves the electromagnetic torque and rotor excitation control decoupling, that is the purpose of rotor converter vector control. When the control volume is rotor current, vector control structure is shown in Fig.4.5.

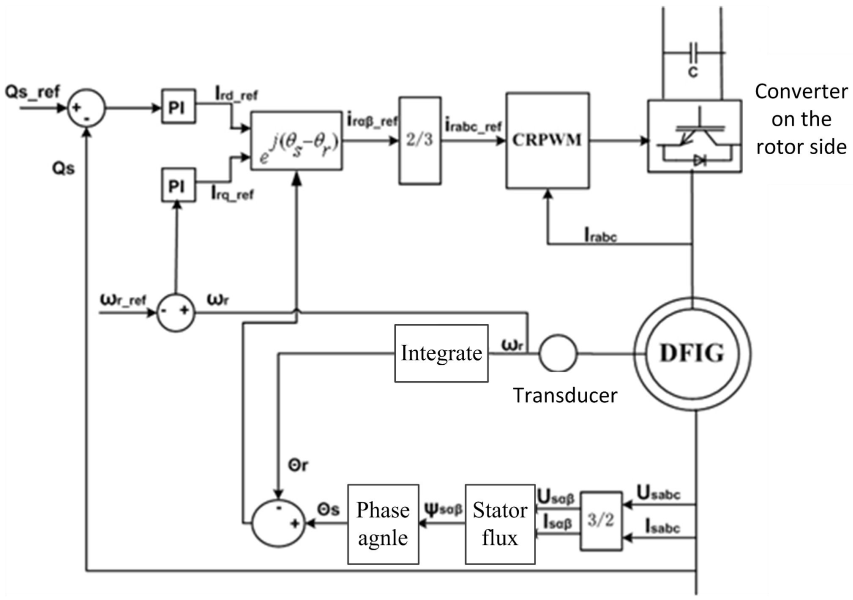


Fig.4. 5 Structure diagram of rotor side inverter vector control

In general control strategy, to achieve unity power factor control of the doubly-fed generator, we set the reactive power reference value of stator side as 0.In the process of tracking maximum wind energy, by using PI control of the deviation between the generator rotational speed and reference speed ωr_ref we get torque component of the rotor current, wherein ωr_ref is corresponding for tracking the maximum wind power point based on the wind speed and generator unit operation.

The control of grid side inverter use vector control program based on the grid voltage orientation. This vector control program is for decoupling control between the active and reactive power which is transferred between the power grid and inverter of grid side. Fig.4.6 shows the inverter structure diagram of the network side.

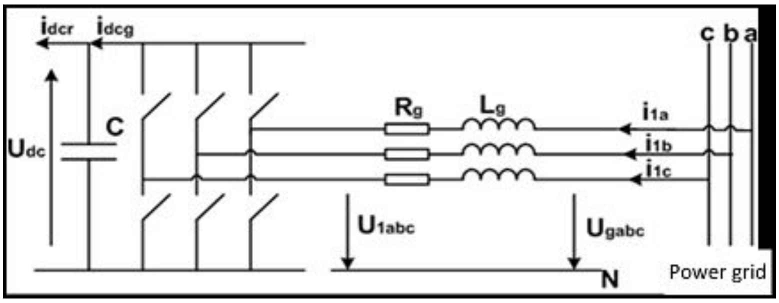


Fig.4. 6 circuit structure diagram of network side inverter

The vector control structure of network side inverter is shown in Fig.4.7.

Grid side inverter vector control is for maintaining the DC bus voltage at a constant value, however, has nothing to do with the direction and size of the rotor power, and control the reference value of i_{1q} based on the requirements of the entire wind turbine for reactive power. In general control strategy, to make full use of the control capacity of the inverter and generate active power as much as possible, we usually set that it has no reactive power exchange between the grid and network side inverter, that is, network side inverter maintain operation in unity power factor.

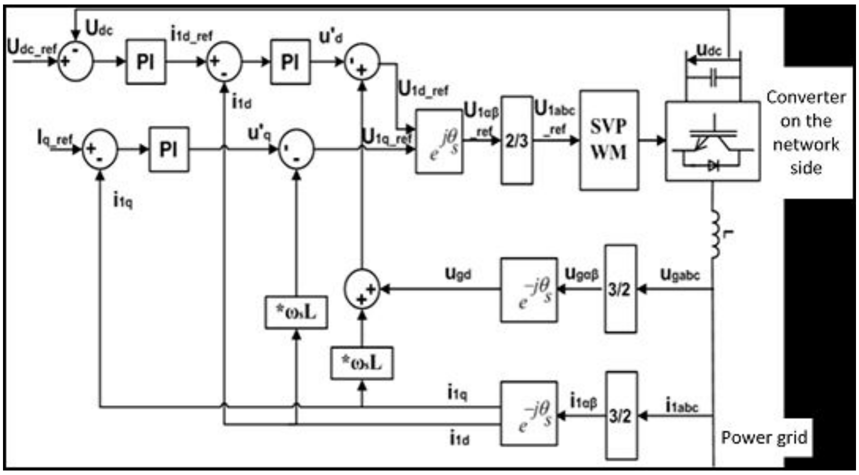


Fig.4. 7 Vector control structure of the network side inverter

4.2 Micro Gas Turbine Technology

4.2.1 Generation technology of micro gas turbine generator

Micro turbine Generator is a newly developed small heat engine which is constituted of gas turbine, compressor, combustion chamber, regenerator, generator and power control. It is fueled with natural gas, methane, gasoline, diesel fuel. The basic structural features of micro turbine generator are using radial impeller mechanical centripetal turbine and centrifugal compressor. The two impellers are back-to-back structure on the rotor, which use efficient plate recuperation, and air bearings that don't need lubrication oil system, so the structure is simpler. Besides, integrated design of gas turbine and generator makes the size and weight of the entire gas turbine generator significantly reduced, and its advantages are significant.

The micro turbine mainly includes the following four parts:

1) micro turbine: this very small, high-speed gas turbine make use of a simple radial design principle and cycle regenerator ,that make it much more simple and reliable, lower maintenance costs, smaller vibration, lower emissions, more compact structure. Its main component are a single-stage radial compressor, the low emissions annular burner, a single stage radial turbine, the pressure ratio and the air bearing, or double Lubricant System bearings.

2) High-speed alternator generators: high-speed generators and micro turbo gas turbine are in the same shaft, because they are very small and can be put into the gas turbine mechanical device, thus they can be composed of a compact, high-speed micro turbo alternator generator group.

3) Efficient recuperator: high efficient, low cost and durable heat exchanger is used to increase the efficiency of the gas turbine. That enables the efficient recuperator to reach the degree of competing with the reciprocating generator group system. Its function is to preheat the air required by the combustion chamber and reduce fuel consumption.

4) Power conversion controller: The high frequency electrical energy output by the generator must be converted into AC power. Power electronic conversion device controlled by the micro-processor can convert the output frequency and voltage, in order to provide different quality and characteristics electrical energy. Power electronic conversion device can adjust the rotation speed according to the load change, also can run according to the external grid load changes, or run as an independent power system micro-controller for remote management, control and monitoring. Since micro turbine has above notable features, micro turbine is used widely. It can be used for distributed generation and CCHP systems and can be used for distributed generation and CCHP systems and micro turbine - fuel cell combined system, etc. Thus, the advanced micro turbine technology has received widespread attention all over the world.

4.2.2 Working Principle and Mathematical Models of the Micro Turbine Power Generation System

The high-speed uniaxial structure micro turbine is the mainstream product, and is used for small CHP power unit the most commonly. When using single axle high-speed structure micro turbine in the micro-grid, the operating status of the unit, control methods and other factors have some impact on its dynamic characteristics, in other words, we can control the active and reactive power according to the given value, and can easily achieve the V/f control to guarantee the stability of frequency and voltage when micro grid is isolated operation. This chapter wills analysis the working principle, mathematical model, varieties of operating characteristics, control strategies of high-speed uniaxial structure micro turbine power generation system in detail.

High efficiency system, compact structure and high reliability are the characteristics of uniaxial structure micro turbine power generation system. Typical uniaxial MT system structure is shown in Fig.4.8. System includes a micro turbine, permanent magnet synchronous generator, power electronics conversion device, heating and refrigeration units. Fuel control system convey the gas to the combustion chamber, and combust with the high pressure gas supplied by the compressor full, then it come into being the high quality gas driving compressors and generators. Usually the rotational speed of the gas turbine is up to 50,000 revolutions/minute to 120,000 revolutions/minute, so it need permanent magnet synchronous generators of high-energy permanent magnet materials (such as Nd, Fe and B material or samarium cobalt materials), its high-frequency alternating current is transformed into power frequency alternating current by power electronic converter device to deliver to the distribution system for users to use. The high temperature tail gas exhausted by the generation part of the micro turbine systems can be used to preheat the compressed air for the combustion chamber, thus reducing the fuel consumption of the combustion process and improve the energy utilization efficiency of the system. The tail gas exhausted by the regenerator can meet the demand of the cold, heat load by means of the LiBr chiller or heat exchanger.

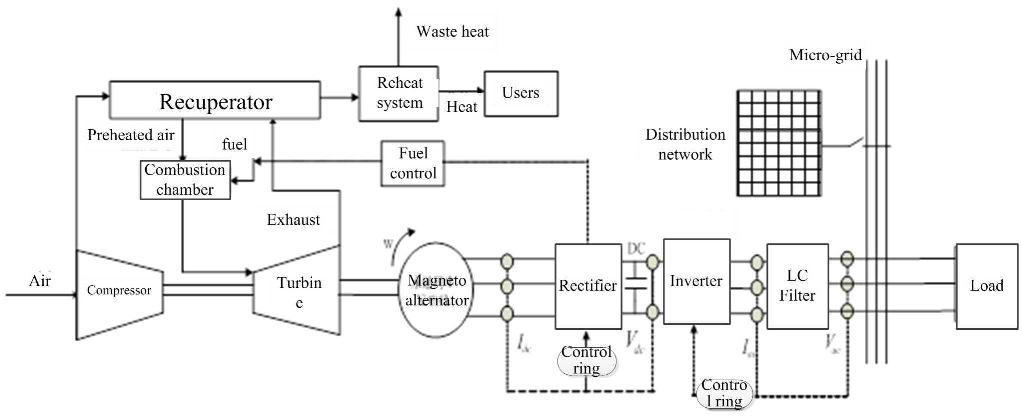


Fig.4. 8 Micro turbine power generation system

The micro turbine use radial-flow impeller mechanical or air bearings, its structure is simple, and the units size is small .It can produce large numbers of extremely high quality residual heat gas, these gas's temperature is about 500℃, its use value is relative high, thus it is the major power equipment of micro-distributed power generation systems, especially small heating and power cogeneration system .

There are two main structure types of micro turbine systems, one is, and another is split-shaft structure. The gas turbine is coaxial with generator in the single-shaft structure micro turbines, thus generator speed is high, and requires power electronic devices to rectify and invert. The power turbine of the split-shaft structure micro turbine uses different coaxial with the gas turbine, and connect with the generator by the transmission gear. Because reducing the generator speed, so it can be incorporated into the power grid directly.

The topic uses the gas turbine of uniaxial single cycle heavy-load proposed by Rowena as the basic model. As it can be seen from Fig.4.9, the single-shaft MT model primarily consist of the temperature control system, speed control system, acceleration control and fuel supply system. The model has been close to perfect, this article will use this model as the model of single-shaft high-speed micro-radial turbine generator. What should to be noted is that this model is based on the following conditions:

1) This model is applicable to transient and steady-state operating conditions, ignoring fast dynamic changes of micro turbine, such as start, stop, and internal fault process.

2) Taking into account the electrical and mechanical characteristics of the micro turbine is the main content of this article, however, energy recovery device is only used to improve the thermoelectric efficiency and do not have a great impact on the dynamic response time of the all model , so we don't consider to model for it.

In addition, except that temperature control use known value, micro gas turbine model and other control module use per-unit value.

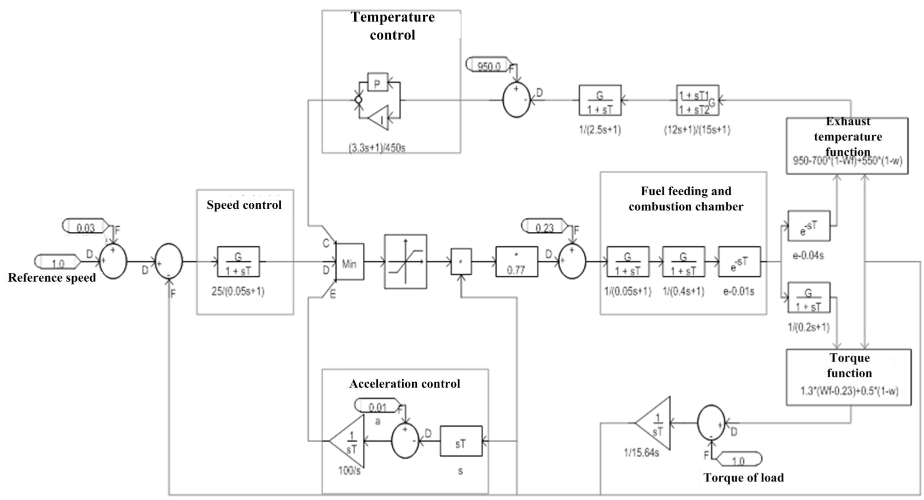


Fig.4. 9 dynamic simulation model of micro turbine

1) The speed and acceleration control system:

Acceleration control regulates the fuel benchmark in accordance with the rotation speed regulation ratio, in order to reduce the thermal shock of the gas turbine's high temperature gas passage parts. Comparing the change rate of the rotational speed with a given speed acceleration reference, if the rotation speed rate is greater than a given reference, reducing the acceleration control value. Otherwise, increase the acceleration control value. I.e. acceleration control system's function is to limit the variation rate of rotational speed not too large, In the process of load shedding and start of the gas turbine, acceleration control system will be involved in the control.

Speed control system of micro turbine is divided into two method of error and non-error adjustment. These two methods are designed for the different load characteristics respectively. In the case that micro-grid is isolated operating, when micro turbine connect to the grid, the control system should use error adjustment method in order to meet the need for tracking changes in load and ensure the stability of the micro-grid frequency and voltage .

The error adjustment system is a proportional regulator, in the case of partial load, the main speed control method of micro turbine is slope control, i.e. error adjustment, and it uses the proportional value of the speed deviation as the output signal. In the actual device, since there are some time constants, therefore, the regulator is actually a proportion - inertia part, it's shown in Fig.4.10.

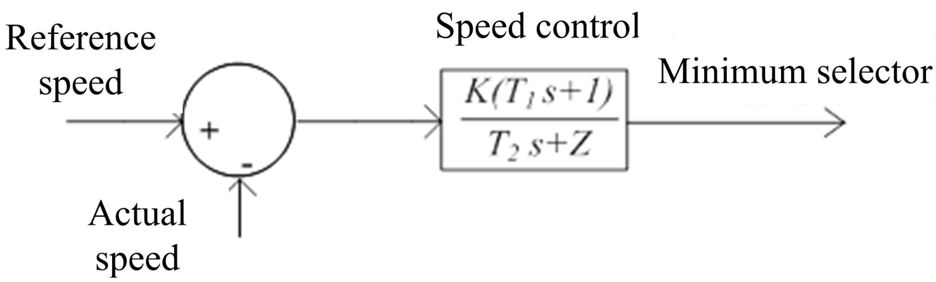


Fig.4. 10 speed control model

In the actual operation of connecting with grid, the rotation speed control system is the most common method to adjust the gas turbine output power. By adjusting the speed benchmark (Fig.4.10), adjusting the deviation between the speed reference and the actual speed, thus change the reference value of the output fuel; further thus achieve the purpose of adjusting the load.

Besides, acceleration control system is to limit the rotor's angular acceleration of the micro turbine on high-speed operation not up for the given value in some special cases, such as the start process or sudden load shedding, in order to reduce the thermal shock of the heat components and ensure the safety of the generator units.

2) Temperature control system

The turbine impeller and blades of the gas turbine work at high temperature, high speed, and the strength of the material is significantly decreased as the temperature increasing, so the intake gas temperature must be limited within a certain range. View from the gas turbine operating accident all over the countries, many of them are due to over-temperature, so temperature control is one of the main characteristics of gas turbine regulation.

Temperature control reflect the turbine intake gas temperature by controlling the fuel flow, due to the rapid change of temperature, the turbine intake gas temperature is difficult to measure and control. However, measuring the temperature of the exhaust gas of the gas turbine is relatively more easy, and is proportional to the turbine intake gas temperature, therefore, using the exhaust temperature of the gas turbine indirectly reflect the turbine intake gas temperature in general. Because the turbine exhaust temperature is lower, the temperature field is uniformity, so we usually arrange a certain number of thermocouple in the turbine exit, and gets the average temperature of the measured turbine exhaust temperature, control the turbine intake temperature by controlling the exhaust temperature.

The main function of the temperature control is:

1) When the gas temperature exceeds the allowable value, send the signal to reduce the amount of fuel so that make the gas temperature not exceed the allowable value.

2) At startup, limit temperature below a certain value, at the end of the warming-machine, raise the temperature by a certain amount of temperature change.

3) Improve the temperature limit value on the spikes running or overloading running.

4) Give out the alarm together with the over-temperature protection when the differences between the measured temperature and the reference value and in each channel exceed a certain value.

The main role of the temperature control system is to limit the turbine intake temperature, and maintain it under certain temperature, so as not to damage the turbine intake blade. Because the intake temperature Tin is too high, the measurement is difficult, so choice the exhaust gas temperature Tx to measure. Therefore, the temperature control system does not directly control the Tin, but the Tx, thus realize the regulation of Tin. As it shown in Fig.4.11, the temperature regulating system is a proportional-integral regulation device (PI). The input signal is an exhaust gas temperature signal Tx measured by thermocouple, then it is compared with the rated exhaust gas temperature Tref, and output temperature control signal to the small value selector. As long as there is a deviation between Tx and Tref, the temperature controller will continue integrating to reduce the fuel reference value until Tx is below Tref . In normal operation, the micro turbine controls the turbine intake temperature not to exceed its maximum design value Tmax also by changing the amount of fuel.

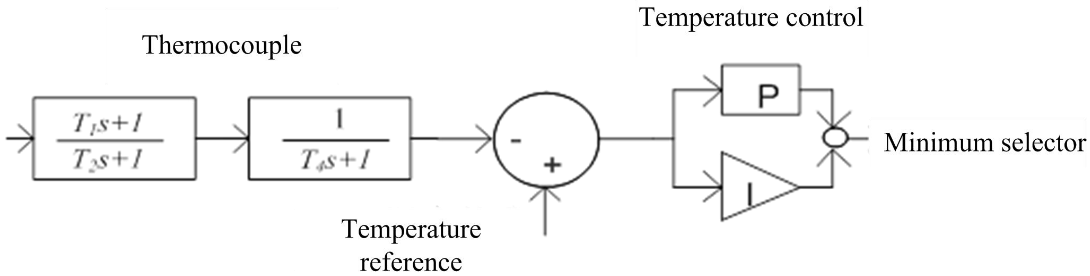


Fig.4. 11 Temperature Control Model

5) Combustion supply system and the combustion chamber

The speed control system, the temperature control system, and the acceleration control system respectively generate a fuel reference, then after the three fuel benchmark command are chosen by a minimum value selector, the minimum fuel reference command enter the fuel supply system. Because the rotation speed of the fuel pump, the fuel pressure are proportional to the rotation speed, thus after the limiter value is multiplied by the actual rotor speed, we get the actual fuel quantity signal.

Different with the steam turbine, the micro turbine need a large proportion of the fuel flow to maintain the normal operation in self-sustaining, no-load conditions, here take K6 = 0.23. Besides, the micro turbine controls the rotational speed by change the amount of fuel. It reaches the purpose of accurate control of the fuel mass flow by the tandem control of speed ratio valve and fuel control valve. As it is shown in Fig.4.12, for the amount of fuel, the combustion chamber is just a delay part.

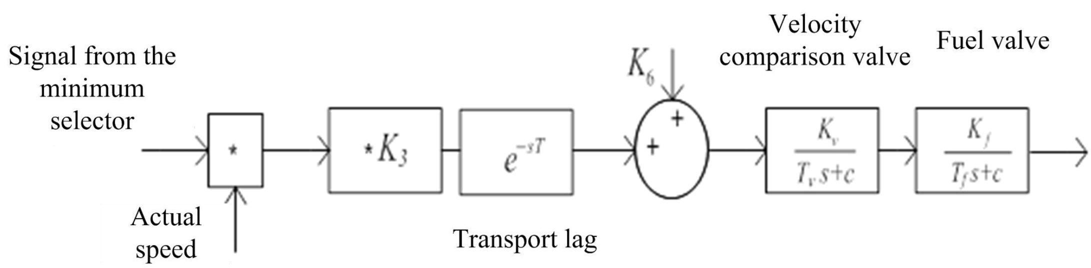


Fig.4. 12 Fuel control model

6) Compressor - turbine systems

Compressor-turbine is an important component of the micro turbine; it's essentially a linear dynamic system (except for the time constant of the rotor).

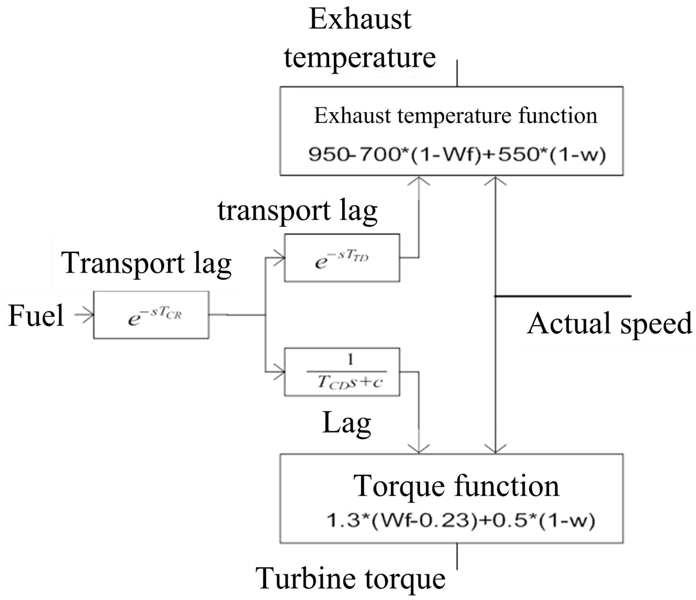


Fig.4. 13 compressors - turbine control model

As it is shown in Fig.4.13, the torque of single axis gas turbine and the exhaust temperature are linear correlation with the fuel flow and the turbine speed, the relational expression is:

Torque= KHHV*(Wf-0.23)+0.5*(1-N) (Nm)

Exhaust temperature= TR-700*(1-Wf)+550*(1-N) (℃) (4-26)

Wherein, the relevant coefficients between KHHV and gas enthalpy value of combustion chamber or thermodynamic value is set as 1.3 , TR is the exhaust temperature reference, the value is 90℃. ω is gas turbine speed, Wf is fuel quantity signal. It should be clear that: The torque equation is basically exact in the case of 100% load, in other cases, there will be less than 5% error, exhaust temperature equation is relatively not very accurate, however, temperature control only effect near the temperature reference value, so you can ignore its impact.

4.3 Fuel Cells Technology

Chemical power, colloquially called battery, is a kind of energy conversion device which converts chemical energy to electrical energy directly, and also a type of electric generator by continuing supplying fuel energy to obtain electrical energy. Fuel cells work in the same way with the ordinary buttery, including electrolyte, electrode, positive and negative connection terminals and so on .Fuel cells are also a device which converts chemical energy to electrical energy directly. The stuff providing chemical energy in the ordinary battery, need to be charged to continue to use after working a period of time, if not, the old one should be replaced. However fuel cells can continuously convert chemical energy to electrical energy as long as electrode is supplied by fuel and oxidant. The fuel cell is just like a generator side constantly adding fuel, side stop power generation. The fuel cell power generation is one of the clean power generations. People call it the forth continuous power generation followed by hydropower generation, thermal generation and nuclear generation. Fuel cell power generation will get a large development in the coming decades, due to the high thermal efficiency than other thermal power, no pollution, widely fuel sources.

4.3.1 Working principle of fuel cell

Fuel cell is a kind of energy conversion device which converts chemical energy to electrical energy directly, its chemical reactant at any time is provided by an external supply (fuel and oxides), and so the fuel cells can output power continually.

When the fuel cells produce electricity, the battery electrolyte (acid, alkali, and a solid oxide, etc.) separate the electrode, the reactants (fuel and oxidant) are respectively supplied to the anode and the cathode of the battery from the outside of the battery, an electrochemical (oxidation of fuel process) starts up, by means of transfer of charged ions through the electrolyte, a potential difference occurs, leading to the electrons flowing to the external circuit, so form a low-voltage DC, and also produce water and carbon dioxide. If continuous fuel be supplied, the battery can provide continuous power generation. The working principle of the fuel cell is shown in Fig.4.14

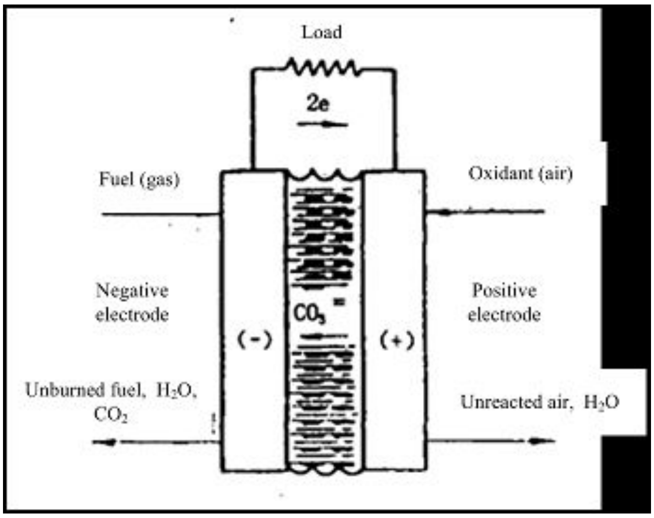


Fig.4. 14 Working principle of fuel cell

The process of fuel by electrochemical reactions to convert chemical energy into electricity is opposite to that of electrolysis of water to produce hydrogen and oxygen in the reaction. Phosphoric acid type battery, for example, the reaction is:

Fuel electrode (negative electrode) $H_2 \rightarrow 2H^+ + 2e^-$ (4-27)

Air electrode (positive electrode) $\frac{1}{2}O_2 + 2H^+ 2e^- \rightarrow H_2O$ (4-28)

Comprehensive reaction $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ (4-29)

It can be seen from the above reaction formula, the reaction is the same with the combustion reaction formula, only emit heat when burning.

4.3.2 The advantage and disadvantage of fuel cell

Advantages:

1) High energy conversion efficiency

Because fuel cells convert chemical energy of fuel directly to electrical energy, so it is not like the usual thermal power generating units to make energy morphological changes through boilers, turbines, generators, so avoid the loss of energy in the conversion process, so as to achieve higher power generation efficiency. Its theoretical efficiency is up to 90% or more, with reliable power supply, low noise, high power quality and high degree of automation. The efficiency of the 250kW ~ 5MW of fuel cell power generation is equal to the advanced thermal power units of 300 ~ 500 MW capacity. Therefore, the fuel cell is an excellent choice for distributed power.

2) No pollution

Substances produced by the fuel cell power generation process is the water, adopt strict desulfurization and separation of carbon dioxide (CO_2) measures, almost no sulfur oxide SO_x and nitrogen oxide NO_x emissions, carbon dioxide emissions are extremely low, and no noise pollution.

3) Less water, small area, short construction period

The fuel cell body structure is simple, compact, modular assembly, small area (such as 2.85MW carbonate battery covers an area of only 420), and the installation, commissioning, running, operation is simple, short construction period, easy maintenance, maintenance and expansion of capacity increase convenience.

4) Fuel diversification

Fuel cell fuel used is very widely, its fuel mainly is hydrogen. Other than hydrogen, any high hydrogen content and easily decomposed substance can be used, such as natural gas, coal gas, oil, methanol, ethanol, methane, etc. And oxygen can be taken directly from the air.

5) Strong ability to withstand changes in load

Fuel cells have a highly flexible load change capability, the variation range of 25% to 100%, and the efficiency of the battery is not affected.

The disadvantage is that the cost of the fuel cell is much higher.

4.3.3 Fuel cell power generation system.

The fuel cell power generation device is a overall energy conversion device, the DC power generated by the reaction process also can be converted into AC by inverter, the heat generated can be recycled to the outside supply. Fuel cell power generation system consists of the following sections: l) fuel supply conversion device, coal feeder and gas generator; 2) air supply device, air compressors and filters; 3) The body of the battery electrode, electrolyte and external circuit; 4) heat recovery unit, waste heat boiler. The fuel cell power generation system is shown in Fig.4.15.

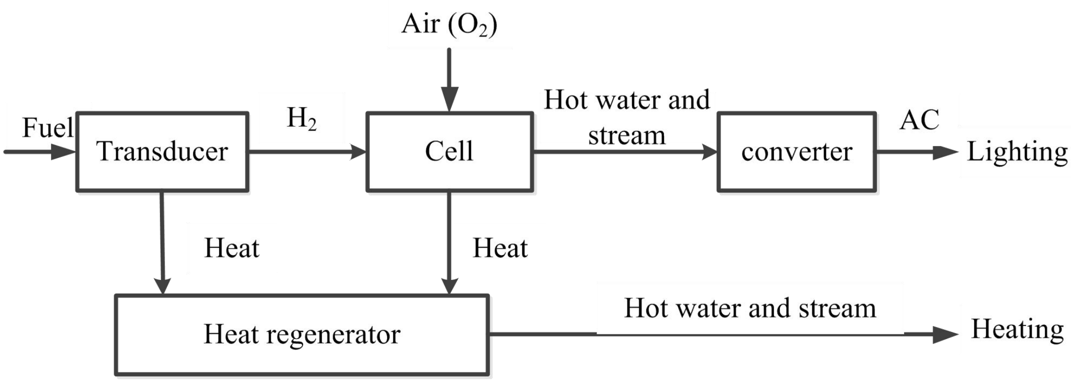


Fig.4. 15 The fuel cell power generation system

The fuel cell can be run independently, can also be run in conjunction with the gas turbine, steam turbine; may be built near the load center or user to implement cogeneration, also may be located in remote areas or connected to the grid. Implementation of fuel cell, gas turbine and steam turbine combined power generation, can improve fuel utilization and power plant efficiency (up to 60%-80%), and increase plant reliability and reduce energy costs.

The output voltage of the fuel cell power generation system equation is as follows:

$$U_{cell} = N \times [E_0 + \frac{RT}{2F} \ln \frac{x_{H_2}^2 x_{O_2}}{x_{H_2O}^2}] - E_{losses} \tag{4-30}$$

N——the number of cells in series

E0——single battery standard potential
T——temperature
X——the molar concentration of the respective gases

Last one as a result of the loss of the electric potential of the system causes
The fuel cell output power is DC, when connected to the distribution network, and the power should be converted into AC by inverter control. Active and reactive inputting from fuel cell to the power grid can be obtained from Fig.4.16

$$\begin{cases} P = \dfrac{mU_{cell}V_s}{X}\sin\delta \\ Q = \dfrac{mV_sV_{cell}}{X} - \dfrac{V_s^2}{X} \end{cases} \qquad (4\text{-}31)$$

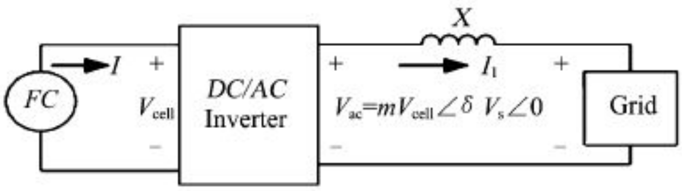


Fig.4. 16 Equivalent diagram of the fuel cell connected to the grid

X is the line impedance connected the fuel cell to the power grid, and the n is side voltage of the distribution network. Inverter controls parameter m, r control the active and reactive power output, it is similar to the principle of regulating power with conventional generators, so fuel cell power flow calculation as PV node. Reactive power output of the inverter is with an upper limit, when reactive process over limit, and then converted to PQ nodes.

4.4 Solar Photovoltaic Generation Technology

4.4.1 Overview

Considering many factors of power supply, solar energy is undoubtedly the ideal green energy in line with the sustainable development strategy. Energy experts from all around the world have concluded that solar energy will become one of the most important energy sources in this century.

Solar photovoltaic power generation has two ways of working which are off-grid and grid-connected, and the grid-connected photovoltaic technology is a trend in today’s world of photovoltaic power generation, and also a major technical steps of PV technology entering the stage of large-scale power generation and steps of becoming an integral part of power industry .Grid-connected photovoltaic power generation system is generally composed of three parts which are the PV array modules, inverters and controllers. Inverters inverse the electricity generated by the photovoltaic battery into sinusoidal current and put it into grid. Controllers control the maximum power point tracking of the photovoltaic cell and control the power of grid and current waveforms, so that the power delivered to the grid and the largest electricity power issued by the photovoltaic array module equilibrium.

4.4.2 The working principle of the photovoltaic cell

Photovoltaic cells convert light energy directly into electricity based on the semiconductor P-N junction producing photovoltaic effect in the sunlight. The working principle is when the sunlight shines on the surface of the semiconductor, the valence electrons of the atoms in the semiconductor internal N area and P area are affected by the solar photons, and by the energy over band gap Eg obtained by optical radiation, the valence electrons break away from constraints of the covalent bond and are finally excited from the valence band into the conduction band, thereby the inner part of the semiconductor material will have many electrons in a non-equilibrium state which are hole pairs. These electrons and holes excited by light collide freely or get together and restored to the equilibrium state in the semiconductor. The composite process doesn't appear conductive externally and it belongs to the automatic loss of part of the energy of photovoltaic cells. Generally more light is wanted to excite a few carriers to the P-N junction, and by the traction of a P-N junction, these carriers drift to the other region and externally form photo-generated electric field contrary to the direction of the electric field of P-N junction barrier. Once it is connected to the external circuit, power can be output. When many such small solar photovoltaic cells unit together through the series and parallel which constitutes the photovoltaic cell assembly, enough power will be output under the influence of solar energy. Fig.4.17 shows the formation process of photo-generated electricity when solar photons impact the P-N junction.

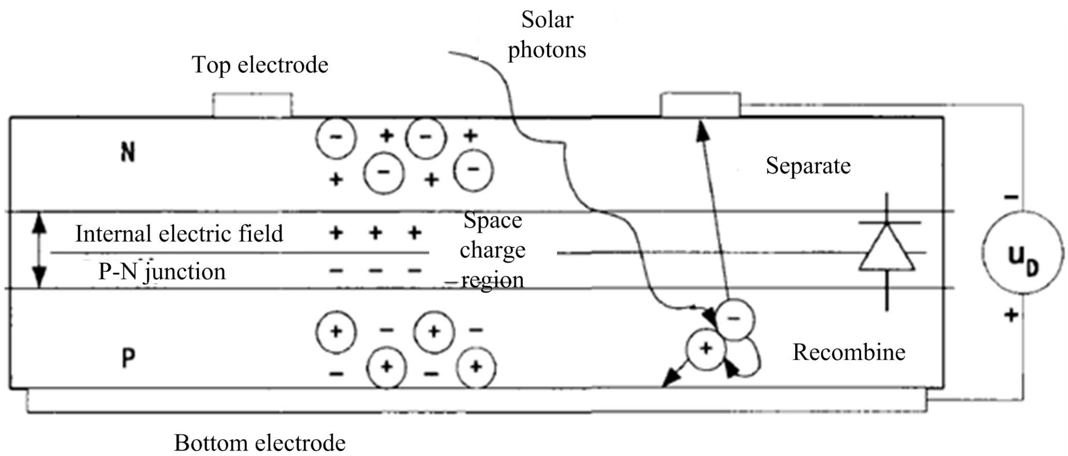


Fig.4. 17 Schematic diagram of photovoltaic cells generating power in the light

As discussed above, it is because of the drift of the few photo-generated carriers close to the P-N junction that N area electrons remain in the N zone and the holes flow to the P zone; Holes in the P zone remain in the P zone, while electrons flow to the N zone, and in this way photo-generated electric field is generated. The photo-generated electric field voltage is

$$\phi_i = \frac{\kappa \bullet T}{q} \bullet \ln\left(\frac{N_a \bullet N_d}{n_i^2}\right) \qquad (4\text{-}32)$$

Among them, N_a、N_d are respectively the electron and the hole density, n_i is the photo-generated minority carrier density, κ is the Boltzmann's constant($1.38\times10^{-23} J/K$), q I is the electron charge($1.6\times10^{-19} C$),T is the absolute temperature.

The energy difference between the top of the valence band and the bottom of the conduction band is the forbidden gap, whose amplitude is represented by Eg, with its unit eV.. The forbidden gaps of different materials are not the same ($E_g = 0.2 \sim 3.7eV$). It determines the conductive properties of the material, and is also an important physical quantity of measuring the photovoltaic cell. The forbidden gap is influenced by the material, the temperature, the amount of semiconductor doping and the P-N junction structure, and its empirical formula is as follows:

$$E_g = E_{g(0)} - \frac{\alpha \bullet T^2}{\beta + T} \qquad (4\text{-}33)$$

Table 4.1 The forbidden band parameters of the semiconductor material

	Germanium (Ge)	Silicon (Si)	Gallium Arsenide (GaAs)	Copper Indium Selenium (CIS)	Cadmium Telluride (CdTe)
$E_g(0)\ [eV]$	0.74	1.17	1.52	-	-
$\alpha[meV\ /\ K]$	0.48	0.47	0.54	-	-
$\beta[K]$	235	636	204	-	-
$E_g[eV]$at$25^0 C$	0.67	1.11	1.40	1.01	1.44

Among them, $E_{g(0)}$ is the forbidden band when it is the absolute temperature 0 K.

Constants $\alpha and \beta$ are shown in Table 4.1.

The incident energy of the solar photons is:

$$\varepsilon = h \bullet f = \frac{h \bullet c}{\lambda} \qquad (4\text{-}34)$$

Among them, h is the Planck's constant $(h = 6.63 \times 10^{-32} J \bullet s = 4.14 \times 10^{-15} eV \cdot s, 1eV = 1.6 \times 10^{-19} J)$, f is the frequency of the incident photon，c is the speed of light($c = 3 \times 10^{8} m/s$)，λ is the wavelength(80％80% of the solar radiation wavelength range from 400nm to 1500nm)。So the solar photons' energy gap is usually between 0.83 eV and 3.10 eV.

Only when the electron from the incident photon energy is greater than the binding energy of the PN covalently, excite electrons from the valence band to the conduction band. When the photon energy is less than the electron energy of departing from the PN covalently bound, it is not excited electron-hole pairs; the self-heating can only make photovoltaic cells.

It is only when the incident photon energy is greater than the energy with which the electron breaks away from the constraints of the P-N covalently; the electron can be excited from the valence band to the conduction band. When the photon energy is less than the electron energy of breaking away from the constraints of the P-N covalently, the holes pairs will not appear. It only heats the photovoltaic cell itself.

4.4.3 The mathematical model of the solar photovoltaic cells

When the lighting is constant, since the photocurrent I_{ph} does not vary with the working status of the photovoltaic cell, it can be viewed as a constant current source in the equivalent circuit. After the load R is connected with both ends of the photovoltaic cell, the photocurrent current flows through the load and terminal voltage V is established between the two ends of the load. The terminal voltage of the load counteracts in the P-N junction of the photovoltaic cell, and current I_d opposite to the direction of the photocurrent current is produced. In addition, due to the electrode around the surface of the solar PV panels and the resistivity of the material itself, the series loss within the solar PV panels will inevitably be caused when the operating current flows through the panel, so the series resistance R_s is introduced. The greater the series resistance is, the greater the line losses, and the lower the output efficiency of the photovoltaic cell is. In actual solar photovoltaic cells,, general series resistance is relatively small mostly in between $10^{-3}\Omega$ and a few Ω .In addition, due to the factors of the manufacturing process, the edge of the photovoltaic cells and the metal electrode may have tiny cracks and scratches during production, ,which will form the leakage and cause the photocurrent originally flowing through the load short-circuit out, so a parallel resistance R_{sh} is introduced as equivalent. With respect to the series resistance, the parallel resistance is relatively large, usually over 1 $\text{K}\Omega$. Fig.4.18 shows the equivalent circuit of the solar photovoltaic cell.

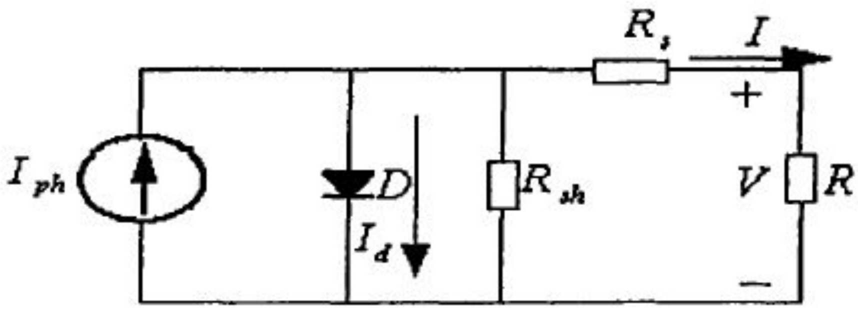


Fig.4. 18 The equivalent circuit of the solar photovoltaic cell

From the equivalent circuit of the solar photovoltaic cell, we can draw:

$$I = I_{ph} - I_d - I_{sh} \tag{4-35}$$

Among them

I —— the current flowing through the load;

I_{ph} ——the photocurrent proportional to sunlight intensity;

I_{sh} ——the leakage current of the solar photovoltaic cell;

While:

$$I_d = I_0\left\{\exp\left[\frac{q(V + IR_s)}{AKT}\right] - 1\right\} \tag{4-36}$$

In the formula above,

I_0 ——the reverse saturation current (its magnitude is 10^{-4} A in general);

q ——the electron charge($1.6\times10^{-19}C$)

K——the Boltzmann constant($1.38\times10^{-23}J/K$)

T——the absolute temperature(t+273K);

A——the ideal factor of P-N junction;

R_{sh}——the parallel resistance of the photovoltaic cell;

R_s——the series resistance of the photovoltaic cell.

In addition

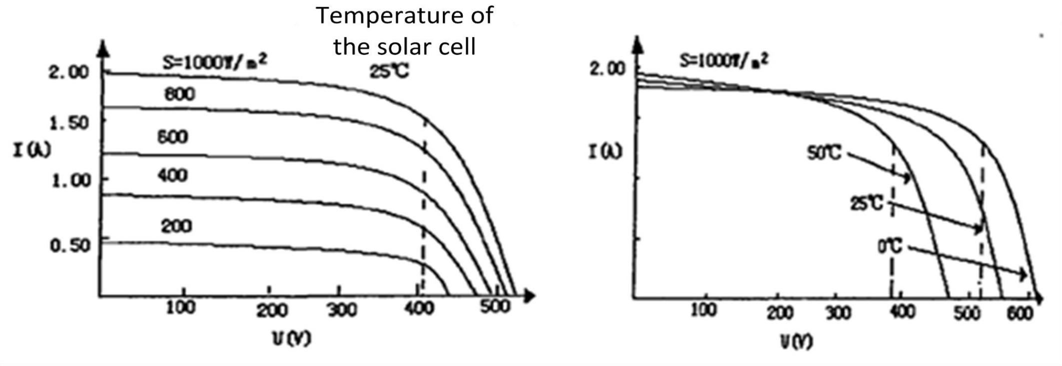
$$I_{sh} = \frac{V + IR_s}{R_{sh}} \tag{4-37}$$

Therefore, sum up formula (4-35), (4-36), (4-37) and the following conclusion can be drawn:

$$I = I_{ph} - I_0 \left\{ \exp\left[\frac{q(V + IR_s)}{AKT} \right] - 1 \right\} - \frac{V + IR_s}{R_{sh}} \tag{4-38}$$

4.4.4 The output characteristics of the solar photovoltaic cell

The solar photovoltaic cell is influenced greatly by external factors (temperature, sunlight intensity, etc), so its output is significantly nonlinear. Fig.4.19 and 4.20 respectively gives the current-voltage curve and the power-voltage curve.

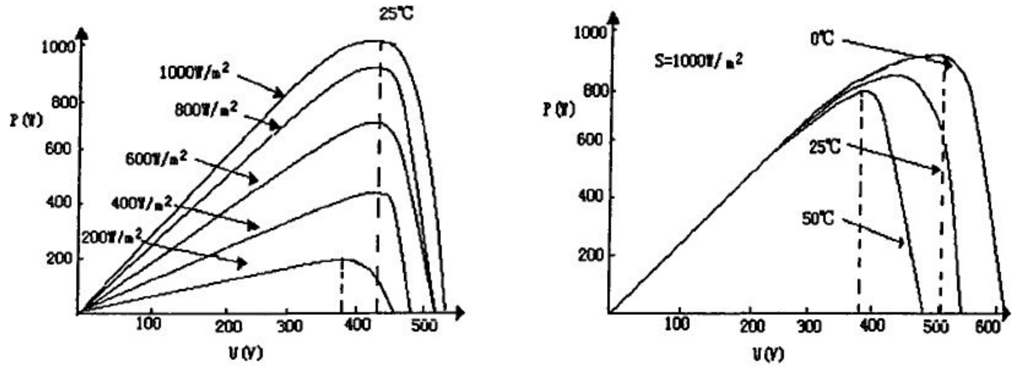


(a) (b)

(a) At room temperature in different sunlight

(b) At different temperature in the same sunlight

Fig.4. 19 The current-voltage characteristics of the solar photovoltaic array



(a) (b)

(a) At room temperature in different sunlight

(b)At different temperature in the same sunlight

Fig.4. 20 The power-voltage characteristics of the solar photovoltaic array

Seen from the above two figures, when the temperature is the same, with the sunlight intensity increasing, the open circuit voltage of the solar photovoltaic cells is almost unchanged, the short circuit current increases a little, and the maximum output power increases; When the sunlight intensity remains the same, with the temperature increasing, the open circuit voltage of the solar photovoltaic cells is decreases a little, the short circuit current increases a little and the maximum output power increases; In addition, regardless of any temperature and sunlight intensity, the solar PV panel always has a maximum power point. When the temperature (or sunlight intensity) is different, the location of the maximum power point is also different. Therefore, in the photovoltaic power generation system, to improve the overall efficiency of the system, an important way is to adjust the operating point of the PV array module in real time, and to make it work in the vicinity of the maximum power point. This process is called MPPT (Maximum Power Point Tracking).

4.5 Energy Storage Technology

Power system energy storage element mainly contains pumped storage, compressed air energy storage (CAES), flywheel energy storage, the Superconducting Magnetic Energy Storage (SMES), super capacitor energy storage, and lead-acid battery energy storage (BESS) and so on.

4.5.1 Types of energy storage technologies and comparison

1) Pumped storage

Pumped storage is the world's oldest method of energy storage. It needs both high and low reservoir, when load of grid is trough , the motor pump water to upstream reservoir, storing electrical energy to potential energy, and when the power grid peak load, the upstream reservoir water to the downstream reservoir to drive generator rotating converting potential energy into electricity generation . There are nearly 300 the pumped storage power stations in the world's totally, China has 15 stations completed and under construction. The key issue of Pumped Storage Power Station is the need to have the appropriate level of two reservoirs, and region complying with such geographical conditions is not much. Besides, Pumped Storage Power Station damage the ecological environment, the construction is too long, investment is large, and therefore Pumped Storage Power Station is not suitable for application in the micro-grid.

2) Compressed air energy storage

The working principle of the compressed air energy storage is using the surplus electric power to drive compressors to store the air in the gas storage device in the grid trough, when the peak arrive, gas storage device is discharged to drive a gas turbine to generate power after the combustion of the mixed fuel of the high-pressure air and natural gas or oill. The world's first CAES power plant was built in 1978 in Germany, a capacity of 290 MW, is still running. In 1991, the United States put a CAES power station into operation, with a capacity of 110 MW. The key problem of the construction of the compressed air storage power station is the storage of compressed air, the best use include ready-made underground rock salt hole, existing mines or digging into the rock hole to store compressed air.

3) The flywheel energy storage

Storing energy with the high-speed rotating flywheel is the so called flywheel energy storage technology. The stored energy is proportional to the mass of it and the square of the speed of rotation. Since the 1990s, the high-strength fiber materials, high-temperature superconducting magnetic levitation bearings, the rapid development of power electronics technology, the flywheel energy storage technologies have matured. Flywheel energy storage has a high energy density, high efficiency, long cycle life, no environmental pollution. At present, the American flywheel Company has developed electric vehicles flywheel battery, AFS Trinity Power's can provide UPS with a capacity of 100kW and 300kW as well as the capacity of 750 kW flywheel system for transport locomotives.

4) Superconducting Magnetic Energy Storage

SMES is to store energy in the magnetic field generated by the DC current flowing through the superconducting coil. The stored energy $E=0.5\times L\times I2$, L is the inductance of the superconducting coil, I is the current flowing through the superconducting coil. SMES has not only rapid electromagnetic response characteristics and high energy storage efficiency, but also long service life span. Currently, many projects of SMES around the world are in progress or in the development stage. The United States is a pioneer in the field of superconducting coil energy storage research, with the American Superconductor Corporation and the U.S. Agency for International magnets GM's small and medium-sized SMES commercialized. Only with the following two breakthroughs accomplished, can the wide application of the SMES be realized: First, low-cost, low loss high-temperature superconducting wire with good mechanical properties can be produced; second, long-term operation of the cryogenic system and cooling system reliability can be improved, and costs of running maintenance can be reduced.

5) Super-capacitor energy storage

The principle of electric double layer is used in the super capacitor energy storage technology to store electric energy directly., The super-capacitor is a new type of energy storage device whose capacity can be up to tens of thousands of Farah, ranging between batteries $E = 0.5 \times C \times V2$s and traditional capacitors. The stored energy in the super-capacitors $E = 0.5 \times C \times V2$, and is proportional to the square of the capacitance C and the operating voltage V The small-sized and light-weighted super-capacitor has fast dynamic response, high power density and long cycle life. What's more, it is also environmentally friendly with wide operating temp erature range, etc. This is definitely a very promising energy storage device. The key issue in the practical use of the super-capacitor storage technology is to reduce the production cost and enhance the energy density of the super-capacitor.

6) BESS

Lead-acid battery is a general-purpose, low-cost energy storage device, as the most mature secondary battery. Now, it is widely used in a variety of electronics UPS, power system, the car starts, locomotive traction, electric vehicles as the auxiliary power supply or power supply. Lead-acid battery has many drawbacks: short cycle life, pollution production, long charging time, affected by temperature, mass maintenance workload. Under the conditions that the various secondary battery technologies are advancing rapidly, all these shortcomings limit the development of BESS.

7) Comprehensive comparison of energy storage technology

Comprehensive comparison of the various energy storage technologies are illustrated in Table 3.2. Battery technology is mature, thus the price is low. While because of its low cycle life and pollution of the environment, it will be taken place of by the upcoming new environmental friendly energy storage element. The excellent energy storage elements as Flywheel, superconductor and super-capacitors are the future of development direction. They can be all applied to the micro-grid for their similar characteristics. Superconducting magnetic energy storage and flywheel energy storage can be used to compensate quickly, but their power density is much lower and they are less effective than the super-capacitor. And compared with other ways of energy storage, superconducting magnetic energy storage is expensive, and in addition to its own costs, cost of maintaining low temperature is considerable. The flywheel energy storage is subject to the restrictions of the speed and the mechanical strength.

In the micro-grid, power quality problems caused by the load or micro power source are often frequent and have a short duration. In comparison, super-capacitor is more preferable as a short term energy storage device, Super-capacitor price remains high, but with the gradual decline of price, super capacitors is bound to become the ideal choice, as an efficient, practical, environmental friendly energy storage device,.

Table 4.2 Comparison of properties of the energy storage system

Name	Storage cell	Super-capacitor	Superconducting	Flywheel
Energy density (Wh/kg)	20～100	1～10	< 1	5～50
Power density (W/kg)	50～200	7000～18000	1 000	180～1800
Cycle life (times)	103	>106	106	106
Efficiency	80～85%	> 95%	90%	90～95%
Safety	High	High	Low	Not so high
Maintenance	little	Quite little	Much	Quite much
Influence on the environment	Pollution	Pollution-free	Pollution-free	Pollution-free
Cost (p.u)	1	8	20	4

4.5.2 The application of energy storage in the micro-grid

The application of energy storage in a micro-grid can be summarized as to provide short-term power supply to amortize the energy, to improve power quality, to optimize the micro-power operation, as well as to improve the economic benefits of the micro-grids

1) To provide short-term power supply

Micro-grid has two typical modes of operation: under normal circumstances micro-grid operates with conventional distribution network , called the network operation mode; When the detected power grid failure or power quality does not meet the requirements, the micro grid will promptly grid-disconnect to run independently, called the isolated operation mode. Micro-grids is often absorb a part of the active power from the conventional distribution network, thus when micro-grid convert to solitary Network mode from grid mode, there will be the power shortfall, the installation of energy storage devices contribute to the smooth transition of the two modes. Batteries, flywheel energy storage with high density energy and providing short-term power supply are suitable for the micro-grid.

2) Used as an energy buffer device

Because the scale of micro-grid is small and the system inertia is not strong, so fluctuations occurring frequently in the network and load are very serious, and have a great impact on the stable operation of the entire micro-grid. We always expect the efficient generators (such as fuel cells) in micro-grid always operate at its rated capacity. Micro-grid load cannot remain the same all day; on the contrary, it will fluctuate as the weather changes. In order to meet the peak load supply, fuel gas peaking power plants should adjust for peak load, but this way of running is too expensive due to high prices of fuel.

In order to solve this problem effectively, super capacitor energy storage is often applied; it can store the excess energy of the power in the low load, back to the micro-grid power in peak load to adjust to needs. The energy storage system as the necessary energy buffer link in the micro-grid becomes increasingly important. It is not only to avoid the generator set installed to meet the peak load, also take full advantage of the low load generating units and avoid waste.

Power density, high energy density properties make super capacitor be the best choice to handle peak load and super capacitors simply store considerable energy with peak load. However batteries should store several times of peak load energy. Batteries are once widely used as a storage unit, but there are frequent charge and discharge control in micro-grid, this is bound to greatly shorten the battery life.

In the micro-grid containing vicious load, such as elevators, hoists, subway power plants and etc, configuring super capacitor energy storage unit can reduce the negative impact affect the electric drive system on micro-grid. In a high load system with motor or transmission in the load side, when a large load is suddenly starting, a large instantaneous current in the load side is needed, at this time, if power supply energy is insufficient, the supply voltage drops momentarily, so that the control circuit misuse, if increasing the power supply capacity, it is obviously a waste for the workplace without large current. High-power super capacitor increased in the system can drive large loads with smaller capacity power system.

3) Improve micro-grid power quality

People are increasingly concerned about power quality problems. On the one hand, the micro-grid work as the grid to meet the requirements of the load on the power supply quality, guarantee the supply frequency and voltage amplitude changes, waveform distortion rate as well as the annual SAIFI in a small range. On the other hand the large grid also proposed stringent requirements to micro-grid which is connected to the grid as a whole, such as load power factor, current harmonic distortion and maximum power.

Energy storage systems play a very important role in improving the quality of the micro-grid power. By means of inverter control unit, reactive and active power of super capacitor energy storage system supplying to the user and the network can be adjusted so as to achieve the purpose of improving the power quality. Because super capacitor can quickly absorbed and release high-power electrical energy, so it is very suitable to apply to the micro-grid power quality adjusting apparatus to solve some transient problems in the system, such as instantaneous power outage, the voltage swells, voltage sag caused by system failure caused, the super capacitor provide fast power buffer, absorbing or additional power, providing active power for active or reactive power compensation to stabilize and smooth grid voltage fluctuations.

Uncontrollable micro power such as wind power, photovoltaic power generation, the fluctuation caused by the generator output power will decline in the quality of the electrical energy. The combination of this class of power and energy storage devices is one of the effective means of methods to solve dynamic power quality problems such as voltage sags, inrush current and instantaneous power interruption,.

4) To optimize micro power run

The characteristics of Green energy such as solar, wind, that energy source come from itself, determine that these power generation often is uneven, and power output easily change. With the changes in the strength of the wind and the sun, the electricity energy output generated by the energy will change accordingly. This requires the use of a buffer to store energy. Because the electrical energy generated by these energy output may be unable to meet the micro-grid peak power demand, so the energy storage device can be used in a short time to provide the required peak power, until the power generation amount increases and the demand decreases.

The right amount of energy storage can play a transitional role in the case that the DG unit does not run. Such as the solar power at night, the wind power generation in the case of no wind, or other types that DG unit is during the maintenance period, at this time the energy storage system will be able to play a transitional role, the amount of energy storage mainly depends on the load needs.

Further, in the case that the process of energy generation is stable but the demand is changing, the energy storage device is also needed. The fuel cell is different from the wind or solar energy, as long as there is fuel, it can continue to output a stable power. However, the load demand changes much over time. If there is no energy storage device, the fuel cell must make very large in order to meet the needs of peak energy, the cost is too high. By the excess energy stored in the energy storage device, it can be a short period of time by the energy storage device to provide the desired peak energy. Combined with a substance with high energy density such as a fuel cell, super capacitors can provide rapid energy release to satisfy the high power demand, so that the fuel cell can work only as an energy source. The combination of the strong performance of the super capacitor and fuel cell make a smaller, lighter, cheaper fuel cell system

5) Improve the economic benefits of the micro-grid

The application of the energy storage system has great impact on improving the economic benefits of micro-grids

a. A substantial increase in the proportion of renewable energy generation can ease the pressure of investment in new transmission and distribution lines, as well as new power plants, and reduce system cost;

b. To provide effective spare capacity, improve power quality (faster start than the generator), and improve the reliability and stability of the system;

c. To provide an effective load management mechanism, reduce the cost of electricity in the peak, thereby reducing tariff and providing economic benefits;

d. In the electricity market, the energy storage system can significantly avoid the interruption of energy trading, and the loss of forecast error, and thus provide a stable electricity prices;

e. DG generation unit cannot be scheduled, such as solar, wind, weather and other natural factors, the DG unit owners cannot formulate certain generation planning, but with energy storage can provide the necessary electrical energy at a particular time without having to consider the issue how much power the DG unit can generate, simply follow the pre-established power generation planning to generate electricity. In electricity market environment, the micro-grid running with grid network, with enough storage power, become scheduling units, micro-grid owners can sell electricity to the power companies according to different situations; provide peaking and emergency power support and other services, to maximize the economic benefits.

4.5.3 The principle and mathematical model of super capacitor energy storage

1) The structure of the super capacitor energy storage system

The basic structure of the super capacitor energy storage system is shown in Fig.4.21. Super capacitors are the structure of the electric double layer, structure between the activated carbon electrode and the electrolyte is spatially distributed, and the characteristics of super capacitor can be described as the plurality of capacitors in series-parallel.

In the process of super capacitor charging and discharging, the terminal voltage range changes, so a DC/DC converter usually must be used as the interface circuit to adjust the super capacitor energy storage and energy release. DC/AC converter can be bi-directional DC/AC inverter or AC/DC rectifiers and DC/AC inverter. The super capacitor energy storage system is paralleled to the micro-grid, on the bus or feeder.

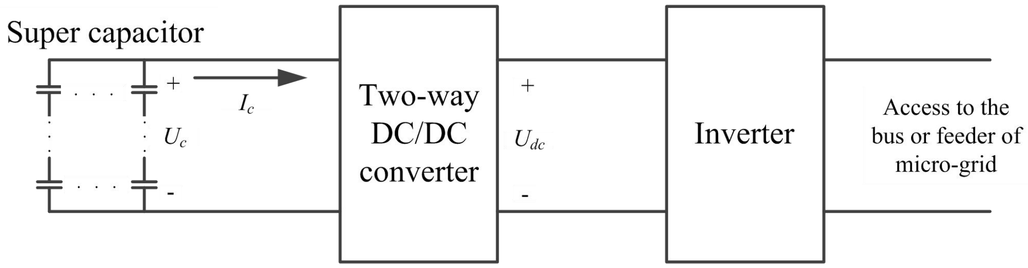


Fig.4. 21 The structure of the super capacitor energy storage system

Super capacitor energy storage system using a number of groups of super capacitors store energy in the form of electric field energy, when energy is emergency lacking or necessary, the stored energy will be released by the control unit to quickly and accurately compensate the desired active and reactive power, thereby achieving energy balance and stability control. The advantages of super capacitor make win in competing with other energy storage methods when it is applied to distributed generation.

2) Strategy of super capacitor in micro-grid

When gridding to network operation, the micro-grid power fluctuations is balanced by large power grids, energy storage will be in rechargeable backup status. When the micro-grid switches from the grid operation to the isolated operation, the central storage starts immediately to make up for the power shortfall. Load fluctuations or micro power fluctuations in the micro-grid isolated operation are balance by the central storage or distributed storage. There are two types of micro-power power fluctuations balance, making distributed generation storage and micro-power needed storage parallel to a feeder, or making storage access directly to the micro-power DC bus.

3) The super capacitors control principle

The super capacitor control is mainly reflected in the control of the DC/DC converter and DC/AC converter. In recent years, the inverter control technology develop rapidly, it has developed from the earliest open-loop control development to the output voltage instantaneous feedback control, from analog control to full digital control. The current methods of Digital control have digital PID control, state feedback control, fuzzy control and neural network control. Digital PID control method is the most widely used control method in engineering practice.

Bidirectional DC/DC converter achieves energy conversion between the super capacitor bank of DC low voltage side and DC high voltage side. DC/DC converter control goals cannot simply be set to maintain the energy storage capacitor voltage of DC high side constant, at the same time must also meet the super capacitor power limit. The control block diagram is shown in Fig.4.22.

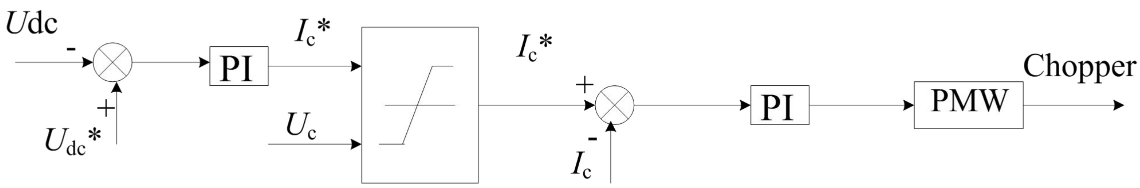


Fig.4. 22 DC/DC converter control

There are a variety of control methods in DC/AC converter. Such as steady-state mode using dq0 coordinate, on this basis designing the PI controller, achieving to adjust active and reactive power at the same time independently; feed forward compensation closed-loop control based on the synchronous rotating coordinate, effectively inhibiting voltage dips problem; intelligent control system based on fuzzy rules, using the forecast wind power, the effect of energy storage device and AC voltage measurement, to adjust and tuning power levels, optimization of micro power running. DC/AC converter control model is shown in Fig.4.23.

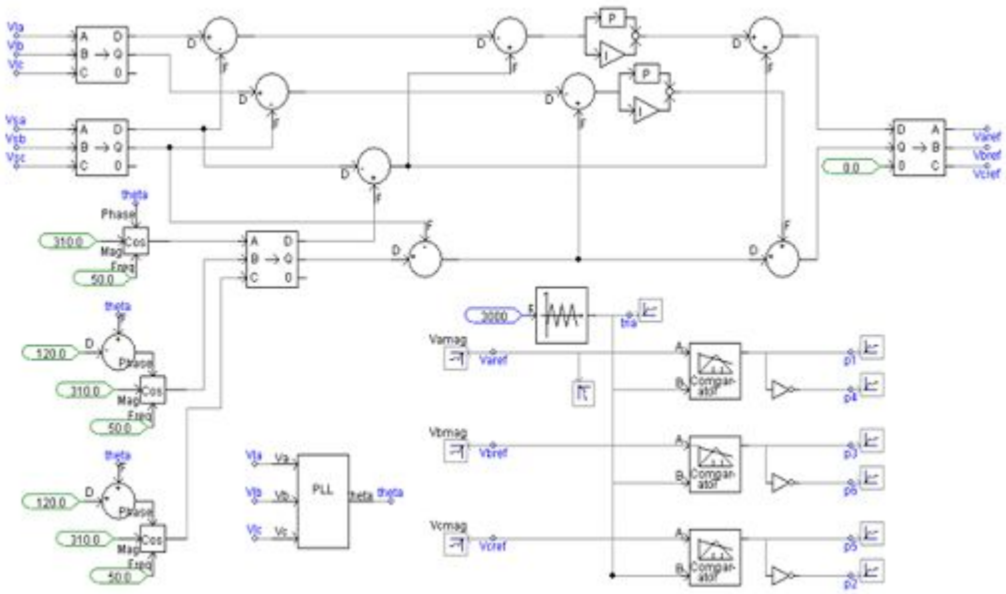


Fig.4. 23 DC/AC converter control

4.6 The Control Model of the Distributed Power Inverter

Distributed power supply based on the power electronic converter access, whether through the AC-DC-AC access, or through the DC-DC-AC access, is required to go through the inverter link, so to study the inverter control technology has a universal significance.

The micro power's control strategies are different in micro-mesh grid operation and island operation. The micro power's control method is related to the type of power generation apparatus. Usually, there are three control methods: Constant power control in micro-mesh grid operation (P/Q control), droop control in micro-mesh grid isolated operation and voltage frequency control (V/f control). This issue has studied these three control methods, as models of various control methods are shown in Fig.4.24-4.25.

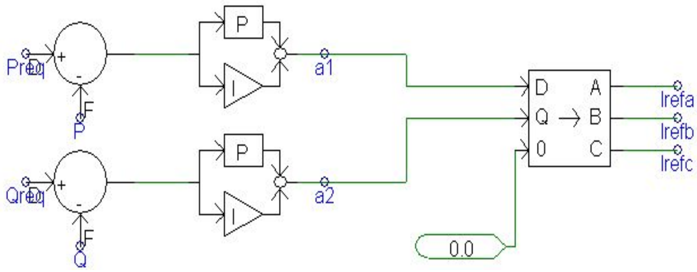


Fig.4. 24 Micro-power simulation system diagram under P/Q control

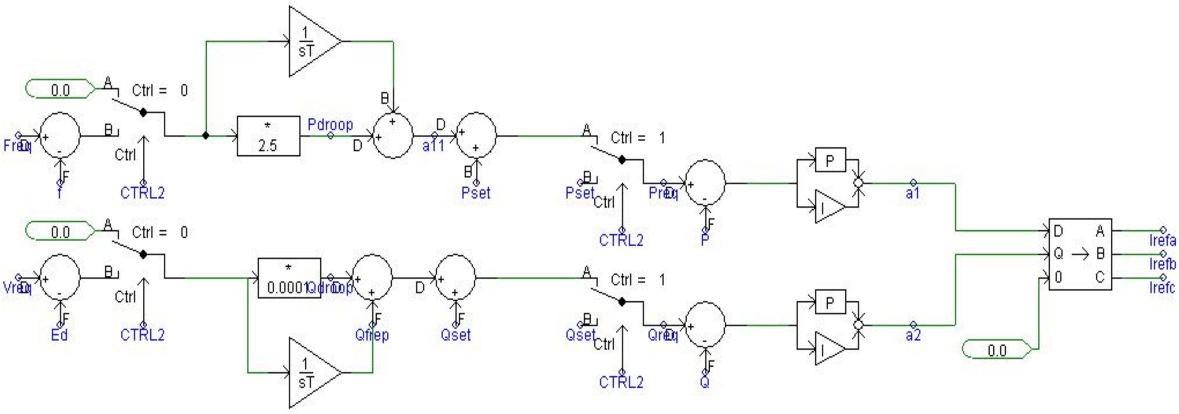


Fig.4. 25 The micro-power simulation system under V/f control

In connection with multi-micro grid structure, many control methods MAS (multi－Agent system) based on multi-agent technology are discussed and the micro-grid control system under high permeability is established on the MAS, as shown in Fig.4.26. To apply the MAS technology to micro-grid voltage control achieves the combination of Agent technology and the micro-grid "plug and play" concept.

A program studying micro-grid voltage/ reactive power optimization is proposed in combination of Inner Mongolia 863 demonstration plots project. A feasible study is conducted about dynamic monitoring of the micro-grid, flexible tracking and coordinated control. The issue studies the micro grid security economic scheduling theory and formulates micro-grid distribution system operating procedures. The issue also develops research and development program of micro-grid control device, and carries on integrated system design of detecting, controlling and protecting the power distribution system.

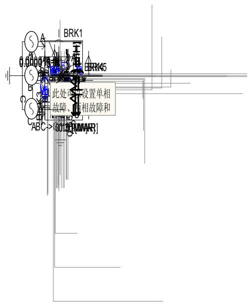


Fig.4. 26 The micro-grid voltage control model based on multi Agent

Chapter 5 Distributed Power Generation Technology and Micro-Grid Demonstration Community in China

The great progresses have been made in field of distributed power generation and micro-grid technology in China during last 10 years. It is vigorous evidence that the Hohhot City Micro-Grid Demonstration Community and Cheng De City Project of Distributed Power Generation/Energy Storage and Technique Connecting into Power Network completed and put into operation successfully.

5.1 Brief Introduction to Micro-Grid Demonstration Community

"Da Shengkui creative industry park of Hohhot City" is a demonstration community. Covering an area of 78,000 square kilometers, "Da Shengkui" is divided into three function zones: Da Shengkui, Ancient Custom Community and Grand View Garden, including exclusive clubs, a 700-meter long pedestrian street that provides catering and entertainment services, four-star hotels, conference centers, art performance centers, office buildings and other amenities. "Da Shengkui" distributed power supply system provides all the heating and hot water and part of the electric power for the 62,000 square kilometers of residential area and 10,000 square kilometers of commercial area.

Based on the utilization data of 32 families in Mingzeyaju community during January to December 2008, and 12 businessmen in Dazhaojiu Street during April 2008 to March 2009 provided by Inner Mongolia power supply bureau, and taking the investigation of utilization data on each 3rd of January, March, July, November provided by Da Shengkui Zhungeer Xuejiawan Energy Company into account, it can be concluded that the maximum electrical load of the entire community is 1820kW which appears in August--the month with the highest temperature locally which may have something to do with a rise in air-conditioning and other electrical equipment. The minimum appears in November and July, about 260kW.

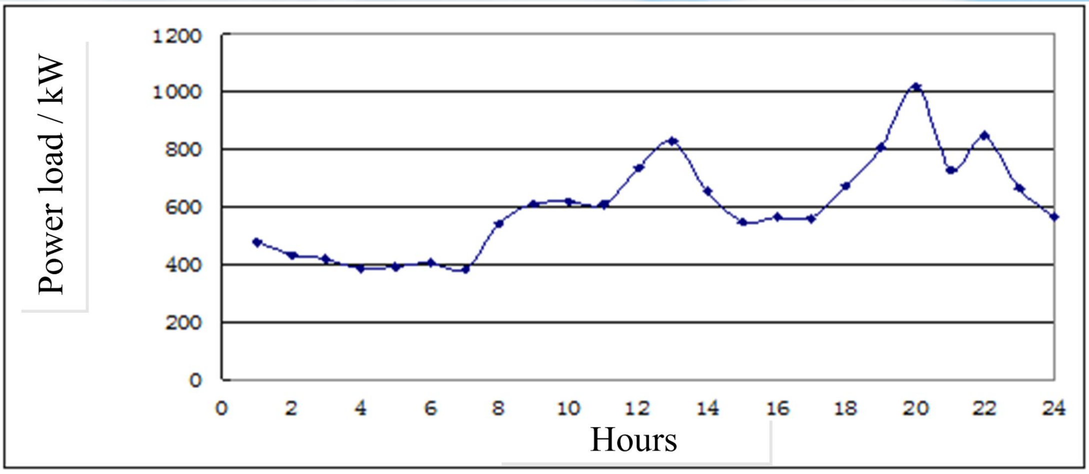


Fig.5. 1 Electrical load on Mar. 15th (interim period)

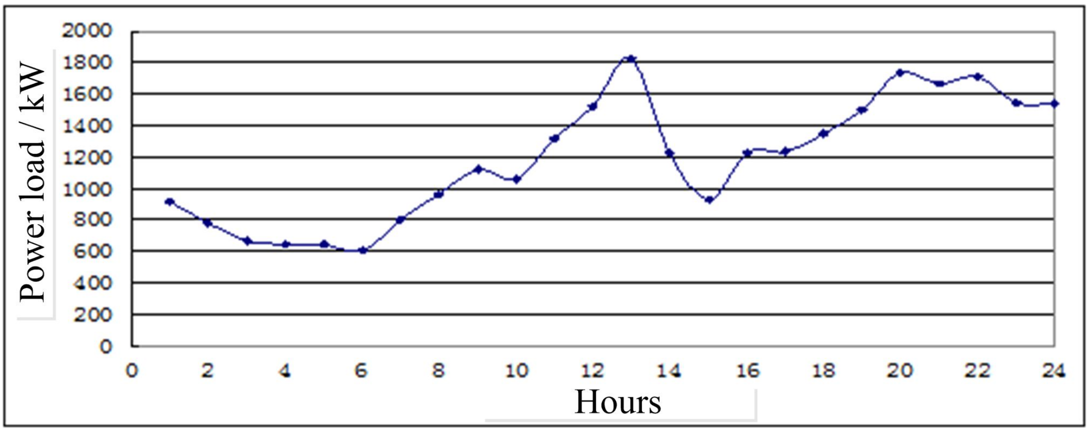


Fig.5. 2 Electrical load on Aug. 15th (air-condition using period in summer)

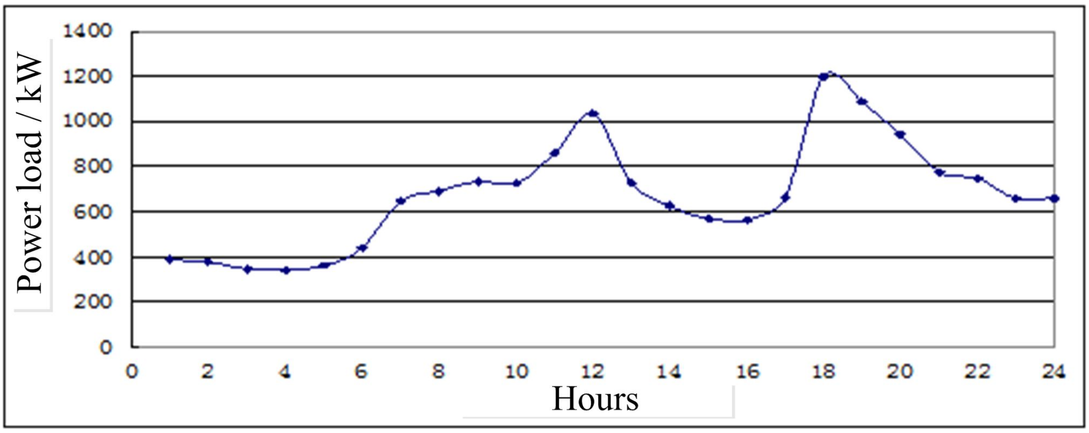


Fig.5. 3 Electrical load on Nov. 25th (heating period in winter)

5.2 System Design of Micro-grid Demonstration Community

The primary electric wiring diagram of “Da Shengkui” distributed power supply system is shown in Fig.5.4.

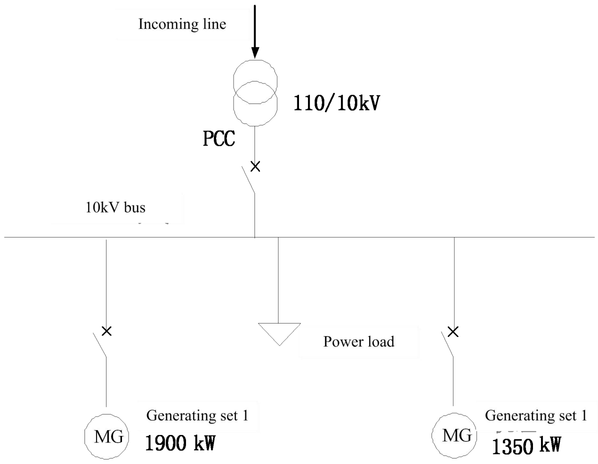


Fig.5. 4 electric wiring diagram of “Da Shengkui” distributed power supply system

The capacity of steam turbine one is 1900kW and the other 1350kW. The system uses single busbar connection, and the steam turbine and load are all connected to the 10 kV bus. What’s more, the system takes in a 110 kV power line.

Under normal working conditions, PCC is closed, corresponding the following three conditions.

1) When the load is less than the gross output of gas turbines, the direction of power flow on PCC is from the micro-grid to the distribution network. And if the load changes within the gross output, the gas turbines will adjust to it.

2) When the load is greater than the gross output, the direction of power flow on PCC is from the distribution network to the micro-grid. The system supplies electricity for the micro-grid and meets its need.

3) When a gas turbine is under repair, the homologous unit is stopped and the switch is turned on. Power output of another unit should also be made adjustment and appropriate steps should be taken on the analysis of load and power output.

5.3 Operation Simulation Analysis of Micro-Grid Demonstration Community

The micro-grid accesses to a 110 kV power line in the power grid of Hohhot in Inner Mongolia. In the end of 2009, the maximum load that accesses to the power grid of Inner Mongolia is 11,698 MW. There are 4 public heat-engine plants with capacity of totally2, 000 MW, one 500 kV substation, ten 220 kV substations with capacity of totally 2, 040 MVA in the area of Hohhot City. The maximum power load in the end of 2009 is 1,414 MW.

The model of public power system is built on basis of equivalence in Inner Mongolia power grid and Hohhot City power grid. The Da Shengkui micro-grid system accesses to the nearest substation that is called You Yi substation in Hohhot City through a single-circuit 110 kV cable. There is now two transformer of 40 MVA and two 110 kV power lines in You Yi substation—one of which is from Hohhot cogeneration power plant and the other from Zhao Jun 220 kV substation.

5.3.1 Micro-grid working from grid connected operation to isolated operation

Suppose that the micro-grid is working in grid connected operation during the first 5 seconds with active power load of 941.0kW, and in isolated operation from the fifth to tenth second.

When the system converts from grid connected operation to isolated operation, the simulation result of voltage change is shown in Fig.5.5. It can be seen that in the transient process of conversion from grid connected operation to isolated operation, there is a short-term fluctuation of the amplitude of voltage on busbar—the maximum 10.40 kV and the minimum 9.30 kV—in the allowable range (+7% to -7% of rated voltage).

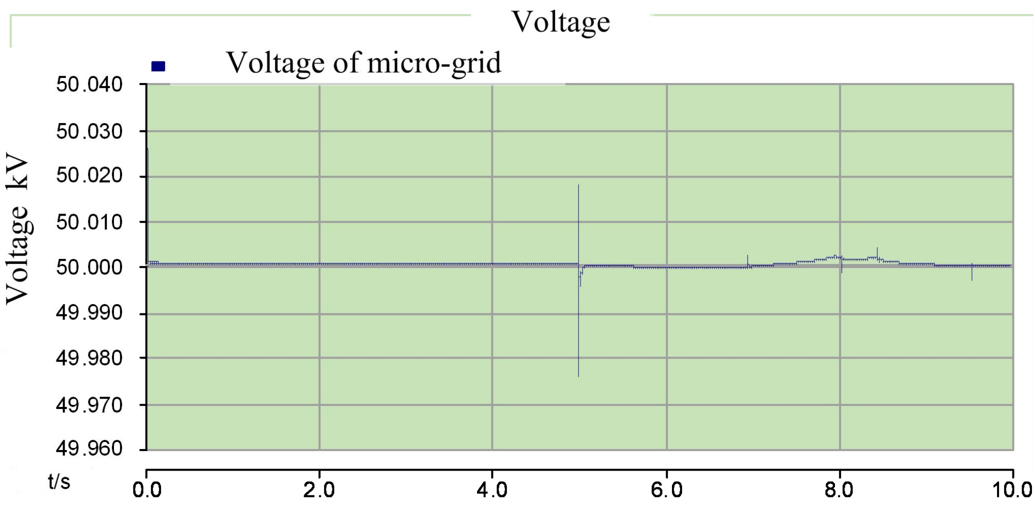


Fig.5. 5 Bus voltage at the conversion

The simulation result of frequency change is shown in Fig. 5.5 when the system converts from grid connected operation to isolated operation. As is shown, in the transient process of conversion, the frequency of system alters little—rises up to 50.07 Hz at the fifth second quickly and soon declines and remains 50 Hz.

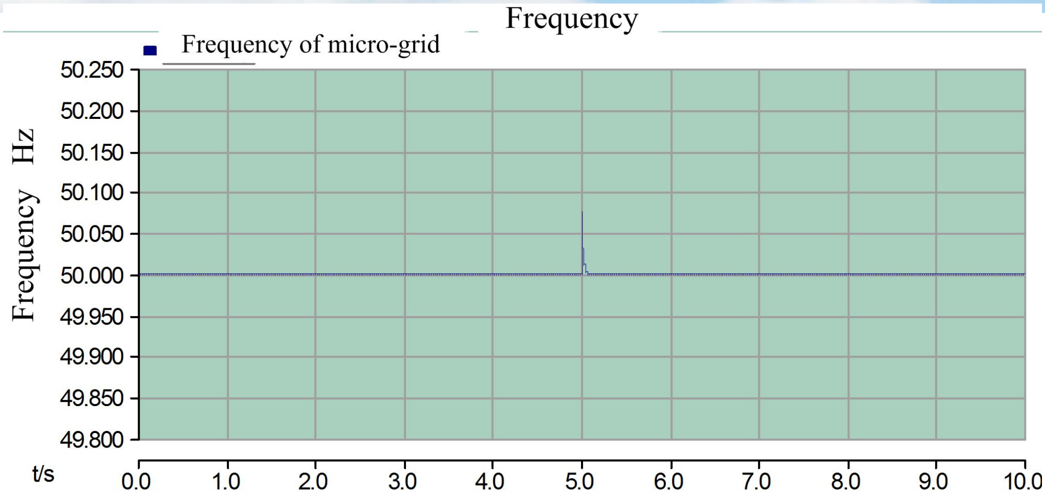


Fig.5. 6 Frequency of system at the conversion

5.3.2 Simulation Analysis of Voltage Stability

Voltage stability refers to the ability to keep the bus voltage of the power system within allowable deviation range both in normal and in the dynamic processes when disturbed.

Simulate 200kVar reactive load fluctuations, and test micro-grid voltage changes in grid connected operation and isolated operation. Set the micro-grid works in grid connected operation in 0.0 to 5.0 seconds, and the load increases to 500kVar from 300kVar in 2.0 to 3.2 seconds, and then drops from 500kVar to 300kVar in 3.3 to 4.5 seconds. The micro-grid starts to work in isolated operation from the fifth second, and the load increases from 300kVar to 500kVar in 7.0 to 8.2 seconds and then drops to 300kVar in 8.3 to 9.5 seconds.

Fig.5.7 shows the simulation result of bus voltage of the power system. It can be seen that the voltage remains unchanged when the micro-grid is in grid connected operation, however changes by a big margin when converts to isolated operation, approximately between 9.6kV to 10.4kV. There is a slow fluctuation in 7.0 to 9.5 seconds, dropping to 10.01 kV and then rising to 10.20 kV and finally getting back to normal. The figure supports that the amplitude of bus voltage can be kept within allowable deviation range in the dynamic processes of reactive load fluctuations (+7% to -7% of rated voltage).

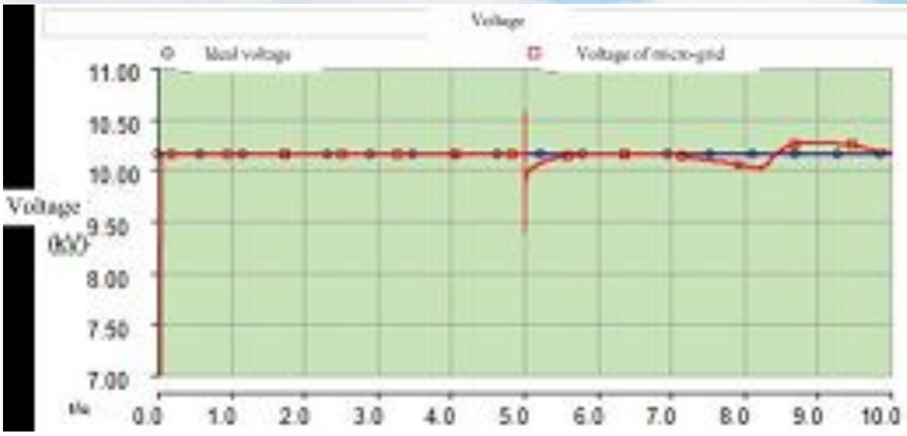


Fig.5. 7 Voltage in load fluctuations

5.3.3 Simulation Analysis of Frequency Stability

The scale of micro-grid is rather smaller than the large electric power grid. In grid connected operation, the active power is balanced by the large grid and the fluctuation can be ignored. So the frequency of micro-grid keeps the same with that of the large grid. In isolated operation however, the stability of micro-grid frequency relies on the regulation of V/f controlling generating unit which can balance the active power in the system.

Simulate 200kW active load fluctuations, and test micro-grid frequency changes in grid connected operation and isolated operation. Set the micro-grid works in grid connected operation in 0.0 to 5.0 seconds, and the load increases to 1564.91kW from 1364.91kW in 2.0 to 3.0 seconds, and then drops back to 1364.91kW in 3.5 to 4.5 seconds. The micro-grid starts to work in isolated operation from the fifth second, and the load increases from 1364.91kW to 1564.91kW in 7.0 to 8.0 seconds and then drops to 1364.91kW in 8.5 to 9.5 seconds.

Fig. 5.8 shows the simulation result of frequency of the system. It can be seen that the frequency remains unchanged when the micro-grid is in grid connected operation, however changes by a steep fluctuation when converts to isolated operation, between 50.019Hz to 49.976Hz. There is a slow fluctuation in 7.0 to 9.5 seconds. By using the output of V/f controlling generating unit, the change of load is efficiently followed. Thus the frequency of micro-grid in isolated operation is kept far less than the allowable deviation range (±0.2Hz).

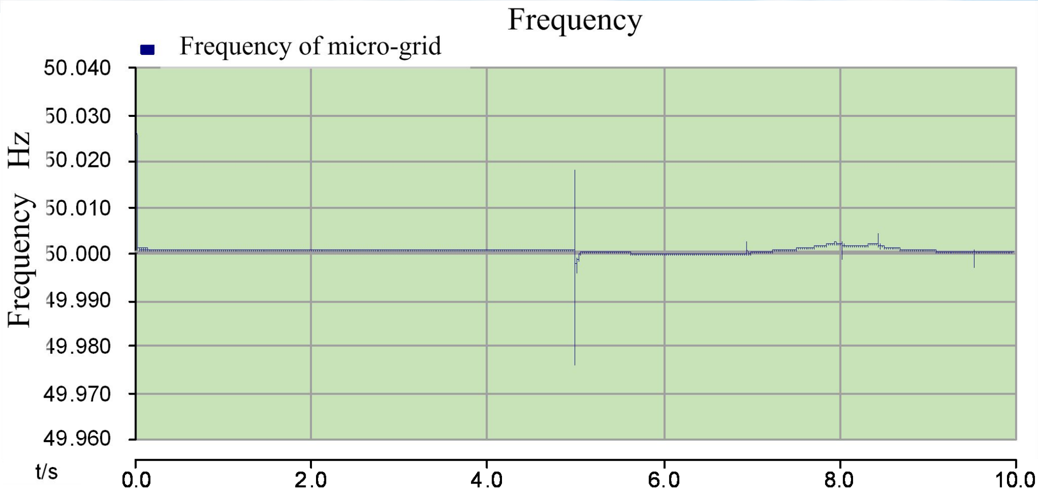


Fig.5. 8 Frequency in in load fluctuations

5.4 The Brief Introduction to Cheng De City Project of Distributed Power Generation/Energy Storage and Control Technique of Micro-Grid Connected into Network

"Cheng De City Project of Distributed Power Generation/Energy Storage and Control Technique of Micro-Grid Connected into Network" is the one of key-trial projects of smart grid of State Grid Corporation of China in 2011. The implementation of the project is aimed at actively exploring and looking-ahead to research on micro-grid operation mode and connect to electric distribution network controlling mode. And focusing on the characteristics of dispersion and intermittent the distributed power generation has, it analyzes the negative influences to the grid power quality, system protection and the system operation reliability, to reduce the impact to power grids and users due to the lot of distributed power generations simple on-grid.

The project is adopted of the power storage converter (PSC), power regulating and power saving device, as well as LV distribution cabinet products provided by Jiangsu Formula Electric Technology Co., Ltd. The energy storage converter is rated at 100kW, playing as main power supply for stabilizing the micro-grid's voltage and frequency. It is the main premise of power storage technology applying and the effective means of achieving power grid interaction management. Power regulating and power saving device is of active power filter (APF), balancing three-phase active power and static VAR compensator (SVC) and other functions to provide stable and high quality electric power.

After the project being put into operation, under the "village mode" the daily on-grid maximum power of 80kW, daily generating capacity was around 600kWh and provided power supply for about 150 rural families. The village mode can generate power of 223,000 kW, saving of 73.6 tons of standard coal, reducing emission of carbon dioxide of 214 tons and sulfur dioxide of 6.7 tons.

On Feb. 20, 2013, the project passed the science and technology fruit appraisal which was organized by Chinese Society for Electrical Engineering, evaluating that the project has reached the international advanced level.

5.5 Environment-friendly Wind-Photovoltaic Power / Energy Storage Distributed Power Generation System

Jiangsu Formula Electric Technology Co., Ltd and China Electric Power Research Institute (CEPRI) Clean-energy Dept. jointly developed the environment-friendly wind-photovoltaic power / energy storage distributed power generation system. The system is actually an micro-grid system grouped of distributed power source、energy storage and power load. The internal power supply is dominated by clean photovoltaic power. The system is able to operate grid-connected or isolated. Relative to the external network, it shows a single autonomous controlled unit. It provide continuous, stable, clean power and improve the ability of network anti-disaster and after-disaster emergency power supply, as well as meeting users demand for electric power quality and power supply security.

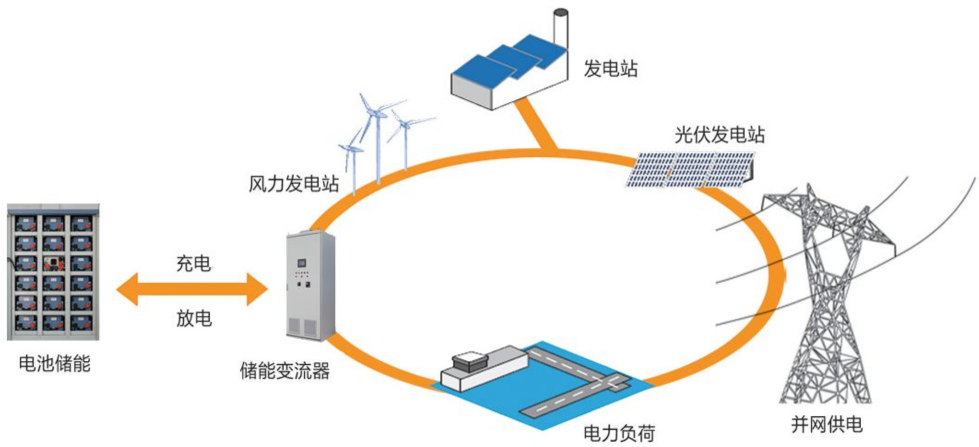


Fig.5. 9 system structure schematic

Micro-grid system electric primary equipment contain the photovoltaic system, the battery energy storage system, electric load, harmonic control and reactive power compensation system, low-voltage power distribution grid and grounding system.

Micro-grid electric secondary equipment includes electric energy measurement system, power quality monitoring system, micro-grid connected point protection simultaneous device, micro-grid coordination controller and micro-grid energy management system.

5.5.1 The main functions of wind-photovoltaic power /energy-storage distributed generation system

The internal power source of wind-photovoltaic power/energy-storage distributed power generation system is dominated by clean photovoltaic power, mainly through power electronic equipment to realize the power transformation. The system mainly possesses the following features:

1) To realize the efficient utilization of clean energy power generation. When the power generation system normally operates, in daytime it uses photovoltaic power generation and supplies for the load. The excess power is stored in the battery energy storage system. In evening the battery energy storage system and the grid jointly supply for the load. When the external power grid in overhauling, the battery energy storage system supplies the load, improving power supply reliability.

2) To realize real-time monitoring for operating equipment. Through micro-grid coordination controller it can conduct the real-time collecting and monitoring for the operation data of the internal key equipment in the power generation system. It includes photovoltaic power generation, battery energy storage, the power load, power measurement, power quality and grid-connected node etc.

3) To set a variety of coordinated controlling strategy. According to different control objectives, the micro-grid can implement different coordinated control strategy and achieve different control objectives. It mainly includes battery energy storage system, planned charge/discharge control, photovoltaic/storage coordinated control and power control of grid connected node.

4) To realize electric power quality control and reactive compensation. The power generation system is configured of active filter and reactive compensation device and formed of integrated static var generator (SVG). It is used for eliminating the distributed power on-grid equipment’s harmonic interference to the grid and load, simultaneously achieving reactive power auto-switching and supplying continuous, stable, clean electric power for the load.

5) To realize smooth switching of power generation system’s on/off-network operation. In accordance with the reserved on/off-network controlling strategy and according to the system’s on-grid or off-grid operation state, the micro-grid coordinated controller implements the relative strategy, guaranteeing the system stable operation on/ off network. At the same time, the coordinated controller conducts an effective coordination and configuration with the on-grid point’s protection devices, in case of failure realizing the artificial seam and smooth switching.

6) To realize the simultaneous function of micro-grid-connected protection function. A power generation system being configured of an on-grid point protection synchronized device, it can test the external grid failure and quickly disconnect the power generation system from the external grid. The simultaneous device also possesses a synchronized function. When the system in off-grid operation, it timely tests the parameters of the on-grid point, such as voltage, frequency and so on. Once an

external grid operation restoring and receiving instructions of allowable on-grid, it issues the synchronized order to the switch of on-grid, realizing simultaneous on-grid of micro-grid system and external grid.

7) To realize an in-place coordinated control and remote energy management functions. Power generation system's energy management system also can receive remote dispatching/controlling instructions. Through optimized calculation it forms the integrated operation control instruction to the micro-grid coordinated controller, which is issued to the micro-grid coordinated controller for implementing. Therefore, the wind-photovoltaic-energy-storage distributed power generation system can not only in-place coordinate control, but also conduct remote energy management.

5.5.2 The features of wind-photovoltaic/energy storage distributed power generation system

The system mainly has following features:

1) The system is easily used with flexibly extension. The wind-photovoltaic-energy-storage distributed power generation system is consisted of photovoltaic power generation subsystem, battery energy storage subsystem. Each subsystem is adopted of blocking, modularity and standardized design, easily for users installing, using and maintenance. According to the load requirement, the distributed power generation system can also take flexible combination and extension for the power generation units.

2) Improves clean energy's utilization rate and decreases enterprises' power purchase cost. During the daytime power utilization peak, it uses photovoltaic power and other clean energy as much as possible and reduces grid supply, at the same time having the surplus power stored in the battery energy storage system and increasing the clean energy absorptive proportion. In the evening power utilization trough through battery energy storage system it supplies to the load. Also in the evening power utilization trough it can have the cheap grid power stored in the battery energy storage system for daytime peak period using. Through application of wind-photovoltaic-energy-storage mutual complementary technology, it plays the role of “peak load shifting” on the electric power system and improves its reliability.

3) Ensures the critical load power supply reliability. The wind-photovoltaic-energy-storage distributed power generation micro-grid system has the characteristics of on-grid, off-grid operation flexible switching. When the system is in on-grid operation and has tested an external grid abnormal or an electricity company cutting power, it will quickly jump off on-grid switch and have the system transformed into off-grid type operation, independently conducting critical load power supply and ensuring the key devices not blackout and avoiding loss due to temporary power outage. When grid power is restored, it can smoothly switch to on-grid

operation mode. The switching process is without power outage.

5.5.3 Application of wind-photovoltaic-energy-storage distributed power generation micro-grid system

The wind-photovoltaic-energy-storage distributed power generation micro-grid system has been applied in the projects of Jiangsu Electric Institute's "Micro-grid System", Yangzhou "Intelligent Grid Comprehensive Engineering Electricity Distribution Automation", Qinghai "Off-grid Type Wind—photovoltaic-energy-storage Mutual Complementary Photovoltaic Power Station", etc.

Jiangsu Formula Electric Technology Co., Ltd. has set up the clean-friendly wind-photovoltaic-energy-storage distributed power generation system at its company location. It mainly includes 23.5kWp photovoltaic power generation system, 100kW/78kWh lithium battery energy storage system, 40kW station service load, LV integrated distribution system, electric energy testing and controlling measurement system, power quality monitoring system, harmonic control and reactive power compensation system, micro-grid coordinated controller, micro-grid energy management system etc. and reserved wind power and other alternative energy sources access interfaces.

Fig.5. 10 Clean-friendly Wind-photovoltaic-energy-storage Distributed Power Generation System

Chapter 6 Distributed Power Electricity in Japan and Development of Intelligent Power Distribution and Utilization Technique

Power system in Japan has basically realized automation in the transmission and distribution system apart from smart meters. The purpose of the current grid intelligent building is to solve the access problem of distributed renewable energy, in particular the various issues that arise when photovoltaic power generation is connected to the grid in large scale, in order to improve the reliability of power supply. At the same time the new technology of long-distance meter reading (smart meters) is opened up to improve business efficiency and provide more customer service. At present, the use of communications technology is limited to the control of the meters, distribution lines and other electrical equipment, and a new generation of smart grid cities (Kanagawa, Kyoto) has been going through related empirical trials since 2010.

Japan develops the smart grid to ensure the quality of the supply of electricity and by the introduction of new technologies to achieve life comfort and other added value before the extensive use of distributed power.

Most of the energy consumption by Japan relies on imports. 2007's energy self-sufficiency rate is only 4%, even considering nuclear power as its energy; self-sufficiency rate is only 18%. Therefore, Japan has been committed to strengthen the nuclear power development to improve energy self-sufficiency rate and achieve low-carbon. With environmental awareness rising, it actively introduces renewable energy sources while developing nuclear power. It published RPS Law (Renewables Portrfolio Standard) in 2002 and set a goal, and decided that power companies must bring in the amount of renewable energy in accordance with the supply of electricity. However, the introduction of renewable energy has made electricity surplus, power system voltage rise, and FM capacity inadequate and other series of problems. To solve these problems, the most effective use of IT technology to control the battery, adjust the output, etc. is needed in order to achieve the lowest social-cost smart grid.

Current statistics of Japan’s electricity show that the rate of transmission and distribution line losses is low, outage time is short and the distribution automation rate achieves 100%. Japan's smart grid is centered on research and development of new power (renewable energy generation, power storage device, and plug-in hybrid vehicle etc.), load and coordination of the use of the existing power system and looks forward to increase revenue while promoting the sound development of the environment. In addition, the recent use of the micro-grid to manage a decentralized power system of certain areas receives wide attention.

6.1 Some Related Policies and Intelligent Power Distribution and Utilization Technology

Japan's wind resources are not very rich, but the number of PV electrical equipment companies is relatively large, so among renewable energy resources, it puts particular emphasis on photovoltaic power generation. In July 2008, in the "low-carbon society action plan" (see Fig. 6.1) decided by the Cabinet, the photovoltaic power generation target of 2020 was 10 times (14,000,000kW) that of the end of 2005 (1.4 million kW), by 2030, year-on-year as 40 times. In April 2009, as the economic countermeasures, the photovoltaic power generation target for the end of 2020 will increase to 20 times that of the end of 2005 (28 millionkW), and popularize photovoltaic power generation to 5.3 million average families. To accomplish these new goals, government subsidies and fixed-price acquisition system policy must be relied on to provide support. The goal of wind power development is to make the end of 2020 be 5 times (500kW) that of the end of 2005.

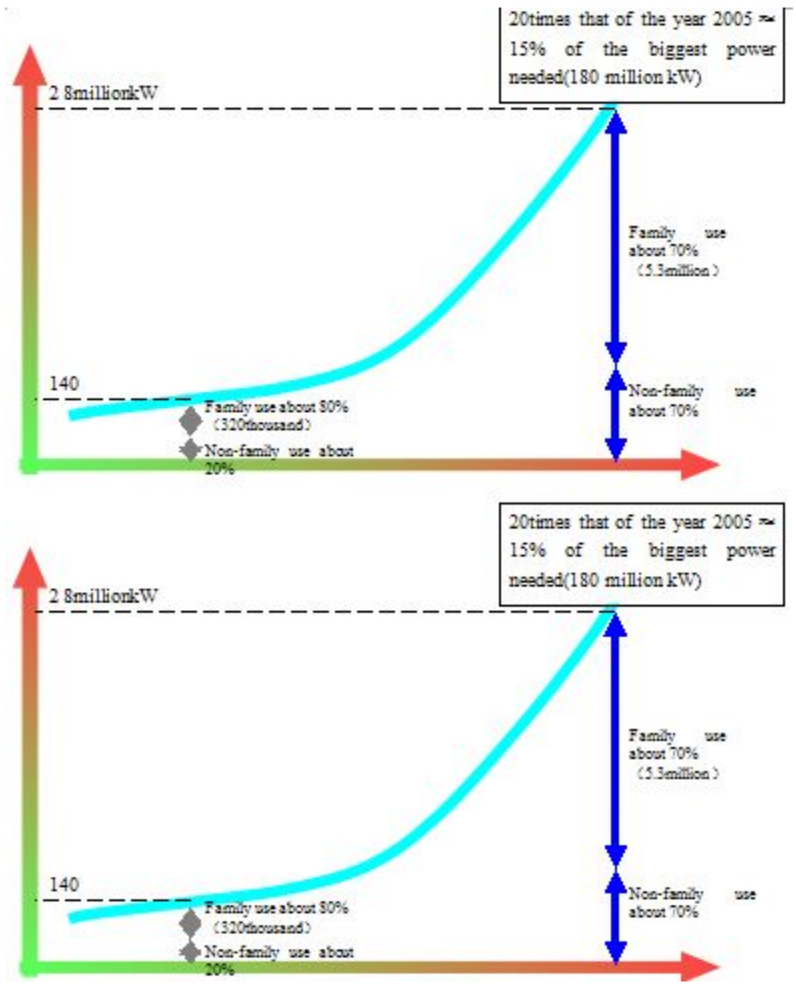


Fig.6. 1 Introduction target of photovoltaic power generation

In June 2010, the government issued "Energy Basic Plan" as the national energy strategy. It brought up the goal of doubling energy self-sufficiency and self-development ratio of fossil fuel by December 2030, and renewable energy and smart distribution network are one of the means to achieve this goal (see Fig.6.2) .

The ministry of economy which administers energy policies organizes various committees and seminars, in the premise of the introduction of large numbers of renewable energy customers, centers on corresponding measures of the power system, and builds a "Japanese smart grid". For the realization of "next-generation energy and social system", they publish the following ideas and technical solutions.

1) A new generation of transmission and distribution network. Through the experiment of the next-generation intelligent transmission and distribution system, to do the pilot test of system control, the photovoltaic power generation output data storage, analysis and islanding micro grid.

2) Heat: the efficient use of unused energy. To build a thermoelectric control system integration, and to do the system improvements based on empirical test data, and finally to determine the best operating techniques and methods.

3) Area energy management. To establish the regional energy management system based on the empirical test data and to verify its effectiveness.

4) Smart meters. That is visualization of the consumption of electric power, and the empirical test of electricity price linkage.

5) The power storage composite system. Through empirical testing, set development in the users' battery and to accumulate experimental data.

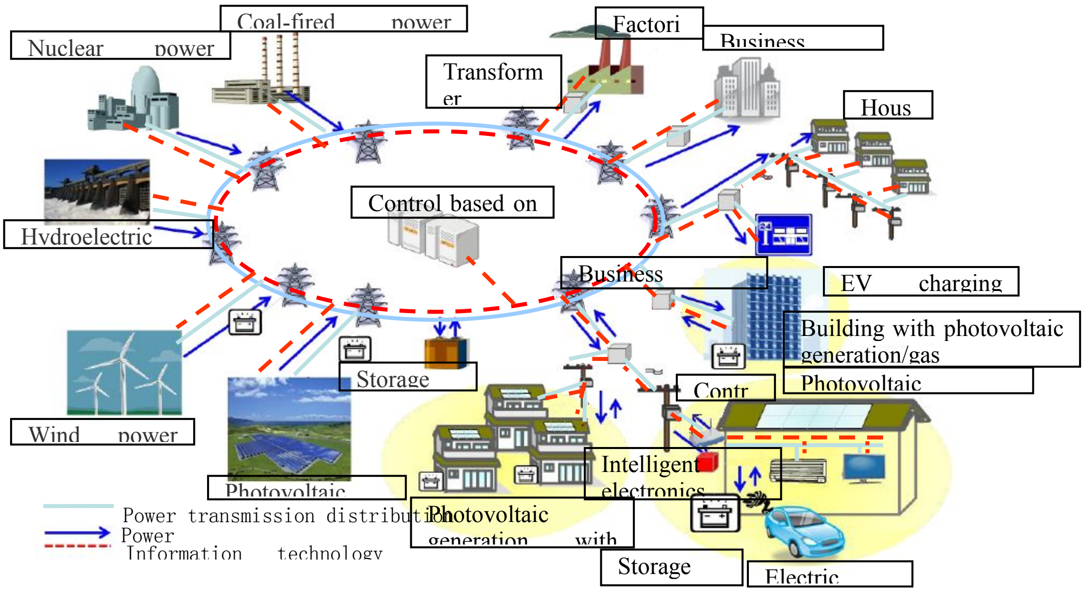
6) Intelligent residential and smart appliances. Corresponding to connected devices of intelligent usage and data standardization.

7) ZEB (zero energy buildings). To strengthen the building's energy efficiency standards in the energy-saving regulations.

8) A new generation of cars. By the end of 2020, about half of new car sales will be the new generation of fuel-efficient cars.

9) The international standardization. That is to set up a special committee to promote international standardization.

10) Overseas expansion. To build a new Mexico energy management system (a common empirical project by the Japan-US smart grid) in cooperation with the United States.



Note: EV (Electric Vehicles): cars powered by electricity

Fig.6. 2 The concept of smart distribution grid and smart distribution park

6.2 Impacts of Renewable Energy and Solutions

The increase of photovoltaic power generation equipments has brought a lot of problems, such as voltage rise, the lack of ability to adjust the frequency, the occurrence of surplus electricity. Much PV power connected to the end of the distribution line results in reverse current, leading to the end of the power distribution system voltage increasing. Its countermeasure is to consider setting the SVR (Static Voltage Regulator), to compensate for reactive power (SVC, Static Var Compensator). The fast SVC speed of response can respond effectively to Instantaneous voltage fluctuations caused by changes in the amount of light. These devices have been used in part of the electrical system.

Under normal circumstances, the power company can ensure that 1% to 2% of the total demand as fast spare ability and can not correspond to renewable energy which has large changes in its output and is difficult to predict. When large amount of renewable energy is put into the system, the instantaneous amount of changes increase, leading to a lack of ability to adjust; as the corresponding means, in addition to setting standby power, the pumping power plants and battery both have building space and cost issues, and there is no fundamental solutions.

In spring and autumn when the demand for electricity is relatively less, the output adjustment of thermal power which is viewed as the basis of the power is limited, and the photovoltaic device power will produce surplus electricity when in generation. Only when the demand for electricity is less can the output of the photovoltaic power be controlled. Effective solutions right now is to implant calendar programs in photovoltaic devices in order to control its generating capacity at a specific date.

6.3 Smart Meters

The government's views of the significance of the introduction of smart meters are summarized as the following points:

1) To accomplish the target of 50% reduction of domestic CO2 emissions by the end of 2030

2) To master energy supply and demand conditions, to promote user control of energy-consuming equipments, and to raise awareness of energy-saving actions.

3) To provide the users to select the most reasonable energy services environment.

4) To introduce renewable energy to achieve zero-energy buildings.

5) To create new service industries which exploit consumption amount and other information and intelligence.

By2015, do repeated empirical testing and performance analysis, and in the early time of 2020, achieve the target of all users in principle introducing smart meters. Currently, the power companies are all trying as hard as possible to achieve the government's target.

For power companies, smart meters can improve and improve the digitization and function sophistication of electricity metering, coupled with two-way communication function, and can improve business efficiency, provide users a variety of services. Table 4.1 is the current situation of empirical tests of the introduction of smart meters by the power companies.

Table 6.1 Empirical tests of the introduction of smart meters by power companies

Power companies	**content**
Hokkaido Electric Power	In order to improve the user quality of service and improve business efficiency - the introduction of new digital energy meter with communication function, and empirical tests are scheduled to run from 2011 with 600 users targeted.
Tohoku Electric Power	In order to obtain remote meter reading technology - scheduled to run from October 2010 to begin long-distance meter reading tests of new digital meters.
Tokyo Electric Power	It aims to test new performance of new digital meters - in October 2010, scheduled to conduct pilot tests in part of the region of Tokyo , and according to the results of the pilot, to

	verify the possibility of the introduction of the meters in the whole supply area
Chubu Electric Power	It aims to obtain remote meter reading technology – scheduled to conduct long-distance meter reading tests of new digital meters from 2011.
Kansai Electric Power	It began to study in 1999, carried on the research of new meters from 2011 and in 2008 conducted empirical tests of electricity meters (a new metering system) with the communication function , approximately 430,000 families by the end of June 2010
Kyushu Electric Power	In 2009 it started using new low-voltage digital power meters with the communication function, which reached about 25,000 families by the end of June 2010, and were gradually expanded after the inspection.

6.4 A New Generation of Energy

To make CO2 emission reduction of people's livelihood and transport sectors. visualized, empirical tests on new generation of energy and society system are conducted by industry, residents and local governments in this year in Yokohama (Kanagawa), Toyota (Aichi) Kansai Science City (Kyoto) and Kitakyushu City (Fukuoka) until 2014 (the implementation time is 5 years). There are 5,500 ordinary families and about 80 power companies and car manufacturers to participate in the empirical tests, and the total cost will be 122.6 billion yen, which will be shared by national and local governments and enterprises.

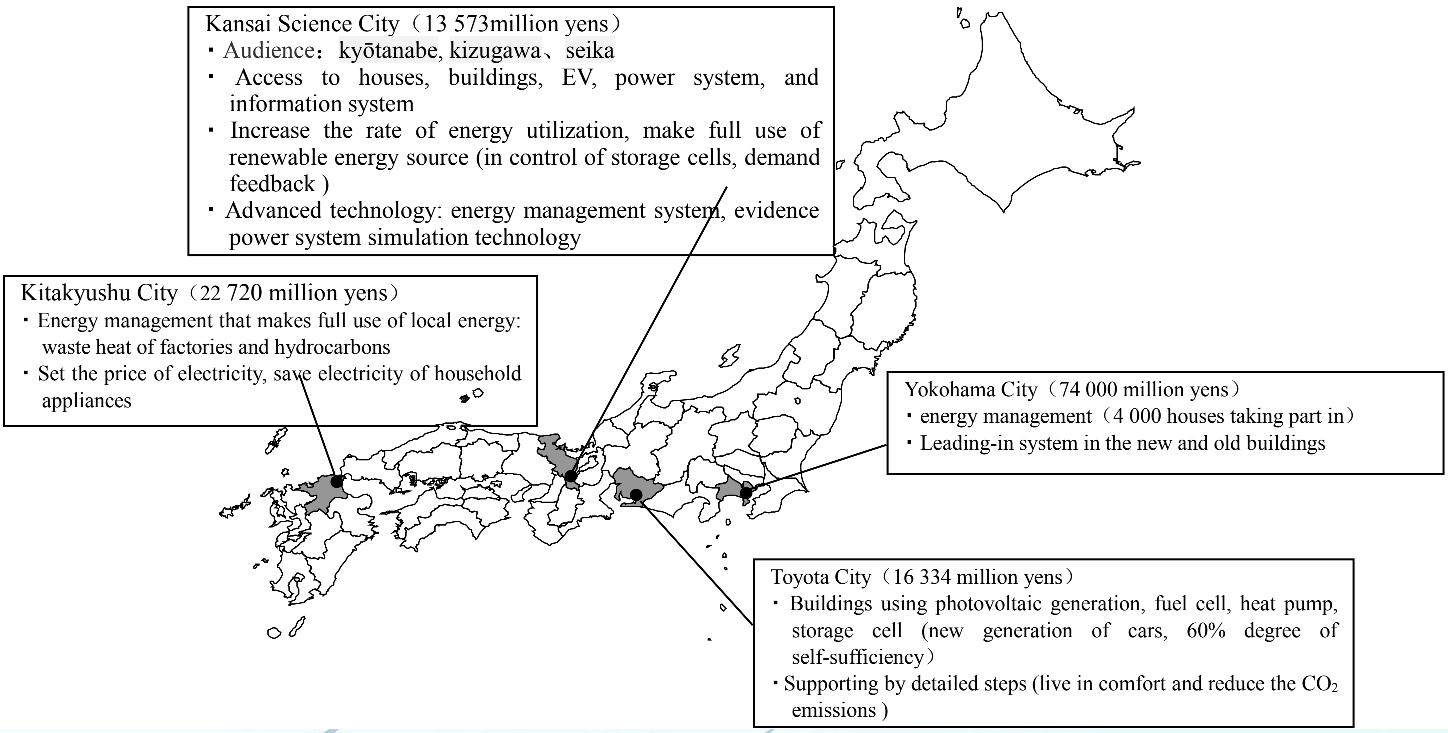


Fig.6. 3 Distributed generation and demonstration area with intelligent power distribution and utilization system

Note: Yokohama Minato Mirai 21: To build the sea-crossing zone between the Yokohama Western and Central areas to be a redevelopment project in line with the image of the 21st century.

According to the basic plans of the four local governments, the target of CO2 emission reduction emission of this test will reach 20% to 50% that of 2005 (Fig.6.3).

6.5 Summary

Distributed power and intelligent power distribution technology have received extensive attention in all walks of life. The major concern and research direction is when a large number of distributed photovoltaic power generation is inserted, how can distribution network maintains a high level of power supply capacity and power quality. Of course, “introduction” is realized within an acceptable, reasonable cost range. Right now a new generation of energy social system which Japanese power companies participate in will be implemented, and the smart grid, smart meters, distributed generation and other access technologies in its central subjects will bring some industry direction, whose research results will receive much attention.

Chapter 7 Smart Grid and Future Grid Research and Development Opportunities and Challenges

7.1 Background

This section provides a general overview of the School of Electrical and Information Engineering, the University of Sydney, Australia and its association with the Australian federal government and Ausgrid's $600million Smart Grid, Smart City project.

The University of Sydney is the first University in Australia established in 1850. Since then the University has been ranked among the very top in Australia and one of the best worldwide. The recent QS ranking of universities ranked the University of Sydney at no. 32 internationally based on its excellence in research, education, prestige, industrial and international impacts.

The School of Electrical and Information Engineering at the University of Sydney is traditionally a strong school in research. In recent Australian government ranking – Excellence in Research Australia, the school is ranked 5 and 4 for its major research areas, which means it is well above world level in research excellence. The School has four strong areas of research, telecommunications, power engineering, fibre and photonics, and computer software engineering. There are 4 IEEE fellows in the school being the highest in all EE schools in Australia.

With substantial funding support from the industry, the school has strong link with the industry, through the school foundation as well as other industrial partners.

In 2010 Ausgrid in association with partner organisations established Ausgrid Centre of Excellence in Intelligent Electricity Networks at the University of Sydney and the University of Newcastle Australia. The two centres are supported by Ausgrid through the Smart Grid, Smart City project with funding up to $100 each year for up to 5 years.

The two centres have been providing RD&D support for Ausgrid and other industrial partners through smart grid related research and consulting projects.

7.2 Smart Grid, Smart City

Smart Grid, Smart City was a $100 million demonstration project funding by the Australian federal government, led by Ausgrid and supported by its consortium partners:

"The project tested a range of smart grid technologies; gathering information about the benefits and costs of implementing these technologies in an Australian setting. Up to 30,000 households will participate in the project which runs between 2010 and 2014.

Ausgrid lead a consortium of partners working together on this trial. EnergyAustralia, the Smart Grid, Smart City retailer partner, tested innovative technology and pricing offers. These products also made the most of new smart meters and were designed to give homes greater choice and control over their bills."

Under the Smart Grid Smart City project, there are a number of trials expected to complete by early 2014, including:

(1) Grid Trials:

Active Volt Var Control which uses smart grid technology to manage voltage delivery across the network to more efficiently manage the power supply.

Fault Detection Isolation & Restoration (FDIR) enables better identification of fault locations and isolations so as to restore power faster.
Substation and Feeder Monitoring (SFM) works through the communications platforms to reduce the cost of getting vital asset information, including from high voltage underground cables.

Wide Area Measurement (WAM) uses integrated Phasor Measurement Devices to better predict system state and possibly prevent network interruptions across a large area.

(2) Network Customer Trials

- Community generation and storage
- Electric cars
- SGSC Home Energy Assessment
- SGSC Home Energy Monitor
- SGSC Home Energy Online
- SGSC Home Energy Rebate
- SGSC Home Energy Network
- The Smart Home Family

(3) EnergyAustralia trial

EnergyAustralia is the electricity retail partner of the Smart Grid, Smart City project. EnergyAustralia trials include new pricing structures alongside household energy management tools, such as new devices that show how much electricity is being consumed in the home. Over the trial period, existing EnergyAustralia customers can participate in this project.

"EnergyAustralia's Smart Grid, Smart City trial is all about proving customers with knowledge about their energy costs and usage, because the more you know about your electricity consumption, the more control you can have over your use and bills. What we learn from our customers during this trial will deliver learnings for the whole of Australia."

Telecommunications infrastructure is a major part of the Smart grid, Smart City project which explored home area network, last mail wireless communications and broadband network infrastructures.

7.3 Selected Projects

(1) Solve PV Project

The findings of the project indicated that the peak demand happens at different hours w.r.t. the PV generation peak; therefore, battery energy storage system is needed to provide better utilization of PV generation at the feeder end, [2][3][4][5];

(2) PV Coating Technology

The presenter also has a special coating material / technology which can be applied on the surface of silicon PV panels to improve the efficiency of power generation by 20-40%.

(3) Feeder load modeling

Load modeling has been traditionally in the form of aggregated load model at transmission substation. More detailed load models at distribution level is either not used or too expensive (to involve customer survey) to do. With smart grid technologies, especially, the measuring devices such as power quality measurement, smart meters etc, the research team has developed technologies and approaches to model load at feeder end. The model development does not require fault recording which is difficult to obtain, instead many routine measurement, such as tap change transformer switching recording, can be used for the load model development. This will greatly enhance the modeling capability and accuracy of distribution network service providers in operations and planning.

(4) Feeder Loss Minimisation with Capacitor Banks

Capacitor banks have been used for power factor correction and voltage support. In this project, an methodology had been developed to consider distribution feeder loss as well as distribution transformer loss together on the longer term basis to provide optimal loss reduction as well as power factor support, [6].

(5) Demand side management for network stability support

With increasing renewable energy generations connected at the electricity networks, the challenges are the intermittency associated with wind and solar based generation. Although battery energy storage system can be used to provide energy storage support, however, the costs associated are too high. In this project, demand side control is explored and used to provide aggregated support as an equivalent energy storage system for the whole network, [7].

(6) Smart Grid Cyber Security

A smart grid include a cyber-system of telecommunication and It networks, together with a physical power system including generation, transmission, distribution, and loads. Security of the cyber system can impact the security of the physical system and vice versa. We developed a complete cyber-physical smart grid model which can model cyber attacks as well as physical power system contingencies and the interactions between the two systems, [8].

(7) Future Grid

This project looks what is going to happen after smart grid which focuses mainly on the distribution network. The future grid project covers transmission network as well to explore the optimal strategies for combined primary energy and electricity planning, modeling of customer behaivour, regulatory and market implications. This is a government funded $13million flagship project lead by the University of Sydney.

7.4 Conclusions

Smart grid technologies provides opportunities and challenges for the power industry. Although smart grid development has been active worldwide for several years, however, there are still many problems need to be solved. Energy storage is one of the challenges and promises out of smart grid era. Beyond smart grid, it is necessary to consider the power system as a whole, for both transmission and distribution networks, such as the future grid concept. The research team at the University of Sydney has been active in providing complete smart grid solutions as well as many operational/consulting support for the industry.

Chapter 8 Smart DC Micro-Grids

8.1 Introduction

The electricity supply industry has to respond to many challenges for which new solutions are always being sought.

These challenges are not new and traditionally include: 1) the provision of continuous and reliable supplies; 2) economy of supply and to keep the prices down.

In recent times, especially with the greater commercialisation of the industry and the growth in the desire to be “green”, the growing challenge is for the sustainability of supplies and the industry.

Although these challenges are not new and have shaped the industry from its very inception, the current solution is to introduce smarter systems, which are all part of the smart grid scenario.

The understanding of the role of electricity in modern life has itself been developing. Some consider it to be a service, others a commodity and others have the idea that it is a human right.

Overall, the goal is simply defined as “to keep the lights on”. Loss of supply is by far the greatest concern for consumers and increases as the supply reliabilities are increased.

The demands for electrical energy are developing. Lighting was the initial driver for the electricity supply industry in the late 1880s and remains the dominant use. Mechanical power quickly followed and facilitated much of modern industry. Heating systems became popular in the mid-nineteenth century, but waned as the direct use of fossil fuels became convenient, namely gas and oil. The major growth area for today is entertainment, communications and information technology. Growth in these areas is expected to put new and significant demands on the electricity industry.

The use of electricity for transport and heating is also expected to grow with the development of the low carbon economy.

Arguably, electrical energy has always been expensive and in recent years costs and prices have invariably increased. This is a major cause of dissatisfaction, commonly resulting in political interest and forced changes to the industry. Although “cheap” energy is accepted as being virtually impossible, there is an accepted need for charges to be “fair” if not minimal.

The electricity supply industry is recognised as being a major source of pollution and greenhouse gasses. Thermal generation dominates the industry and fossil fuels still provide the greatest primary source of energy.

World-wide there is a universal desire to be "good citizens" with the push to eliminate pollution and dramatically reduce CO_2 emissions. Most countries have a drive to develop renewable sources of energy as part of the move to provide a sustainable electricity power industry.

Alongside this is the acceptance of the need for an economically sustainable industry. In order to survive, the power industry must provide an acceptable return for investors to finance the sector and fund future investment. This investment is seen as inherent in the development of a viable industry with the pressures of today's society.

8.1.1 Smart Grids.

The term "Smart grid" is widely used worldwide. Confusingly, there are many, many different definitions of smart grids and invariably individual engineers have several of their own favourites.

Fig.8. 1 The Signing of "The American Recovery and Reinvestment Act", January 16th 2009 [9].

The President of the USA is widely recognised as a leading supporter of the 'smart grid' and used the term in the 2009 American Recovery and Reinvestment Act [9] which promised 3000 miles of new transmission line, 40 million smart meters and one million electric vehicles by 2015.

In China, the definition from the Institute of Electrical Engineering Chinese Academy of Sciences states that "The smart grid integrates the physical power grid with a series of modern advanced technologies, and finally forms an innovative type of electric power grid." The physical power grid is the foundation of the smart grid, which contains a variety of power generation equipment, transmission and distribution networks, consumer units and energy storage devices. The techniques involved include sensing measurement technology, network construction technology, communication technology, computing technology, automation and smart control technology.

Based on this:

1. The smart grid is observable.
2. The smart grid is controllable.
3. The smart grid is completely automatic.
4. The smart grid can achieve system optimization and balance.

In UK, one representative definition of the smart grid, by Rachel Fletcher a Director of OFGEM (Office of Gas and Electricity Market), has described it as: “A Smart Grid as part of an electricity power system can intelligently integrate the actions of all users connect to it- generators, consumers, and those that do both- in order to efficiently deliver sustainable, economic and secure electricity supplies.” The smart grid is an integration of communication, innovative devices and specific services together with advanced monitoring and control technology to achieve the intellectualization of the power grid [10].

Each of these addresses the particular challenges in their different countries. In the USA, the challenge is to revitalise the aging infrastructure. In China, the challenge to build a system which will satisfy the needs of a large country with a large demand together with the needs of future demands. In the UK, there is the challenge to accommodate increasing levels of renewable energy and the resultant increase in distributed generation.

Despite the many differences in these definitions, they are all aimed at facilitating the basic objectives of the electricity supply industry; security, economy and sustainability.

8.1.2 Micro-Grids

As with “smart grids”, there are many different definitions of “micro-grids”. Several groups regards micro-grids as something new, others regard them as the foundation of the modern electricity supply systems.

A micro-grid is defined as “A micro-grid is a localized grouping of electricity generation, energy storage, and loads that normally operate connected to a traditional centralised grid, 2009 [11]. This single point of common coupling with the traditional centralised grid can be disconnected. The micro-grid can then function autonomously. Generation and loads in a micro-grid are usually interconnected at low voltage. From the point of view of the grid operator, a connected micro-grid can be controlled as if it were one entity."

Accepting that micro-grids are nothing new, in 1918, London had 50 different power networks, micro-grids, operating at 24 different voltages and 10 different frequencies. This highlights the major challenges of the micro-grid namely, standardisation and integration. The principal weakness of the micro-grid is economy due to the need to meet the maximum demand placed on the system. Integration of micro-grids into a centralised grid was the solution since loads and generation could be shared.

The recent interest in micro-grids has been spurred by blackouts of the centralised grid with major examples being China in 2008, the USA 2012 and India in 2012.

The integration offered by the centralised grid has become a threat. Dependency on the large integrated system becomes a threat when that network is disrupted and the link between generation and consumption is broken.

"The U.S. Department of Defence is actively pursuing micro-grids as a means to achieve energy surety, security and economics at military facilities." 2013 [12].

"Storms such as Katrina, Irene and Sandy have heightened the need for local pack-up power to withstand multi-day outages, especially for any load that is critical to public safety, health and welfare." 2013 [12].

Although these disturbances have given a great impetus to the development of micro-grids, other factors have provided greater, less public drivers.

The desire to develop "green" energy has led to a development of small and medium sized generation connected to local loads as a micro-grid.

The cost of distributed generation is continuing to fall and in several areas is comparable to that of grid supplied energy.

The cost of Photo-voltaic panels and inverters continue to fall.

CHP systems, providing both heat and electrical power are popular in Northern latitudes.

In several countries, legislation encourages independent power generation and has led to the development of associated micro-grids.

8.1.3 DC-AC Supplies

The "war of the currents" raged from 1890 to 1930 and led to AC proving to be the overall winner. AC now dominates the electricity supply industry and DC power supply systems have been relegated to a few specialist applications.

Most of the first public electricity supply systems were DC. Both the Holborn Viaduct Generating Station in London, 1882, and the Pearl Street Generating Station in New York, 1882, generated DC power [13].

The move to AC supplies was accelerated by the invention of the induction motor and the transformer and AC was the dominant supply by the 1960s.

The last public DC supplies continued into the 21st century. In January 1998, the Consolidated Edison Company started to eliminate their DC services. At that time there were 4,600 DC customers. By 2006, there were only 60 customers and on November 14, 2007, the last DC distribution by Consolidated Edison was shut down [14].

In the UK, the Central Electricity Generating Board continued to maintain a 200 volt DC generating station at Bankside Power Station in London as late as 1981. This supplied printing equipment in Fleet Street and was only withdrawn due to the move of the print works to the London docklands area.

Today, DC is staging a comeback. Not as a competitor to AC but as a partner, where DC offers advantages which AC cannot match.

DC has advantages where distances are small, where DC loads dominate, where DC generation is included and where storage is involved.

Applications of DC include computing, communications and control. They also provide the idea power source for low energy lighting and storage.

In the early days of electricity, lighting provided the catalyst to drive the industry. LED lighting offers the promise of the future for low energy systems. With the development in the exploitation of renewable energy sources, storage is growing in importance. Both of these are better served by DC rather than AC.

8.2 Project Edison: SMART DC [15].

Project Edison is a demonstration project involving a DC micro-grid operating in the library at the University of Bath. The library is a 24 hour study centre with 500 computer work stations for students and staff to support their studies and research. The micro-grid is located on the fifth floor of the library which supports Management and Social Sciences and has a suit of 50 computers. It includes local storage and offers options for DC lighting and easy access for local generation using renewable energy sources.

It is a ground breaking project to explore the potential energy savings and associated advantages by using a localised DC electricity supply network. The project was funded from a Knowledge Transfer Account Partnership Development Award, which was matched by RWE Npower.

The micro-grid was designed to demonstrate the feasibility and potential benefits of local DC Networks in terms of system efficiency, financial and environmental benefits together with flexibility gains.

The structure of the micro-grid is shown in Fig 8.2. The principal energy source is the three phase AC supply. This is converted into a low voltage DC supply which provides the nominally 24v DC bus which is connected to the 20kWh valve regulated lead acid batteries. The DC distribution panel provides the feeder circuits for the DC computers and their monitors.

The DC computers have the same specification as the current generation of library work-stations except for the power source, which is 24v.DC. The monitors are similar to the standard monitors used elsewhere except that they are powered from the 12v DC bus generated within the computer.

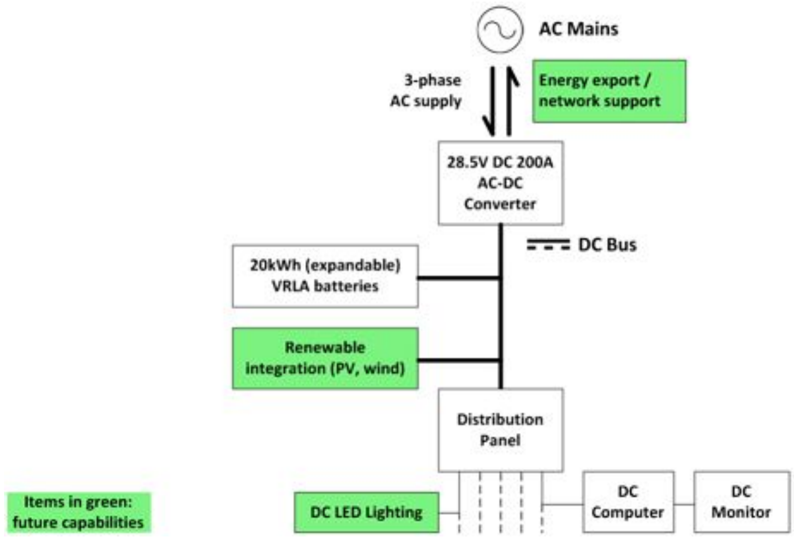


Fig.8. 2 Project Edison, the DC Micro-grid.

Fig.8. 3 Project Edison, the suit of DC computer workstations.

Fig.8. 4 Project Edison, the DC workstation.

Fig 8.4 shows the components in the workstation comprised of the computer and its monitor. These have the same performance specification as the standard library system and as such have a similar motherboard and peripherals. Using a DC powered power supply, they have proven to use a lower energy, provide less waste heat and be quieter. During the winter months, the area's central heating had to be turned up whereas during the summer, the air-conditioning could be reduced.

Fig.8. 5 Project Edison, the AC-DC converter and battery management controller.

The AC-DC converter and battery management controller are shown in Fig 8.5. These are housed in the plant room on the 6th floor of the library. This area also houses the heating and air-conditioner systems together with the lift systems.

Fig.8. 6 Project Edison, the AC-DC power converter and control systems.

Fig.8. 7 Project Edison, the battery storage.

The battery storage comprises of eight voltage regulated lead acid units with a storage capacity of 20kWhr.

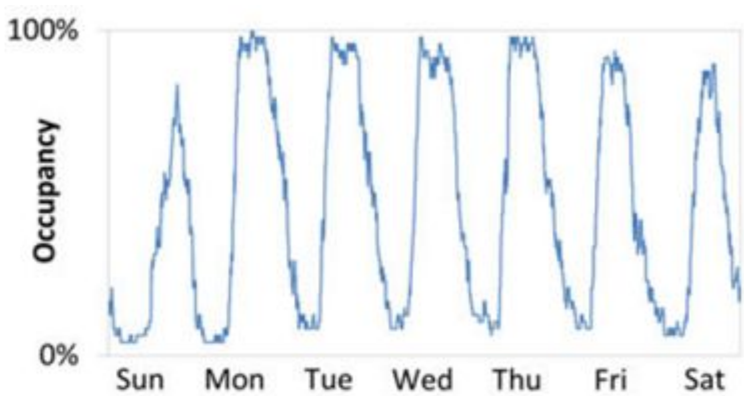


Fig.8. 8 Project Edison, typical term-time day-to-day computer occupancy.

The suit is continually monitored for its usage, the AC power consumption, the time-of-use, waveform distortion, power factor, the DC power consumption and the conversion efficiencies.

Throughout the day time period, the utilisation factor is high, ranging from 96 to 100%. The facility is used 24 hours of the day apart from Saturday and Sunday nights when there are periods that none of the work-stations are in use. Both Saturday and Sunday have a good loading apart from overnight.

The energy storage facility provides security of supply and flexibility for 'smart' demand management.

The security of supply facility provides an uninterruptable power supply capability for several hours. The design capability was for full day's operation, although this has never been tested. Several short durations of loss-of-grid have been experienced of up to 30 minutes. For the first interruptions, the loss of the network did cause the computers to fail, however after this was resolved, during subsequent disturbances, the system continued to operate and users were not aware of problems.

Smart management of the supply involves using the AC-DC converter only when the bulk supply is economic and relying on the battery storage to maintain the system at other times. This can be tied to periods of low-tariff or when there are low CO2 emissions.

Currently, the University operates under a single tariff and there are no low-tariff periods available for preferential charging. However, the prospect of smart metering and varying tariffs governed by energy costs, would make off-peak charging and the use of storage during periods of peak tariff beneficial. The opportunities offered by such a regime are illustrated in Fig 8.9.

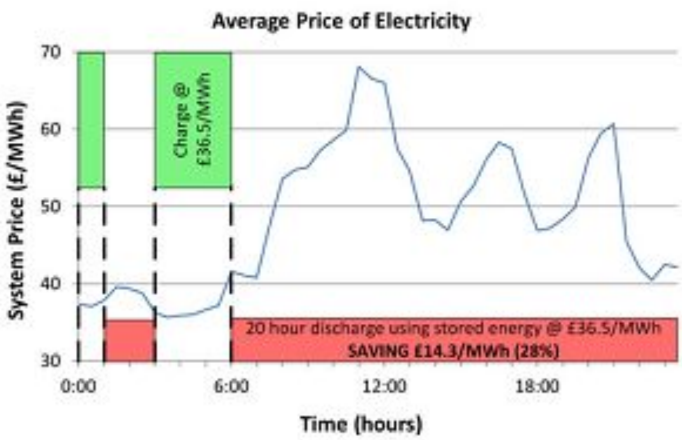


Fig.8. 9 Project Edison, potential cost savings from smart charging of the batteries.

A similar scenario can be seen from using the level of CO2 emissions to control the charging period and those when the micro-grid is powered by the storage, as shown on Fig 8.10.

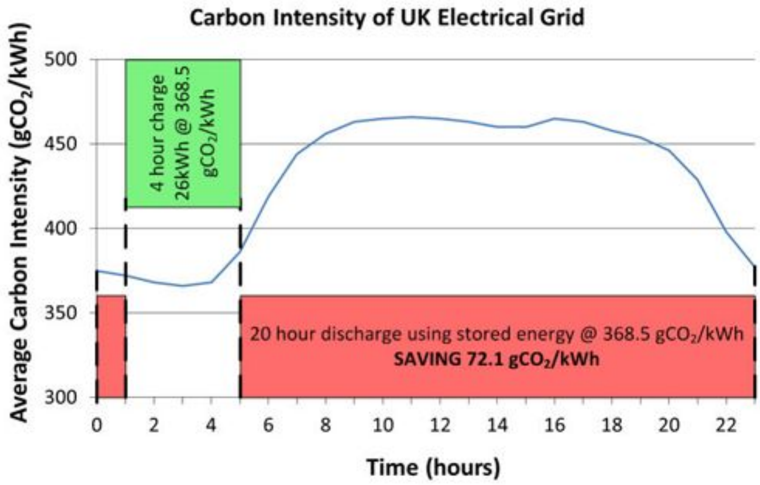


Fig.8. 10 Project Edison, potential CO2 savings form smart charging of the batteries.

The most immediate benefit for using the micro-grid was the dramatic reduction in waveform distortion by using the DC supply rather than the bulk AC supply.

Waveform distortion, harmonics, is a major challenge associated with the use of a high density of computers in one location. The conversion from 3-phase AC to DC can be achieved with the minimum of distortion leading to an immediate advantage over a suit of AC computers.

The experience with Project Edison is illustrated in Fig 8.11.

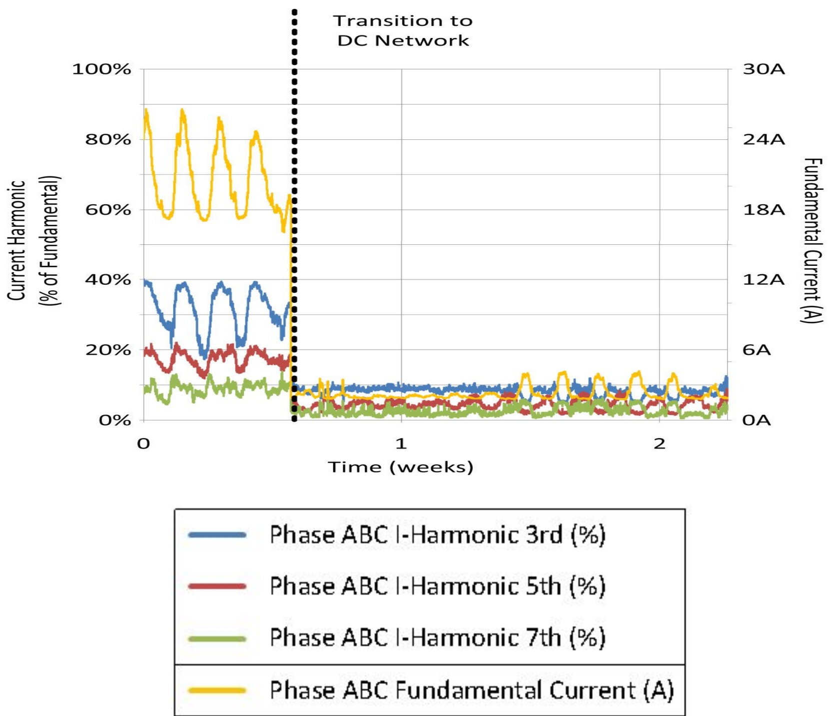


Fig.8. 11 Project Edison, the dramatic reduction in AC Harmonics.

This reduction in harmonics not only reduces system losses, but also avoids the addition costs of filters to ensure that distortions are not imposed on the utility connection.

Project Edison, Smart DC has been a proof of concept project demonstrating the attributes of a DC micro-grid and highlighting the principal opportunities and challenges of such a system.

Overall, the project has run smoothly although some of the challenges have been revelations:-

The need for standards.
The need to settle on a standard voltage.
The need for suitable connectors for DC supplies.

Project Edison chose to use a 24v DC supply. There was considerable debate about whether to use 12v, 24v or 48v. 24v was chosen in consideration of the availability of suitable computers.

The 24v connectors were also selected on availability, taking advantage of the now obsolete 15A round plugs and sockets.

Despite its opportunities, the plan to include renewable, photo-voltaic generation was shelved. This was due not for financial or technical reasons but for aesthetic ones. Further studies have been instigated to explore this issue and to demonstrate how renewable generation and storage can provide benefits for both the consumer as well as the local power utility, project SoLa BRISTOL.

8.3 Project SoLa BRISTOL [16].

Project SoLa BRISTOL is funded by OFGEM, the Office of Gas and Electricity Markets in the UK, as part of their Low Carbon Network Fund project investigating the implications of using in DC micro-grids for homes, schools and offices.

Project Sola Bristol considers Buildings, Renewables and Integrated Storage with Tariffs to Overcome network Limitations. The DNO partner is Western Power Distribution, the technology partner is Siemens, the academic partner is the University of Bath and the hosting partner is Bristol City Council together with Knowle West Media Centre and Galomaner Ltd..

The project is to investigate and demonstrate the use of DC micro-grids which include storage and PV generation for the benefits of both the electricity consumer and the local distribution network operator. The consumers benefit from the ability to offset peak-time energy with stored off-peak energy together with greater on-site utilisation of PV generated energy. The DNO benefits from embedded storage which can be used for peak load lopping to alleviate congestion problems and avoid the need for network reinforcement.

The three year project started in January 2012 and involves equipping 30 homes, 10 schools and an office with PV panels, a battery storage facility, a DC micro-grid and communications with the local sub-station. Demand side management and variable tariffs will be examined to control the loads in 10 secondary substations and the local LV network.

The prototype system for the home installations has been installed into the Bristol Council "ecohome" not only to a platform to refine the system design but also to provide an live demonstrator for the general public and those householders involved in the domestic installations. It has provided an excellent trial system for the hardware, communications and control software, and the procedures which will be used in the domestic installations.

Fig.8. 12 The SoLa Bristol "ecohome".

The "ecohome", as shown in Fig 8.12, is a purpose built, south facing, 100 sq metres, three bedroom property built on two floors. It is used to demonstrate eco-friendly building techniques and materials. To demonstrate the opportunities for local renewable generation, a 3.2 kWp PV panel has been installed.

The first challenge is to enhance the value of PV generated electricity for the site. As shown in Fig 8.13 and Fig 8.14, the power output from the PV is not aligned with the typical site demand.

In the summer months, Fig 8.13, the peaks in demand are in the morning and the evening. Although the mid-day period has a raised demand, it does not include the peaks. Without local storage the surplus generation would be exported to the local utility. This constitutes a loss to the site and a burden to the utility.

In the winter months, Fig 8.14, the PV generated energy is only able to offset part of the mid-day demand and has little to contribute. The peak in demand is in the evening and loads the local utility. Storage offers the promise of being able to reduce this peak by supplementing this demand with energy stored either at off-peak periods or when the utility is less heavily loaded. This facility can therefore offset peak energy with off-peak energy and can move the time of use from the evening period to a time more convenient to the utility.

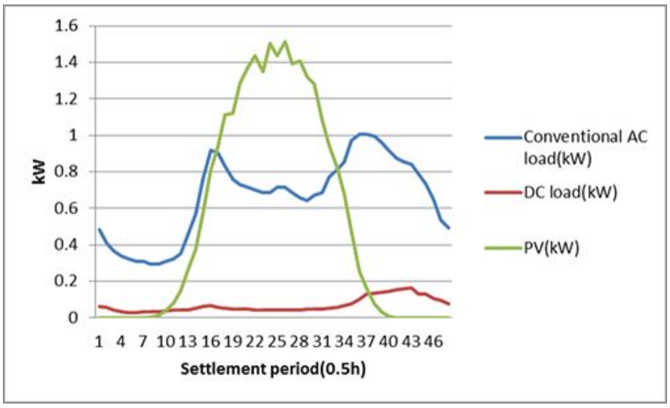


Fig.8. 13 Typical load and PV output profiles for a domestic household in summer

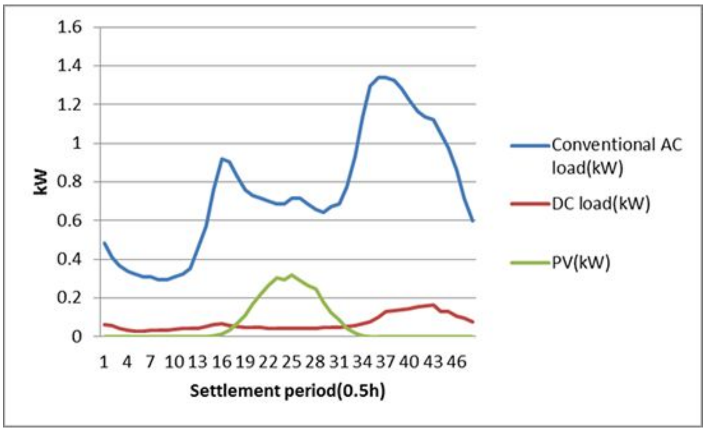


Fig.8. 14 Typical load and PV output profiles for a domestic household in winter.

Included in both Fig 8.13 and Fig 8.14 are the anticipated DC loads for the homes. These loads include lighting, communications and information technology applications. In both the summer and winter months, these show an evening peak.

The electricity network used in the "ecohome" is shown in Fig 8.15. Electrical energy is derived from both the local utility's grid supply and the PV array. The batteries are supplied from both the utility supply via and AC/DC converter and the PV array via a DC/DC converter. The AC loads are supplied directly from the utility supply and from the battery via a DC/AC converter. The DC loads are derived from the battery connections.

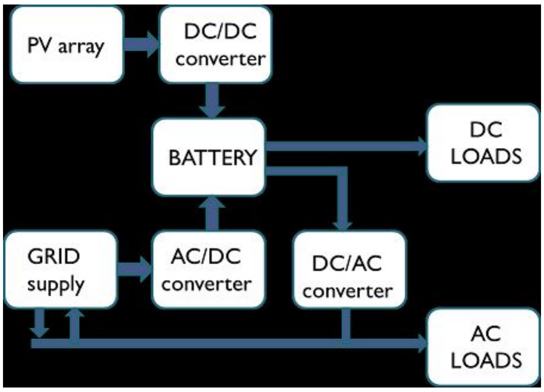


Fig.8. 15 The SoLa Bristol Domestic consumer electricity network.

The power switchgear and control equipment consists of:-

- the combined inverter-charger,
- the DC-DC charge controller,
- wiring to the twin PV input strings operating at greater than 300Vdc
- the protection and control switch gear with DC Bus,
- Inverter-charger cabling,
- AC mains in-out cabling

and,

- battery bank isolation handles.

These are shown in Fig 8.16.

Fig.8. 16 The power switchgear and control equipment.

The bidirectional combined inverter and charger is shown in Fig 8.17. It provides for export power to the grid and top-up charging of the batteries during both on-peak or off-peak periods.

This uses a highly configurable micro-computer controlled unit, where the parameters can be configured to provide different functions depending on the time of day, controlling the duration of any export, and control the output current during export.

The charging parameters and durations are set and the charging profiles can be configured to provide three, four or five stage charging.

The charging of the battery from the grid side is also based on the battery's state of charge using the DC bus voltage levels.

Fig.8. 17 The combined inverter and charger unit.

The primary storage system used Valve Regulated Lead Acid (VRLA) batteries, for the reasons of lower initial capital investment and post installation lower maintenance costs in the domestic environment. The advantage of VRLA batteries is that being sealed they are virtually maintenance free. Due to their construction, they do not require ventilation and can be used in confined or poorly ventilated spaces.

Four 12V 100 Ah VRLA batteries were used providing the 24V supply with a capacity of 200Ah.

Since the PV power generation has both seasonal, day-to-day and time of day variations, four seasonal profiles were proposed for basic charging regimes.

The control system has the capability to provide charging from the grid during off-peak periods to ensure that a "high" level of charge is available for peak load periods. This provides time of use advantages as well as facilities for network congestion limitation.

The battery system is shown in Fig 8.18.

Fig.8. 18 The battery system for the "ecohome".

The DC loads include in the "ecohome" include LED lighting, both white light for working areas and warm light for relaxation and entertaining areas together with DC power points for mobile phones, lap-top computers, local monitoring equipment and actuators. The mobile phone charges use 5v USB outlets.

The communications system includes local control for the storage and converters, communications with the local substation for network interaction and, communications with the network controller for smart tariff information. The project is investigating the use of variable tariffs in advance of the national rollout.

The communications network is shown in Fig 8.19 and the "ecohome" hub is shown in Fig 8.20.

Within the UK, any Grid connected generation system is governed by G59 specifications. A G59 protection relay is required to supervise the connection with the grid supply to ensure that there are no safety issues and that the generation will not cause any problems for the utility network. The G59 relay included Under-voltage, Over-voltage, Under-frequency, Over-frequency and loss of mains protection functions.

During export period, if loss of mains is detected, the inverter is stopped from exporting to the grid.

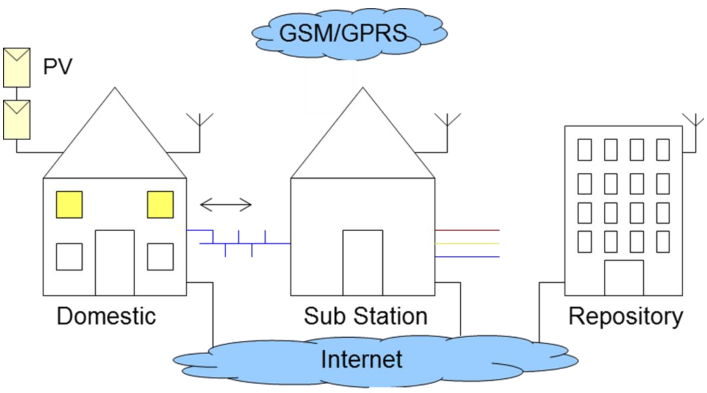


Fig.8. 19 The SoLa BRISTOL communications system.

Fig.8. 20 The "ecohome" communications hub.

Project SoLa BRISTOL has highlighted many of the opportunities and challenges in developing DC micro-grids. Although many of the basic components are commercially available, the requirements for the central converter and control system are only now being identified. The value and limitations of renewable energy sources are also becoming clearer. The role and importance of local storage is also being recognised.

Although the technology has its own challenges, project SoLa BRISTOL has highlighted the importance of the people factors. Consumer participation has been identified as a key factor in the potential success of the project.

8.4 Storage and Vehicle to Grid Opportunities

Both projects Edison and SoLa BRISTOL have highlighted the value and importance of storage in the DC micro-grid. Both projects have involved battery storage as a key element in the demand management.

Batteries are expensive and have a limited life. They require proper housing. Both charging and discharging incur losses. Although the science of battery storage has been understood for several centuries, the science of battery management is a new poorly understood field.

Potentially, the greatest growth area for storage is in electric vehicles. The move to electric transport is a key component of the green agenda and as it accounts for a comparable energy use as today's electricity usage, the development and future investment in storage technology will be significant.

Plug-in electric vehicles rely on mobile storage. Can this storage provide a dual role of not only providing the storage for transport but also a grid connectable storage for fixed applications.

Several researchers have demonstrated that electric vehicle charging can be developed as an asset for the public electricity supply network rather than a curse. Rather than allowing the additional demand required for electric transport to add to the peak in the daily demand curve, 'intelligent' charging can move the demand to fill the over-night trough.

Further development can exploit the charge capability of electric vehicles to provide a source of energy to offset the peak in the demand curve. This has widely become referred to as vehicle to grid, V2G, systems.

Electrifying transportation has a potential to provide a 40% reduction of CO2. Since 2008, more and more manufacturers have been marketing electric vehicles. Generally, electric vehicles are acknowledged to be clean, easy to drive, to offer flexible load and flexible storage and to be green. The principal challenge is range anxiety where users need to have the confidence that they can complete their journeys.

Research into the opportunities of using vehicle to grid based on light vehicles was recently undertaken at the University of Bath [17]. This was to demonstrate how staff and student vehicles could contribute to the electricity demand profile. The vehicle would use off-peak charging and then contribute part of this to offset the energy demands of the campus.

The University of Bath has approximately 12000 students and nearly 3000 staff. There are approximately 2000 parking slots which are occupied for most of the working day.

The average journey time for people travelling to and from campus was between 30 to 39 minutes. Consulting various staff and students, suggested that this equated to journeys of around 10 miles, well within the charge capacity of plug-in electric vehicles. The amount of charge available for offsetting the University's load would have to consider the required return journey plus a contingency.

The University's load has an average value of 6 MVA with a peak of 10 MVA. The load profile is dominated by the working day for staff and students.

Currently, there are very few electric vehicles on campus and hence the analysis was based on the characteristics of the Nissan Leaf plug–in electric vehicle. This has a range of 109 miles using a 24 kWh Li-ion battery. The trickle charging rate is 1.4 kW and has a fast charging rate of 50 to 70 kWh.

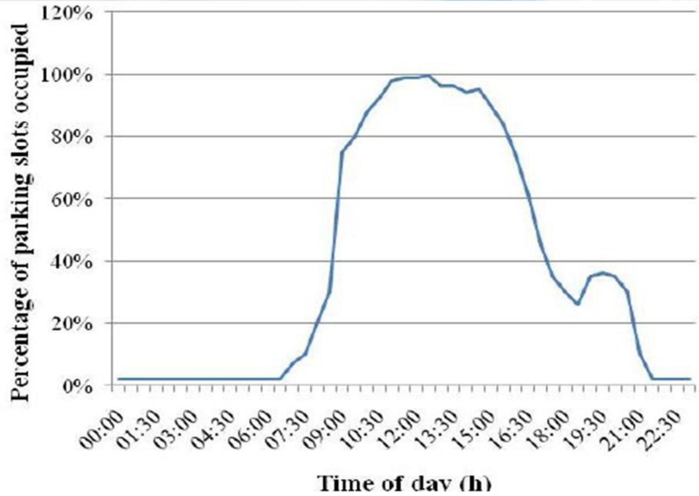


Fig.8. 21 Typical working day parked vehicle volume on campus.

From the volume of vehicles parked on campus during a typical working day, as shown in Fig 8.21, it can be seen 80% of slots are occupied from 09:30 to 16:00 hours.

A driver-friendly discharge scenario was considered ensuring that drivers will still have 60% state of charge, SOC, of their battery when they leave. Based on typical commuting distances, it was assumed that when the vehicle arrived, its battery had an 80% SOC.

The study considered three offers to drivers:-

i. drivers stay from between 07:00 and 21:00 and discharge at 0.51 kW.

ii. drivers stay from 08:30 and 18:30 and discharge at 0.72 kW.

iii. drivers would stay from 09:30 and 16:30 and discharge at 1.03 kW

The control system would accommodate these different discharging regimes and provide some drivers with the facility to charge their vehicles.

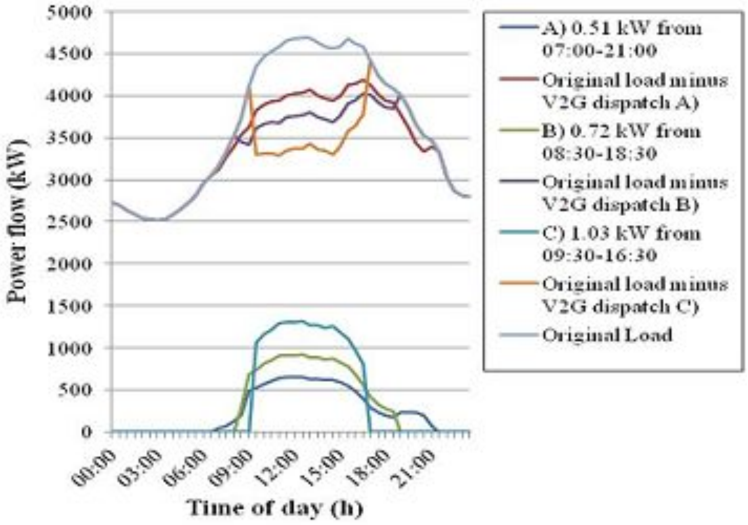


Fig.8. 22 The impact of Vehicle-to-Grid (V2G) contribution on the University's demand profile

Fig 8.22 shows how the use of vehicle to grid stored energy can contribute between 3.5 and 7 MWh to the University's demand profile and reduce its peak demand by 1.5 MW. Further reductions in the peak could be achieved by extending the discharge period for the high rate contributors.

The study into Vehicle to Grid, V2G, opportunities demonstrated the potential for reducing campus demand during usual peak demand periods using the stored charge in vehicles parked on-campus.

The financial benefits could be higher when variable tariffs come are introduced and V2G could become a powerful element in the University's future demand side management strategy.

8.5 The Future

A key feature of the electricity supply industry is its potential for change and innovation. Electricity has the immediate advantage that it is both clean and green at the point of use. It has the major disadvantage of being expensive.

Electricity is already used for approximately one third of modern society's energy demand. Approximately another third is used for transport and a third for heating.

Electricity powered transport, electric vehicles, are viable. The technology is well developed and the basic infrastructure is in place. Consumer fears concerning charge anxiety can be resolved. The inertia in the area with the internal combustion engine and the massive size of the industry will take a long time to overcome.

"Clean and Green" heating, facilitated by electricity, is viable. Accepting that electric heating is too expensive, combined heat and power, geothermal power and exploiting waste-heat opportunities can all be developed with the aid of electricity.

Developments in greater efficiency of generation and ensuring that these have environmental acceptance is promoting many new ideas on generation. The penetration of small and medium sized generators is growing and is promoting a re-examination of the structure of bulk electric power supply systems.

The re-invention of local micro-grids is occurring in many countries and is expected to become wide spread. Although the advantages of an integrated supply network are well known, the dangers of such systems are being recognised.

The dramatic growth in information technology and communications is the area for greatest expansion of the electricity industry. Including entertainment and together with high efficiency lighting, there is a great potential for the development and application of DC micro-grids. Although, the "war of the currents" considered AC or DC, future developments will be driven by 'which is best for the application?' and take advantage of both AC and DC.

The intermittency or fluctuations associate with most renewable energy sources and the need to better control demand profiles has highlighted the importance of storage. At a local level, the promotes the development of DC and local DC micro-grids.

Projects Edison and SoLa BRISTOL have demonstrated the viability of local DC micro-grids. Project Edison responded to the demands of the loads, computing and to a lesser extent lighting. Project SoLa BRISTOL demonstrated the opportunities for exploiting local storage to enhance the value of local generation using renewable energy sources and modifying the load profile to provide benefits to the local distribution network operator.

Being practical demonstrators has provided the great benefit of public participation and understanding. Accepting that there are many technical challenges, understanding consumer needs and expectations is the new component in successful engineering.

8.6 Conclusions.

The opportunities and challenges offered by smart DC micro-grids have been outlined in this paper.

Generally, however, the conclusions are;-

"The future is bright." "The future is electric."

Chapter 9 Conclusions

The research report summarized the recent development of distributed power supply and community with smart power distribution & utilization system, and analysed the operating principle and control model of typical distributed power supply such as wind power, solar power, gas turbine, fuel cell, energy-storage system, and introduced the development of distributed power supply and smart power distribution system in Japan, Australia and the UK, described the development of distributed power generation system and operating experience of micro-grid demonstration community in China. The authors hope to offer references for the developing countries of building distributed power supply and smart power distribution & utilization community.

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Initials

AC	Alternating Current
AEN	Autonomous Electricity Networks
AGC	Automatic Generation Control
AMI	Advanced Metering Infrastructure
APF	Active Power Filter
BESS	Battery Energy Storage
CAES	Compressed Air Energy Storage
CCHP	Combined Cooling Heating and Power
CEC	California Energy Commission
CERTS	Consortium for Electric Reliability Technology Solutions
CEPRI	China Electric Power Research Institute
CHP	Combined Head and Power
DAS	Distribution Automation System
DC	Direct Current
DG	Distributed Generation
DMS	Distribution Management System
DOE	Department of Energy
EMS	Energy Management System
ESB	Enterprise Service Bus
EU	United Union
EV	Electric Vehicles
FA	Feeder Automation
FP	Framework Program
GE	General Electric Company
GPS	Global Positioning System
ICT	Information and Communication Technologies
ISET	Institute for Solar Energy
LAN	Local Area Network
MAS	Multi-Agent System
MDMS	Meter Data Management System
NEDO	New Energy and Industrial Technology Development Organization
OFGEM	Office of Gas and Electricity Markets
PCC	Point of Common Coupling
PDC	Phasor Data Concentrator
PI	Proportional-integral
PMU	Phasor Measurement Units
PSC	Power Storage Converter
PV	Photovoltaic
RT	Real-time
RTU	Remote Terminal Unit
SA	Substation Automation
SCADA	Supervisory Control and Data Acquisition

SMES	Superconducting Magnetic Energy Storage
SOC	State of Charge
SVC	Static Var Compensator
SVG	Static Var Generator
SVR	Static Voltage Regulator
T&D	Transmission and Distribution
TOU	Time of Use
VRLA	Valve Regulated Lead Acid
V2G	Electric Vehicle to Grid
WAMS	Wide Area Management System
WAN	Wide Area Network
WMS	Wide Area Management System
ZEB	Zero Energy Buildings

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