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A survey of the Smart Grid Technologies: background, motivation and practical applications

Abstract. *This paper presents the survey of the smart grid technologies, including the background, motivation and practical applications. The driving forces for the smart grid technologies are presented, including the blackout, global energy crisis and environmental protection requirement. The key technology issues for building the smart grid are discussed. The crucial elements of the smart grid and their applications are introduced, including the un-interruptible power supply (UPS), adaptive var compensator (AVC), static synchronous compensator (STATCOM), active power filter (APF), unified power quality conditioner (UPQC), micro-grid, solar and wind generation, and high voltage direct current (HVDC) transmission technologies.*

Streszczenie. *Artykuł prezentuje przegląd technologii smart grid". Uwzględniono takie zjawiska jak blackout, globalny kryzys energetyczny i zalecenia ochrony środowiska. Omówiono podstawowe elementy sieci „smart grid" i jej zastosowania, uwzględniając systemy UPS, AVC, STATCOM, APF, UPQC, źródła słoneczne i wiatrowe oraz technologię transmisji napięcia stałego HVDC.* (***Przegląd technologii „smart grid" – tło, motywacje i praktyczne zastosowania***)

Keywords: Smart grid, Micro-grid, FACTS, HVDC, UPS, STATCOM, APF, DVR, UPQC, Solar power, Wind generation
Słowa kluczowe: Smart grid, Micro-grid, FACTS, HVDC, UPS, STATCOM, APF, DVR, UPQC

I. Introduction

The electric industry is poised to make transformation from a centralized, producer-controlled network to one that is less centralized and more consumer-interactive. The move to a smarter grid promises to change the industry's entire business model and its relationship with all stakeholders, involving utilities, regulators, energy service providers, technology and automation vendors and all consumers of electric power [1-8].

As automated and distributed energy delivery network, the smart grid will be characterized by a two-way flow of electricity and information and will be capable of monitoring everything from power plants to customer preferences to the individual appliances. It incorporates into the grid the benefits of distributed computing and communications to deliver real-time information and enable the instantaneous balance of supply and demand at the device level.

A smart grid uses digital technology to improve reliability, security, and efficiency of the electric system. Due to the vast number of stakeholders and their various perspectives, there has been debate on a definition of a smart grid that addresses special emphasis desired by each participant. The following areas represent a reasonable partitioning of the electric system that covers the scope of smart grid concerns [9-13].

- Area, Regional and National Coordination Regimes

A series of the interrelated, hierarchical coordination functions exists for the economic and reliable operation of the electric system, which includes independent system operators (ISOs), regional transmission operators (RTOs), electricity market operations, etc. Smart grid elements in this area includes measurement data to determine system state and health, and put forward coordinating actions to enhance efficiency, reliability, environmental compliance or response to network disturbances.

- Distributed Energy Resources (DERs) Technology

This area includes the integration of distributed energy, storage, and demand-side resources for participation in the electric system operation. Consumer products such as the smart appliances and electric vehicles are expected to be important components of this area as are the renewable generation components such as those derived from solar and wind generation sources.

- Transmission and Distribution Infrastructure

Smart-grid items at distribution-level include substation automation, dynamic limits, relay coordination and the associated sensing, communication and coordinated action. Distribution-level items include the feeder load balancing, capacitor switching, and the advanced metering, such as meter reading, remote service enabling and disabling and demand-response gateways.

- Information Networks and Finance

It must be pointed out that the information technology and pervasive communications are cornerstones of smart grid. Though the information networks requirements, i.e., the capabilities and performance, will be different in different areas, their attributes tend to transcend application areas. The examples include interoperability and the ease of integration of the automation components as well as cyber security concerns. Moreover, the economic and investment environment for procuring smart grid is a vital part for the implementation progress.

The organization of this paper is as follows. Secition II presents the driving forces for the smart grid technologies, such as the catastrophic blackout, energy crisis and global financial crisis, and the enviroment protection requirement. Section III presents the crucial elements of the smart grid and their applications, such as the un-interruptible power supply (UPS), adaptive Var compensators (AVC), static synchronous compensator (STATCOM), active power filter (APF), unified power quality conditioner (UPQC), micro-grid, solar and wind generation, and high voltage direct current (HVDC) transmission technologies. Finally, Section IV concludes this paper.

II. The Driving Forces of the Smart Grid

The smart grid (SG) is the next generation intelligent electricity network which optimizes the energy efficiency to graft information technology onto the existing network and exchange real-time information between electric suppliers and customers.

Moreover, the smart grid is an integration of electrical and information infrastructures, and the incorporation of automation and information technologies with our existing electrical network. It provides comprehensive solutions that improve the utility's power supply reliability, operational performance and overall productivity, deliver increases in energy efficiencies and decreases in carbon emissions, and empower consumers to mangage their energy usage and save money without compromising their lifestyle.In addition, smart grid is also the solution that can optimize the renewable energy integration and enabling its broader penetration. To conclude, smart grid is the infrastructure that would deliver meaningful, measurable and sustainable benefits to the utility, the consumer, the economy and the environment.

To better understand the background and motivation of the smart grid technologies, the US backout in 2003 is first briefly reviewed, followed by the introduction of low carbon emission target of various nations as well as the economic crisis and energy crisis.

Fig.1 The photoes of the 2003 US blackout areas.(left: the photo taken on Aug 13, right: the photo taken on Aug 14)

Fig.1 shows the photoes of 2003 US blackout striken areas due to a cascaded power grid failure. The procedure of the catastrophic blackout is reviewed as follows:

- Time: August 14, 2003, at approximately 4:15 pm EDT.
- Affected 55 million people in eight US states, 1 province in Canada and 256 power plant went off-line.
- 4:10:38 p.m. The Cleveland grid separates from the Pennsylvania grid;
- 4:10:46 p.m. New York grid separates from the New England Grid;
- 4:10:50 p.m. Ontario grid separates from the western New York Grid;
- 4:12:58 p.m. Northern New Jersey grid separates its power-grids from New York and the Philadelphia area;
- 4:13 p.m. End of cascading failure.

In total, nearly 85% of power plants which went offline after the grid separations occurred, due to the action of automatic protective control. The footprint of the blackout on both sides of the US-Canadian border includes large urban centers that are heavily industrialized and important financial centers (e.g., New York City and Toronto). Nearly half the Canadian economy is located in Ontario and was affected by the blackout. Service in the affected states and provinces was gradually restored with most areas fully restored within two days, but parts of Ontario experienced rolling blackouts for more than a week before full power was restored.

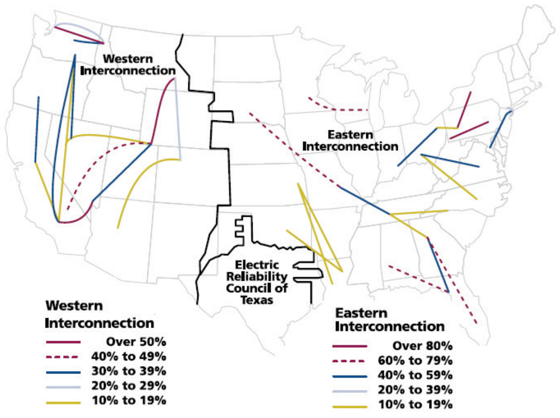


Fig.2 The transmisison congestion of the US grid in 2002 (Source: US Department of Energy, National Transmision Grid study report)

Tramsmision congestion is one of the major problems of the modern electric networks throughtout the world. Take the example of the US national grid for example, both the western and eastern interconnection networks suffer from significant transmission congestion problems. As indicated in Fig.2, thousands of miles of transmission networks in the western interconnection suffer from nearly 50% congestion, and the eastern interconnection networks also show heavy congestion in the middle and southeastern states in the year 2002.

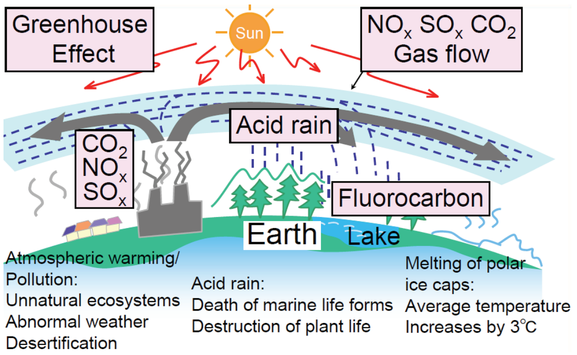


Fig.3 The demonstration of the degradation of global envieroment

The ever-increasing global energy consumption causes severe damage to the environment. As the major producer of electricity, the fossil power plants produce almost one third of the carbon and sulfer pollution. Fig.3 shows a vivid illustration of the various pollution, which causes the global warming, acid rain and the melting of the polar ice caps. As a result, abnormal weather condition, unnatural ecology systems and desertification would be the unavoidable consequences. Hence, the new energy resources, such as the wind power generation, solar generation are excellent alternatives for the existing fossil power plants.

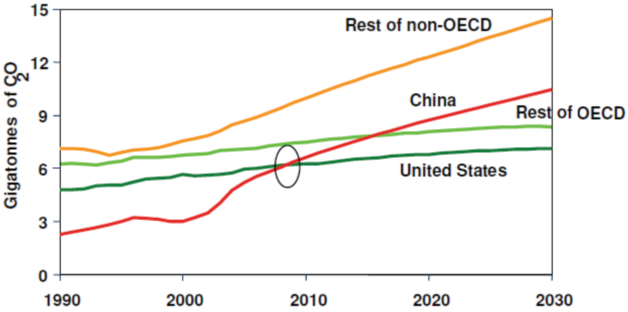


Fig.4 A comparison of the CO_2 emission among China, United States, OECD and non-OECD countries (OECD: Organization for Economic Co-operation and Development).

Fig.4 shows a comparision of the CO_2 emission among China, United States, the OECD and non-OECD countries. It shows that a few decades ago, China has the least CO_2 emission, much less than the United States and the OECD countries. However, in recently years, China overtakes the United States and the rest of OECD countries in terms of CO_2 emission, which is a threat for China's environment and sustainable economic development. This is one of the major contributor for China's strategic plan to develop the smart grid technologis to effectively reduce the emission and improve energy utilization efficiency.

Fig.5 shows the illustration of the CO_2 reduction target of the United States for the year 2050.It shows that the US electric sector produces approximately one third of the total emission, reaching 2 billion tons. The total emission target in the coming decades shows a steady decline, and 83% reduction in the CO_2 emission must be achieved compared to the emission in 2005. The ambitious plan of emission reduction is one of the major driving forces for developing the renewable energy sources, such as wind energy and solar energy, and the smart grid technologies become the most important issues for the electric industries.

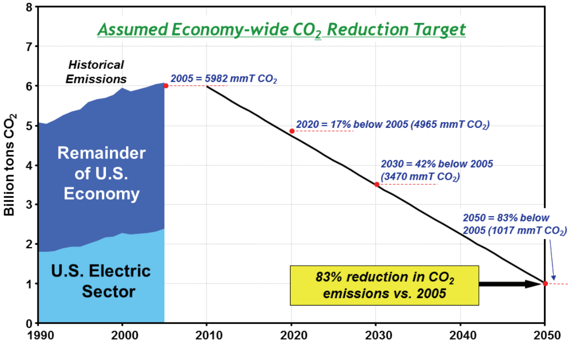


Fig.5 The US CO_2 emission reduction target for the year 2050

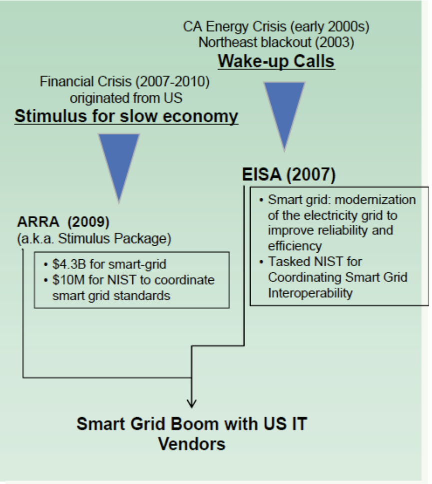


Fig.6 The driving force of the United States for the smart grid technologies. (US: Focus on businesses and infrastructure;EISA: Energy Indepdence and Security Act of 2007; ARRA: American recovery and reinvestment Act of 2009; NIST: National Institute for Standards and Technology).

Fig.6 shows the flowchart of the driving forces of the US for developing smart grid technologies. The wake-up calls were stimulated by the california energy crisis in 2000 and the blackout in the northeastern states in 2003. Hence, the EISA Act in 2007 decided to develop the smart grid in order to modernize the electricity network to improve the reliability and transmission efficiency. On the other hand, the global financial crisis originated from US stimulated the new economy, hence the US launched 4.3 billion dollars for smart grid technologies and 10 million dollars for the NIST to coordinate the smart grid standards. These factors are the major driving forces for the US smart grid boom.

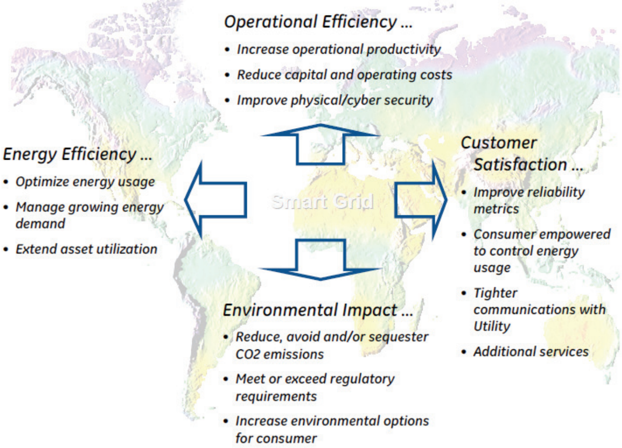


Fig.7 The positive effect of the smart grid technologies.

Fig.7 shows the positive effect of developing smart grid technologies.The energy utilization efficiency is achieved by optimizing energy usage and extended asset utilization. The operational efficiency is improved by the increased operational productivity, reduced capital and operational costs and enhanced cyber security. Customer satisfaction is enhanced by the improved reliability metrics, additional services, and tighter communications with utility. The smart grid technology also has huge impact on the environment protection by the reduction of CO_2 emissions.

III. The Vision and Technologies of the Smart Grid

Fig.8 shows the various focus areas that lead to various definition of smart grid, which can be summarized in the following aspects:

- Intelligent transmission and distribution automation;
- Distributed generation and storage;
- Advanced metering infrastructure;
- Demand response and load control.

The intelligent transmission and distribution automation is the fundamental requirement of smart grid, which also includes reliability analysis, advanced monitoring facilities, energy management systems (EMSs) and demand side management systems (DMSs). The distributed generation and storage include the wind generation, solar generation, and micro-turbine and flywheel applications. The advanced metering system focuses on the communication networks, such as meter reading, remote sensing and control, home area network (HAN) and energy efficiency management. The demand response and load control focus on customer interaction with the smart grid.

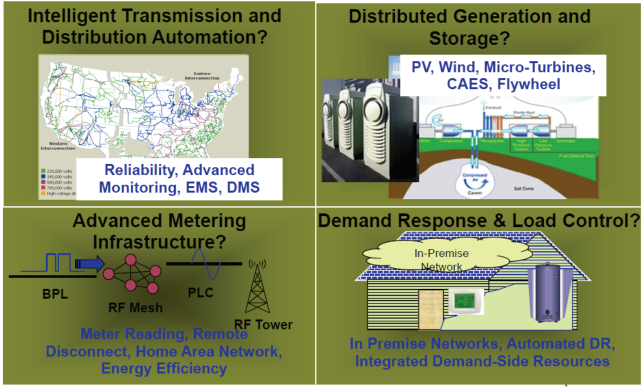


Fig.8 Diverse focus areas lead to various definition of smart grid.

The present case of low energy efficiency for the US grid: 65.5% loss at the generation stage (coal-fired power plants efficiency=60%), 5% auxiliary loss, 3.7%~4.8% loss at the transmission level, and 4.8%~5.1% loss at the distribution level. In total, approximately one third is delivered for the end user. Therefore, how to improve the energy efficiency, enhance the transmission capacity and reliability are the major concerns for the experts and engineers in the this area.The technological requirements for the smart grid can be summerized in the following aspects [2, 3, 7-10].

(1) Advanced control methods, such as:

- Real time and predictive control;
- Monitor and collect data from sensors;
- Determine and take action autonomously;
- Analyze data to diagnose and provide solutions;
- Provide information and solutions to the operators;
- Integrate with enterprise processes and technologies.

(2) Advanced components for the smart grid:

- Micro-grids;
- Fault current limiters (FCLs);
- Advanced switches and conductors;
- Next generation FACTS/PQ devices;

- Advanced distributed generation and energy storage;
- Superconducting cable & rotating machines,etc;

(3) Improved interfaces and decision support:
- Visualization;
- Data reduction;
- Data to information;
- Speed of comprehension;
- System operator training,etc.

(4) Integrated communication for the smart grid:
- Micro-grids;
- Smart meters;
- Smart sensors;
- Markets feedback;
- Demand-side response;
- Distribution automation;
- Work-force management;
- Mobile premises (PHEV's);
- Distributed generation (DG) dispatch,etc.

Fig.9 shows the vision and expectation of the smart grid. Notably, a large proportion of the electricity generated by onventional power plants will be displaced by distributed generation. Additional stand-by capacity might be required, which is called upon whenever the intermittent renewable resource ceases to generate power. Efficient integration of DG is unlikely to be made without changes to transmission and distribution network structure, planning and operating procedures. The key smart grid research and development areas can be summarized as follows [1-8, 16, 17]:
- Cyber security;
- Smart grid standards;
- FACTS/HVDC technologies;
- How the smart grid operates;
- Consumers respond to price signals;
- Communication architecture and technologies;
- Power electronics and advanced digital control,etc.

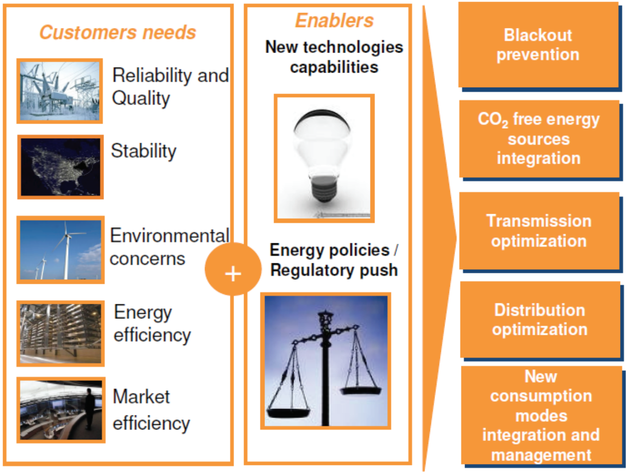


Fig.9 The vision and expectation of the smart grid.

Fig.10 shows the FACTS devices which can be utilized to adjust power flow of the transmission and distribution systems. The mechanical switched capacitors (MSCs) are used for the high voltage transmission systems to provide capactive reactive power thus enhance the power factor. Moreover, the mechanical switched reactors (MSRs) are used to absorb the excessive capacitive power of the distribution network, normally installed at the 110kV and 35kV distribution sytems to mitigate overover phenomenon during light load conditions in the evening. The series capacitors (SCs) and the series reactors (SRs) are intalled in series with the transmission line to adjust the effective electrical impedance of the network [9-13].

The phase shifting transformers(PSTs) are utilized at the distribution systems to modify the phase angles of the grid voltage, thus improve the harmonic properties. The static var compensators (SVCs) are a cominbation of thyristor controlled reactors and thyristor switched capacitors, which are widely used in distribution and transmission systems to dynamically modify the reactive power of the network, improve system stability and increase network efficiency. With the development of the power electronic devices, and with the advent of insulated gate bipolar transistors (ITBTs), the static synchronous compensators (STATCOMs) are developed, as the upgrated version of SVCs, which are widely utilized in the modern electric power networks and considered as one of the major building blocks of the smart grid. The D-STATCOM is abbreviated for the STATCOM used in the distribution system [16, 17, 20].

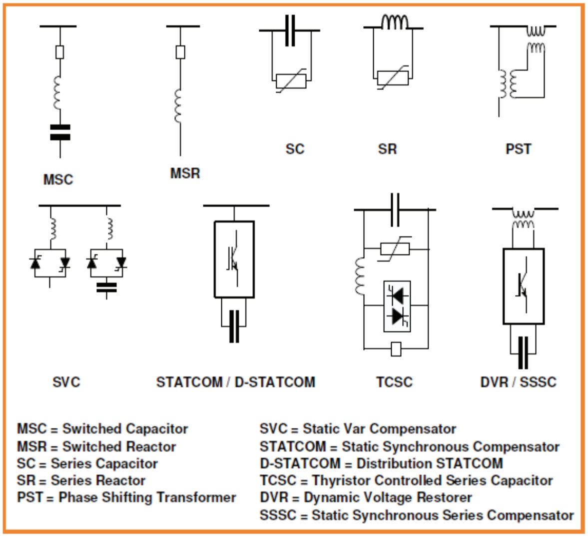


Fig.10 FACTS devices to improve system stability and reliability.

The thyristor controlled series capacitors (TCSCs) are the new generation FACTS controlled utilized in the high voltage transmission systems to enhance the transmission capacity, improve the transient stability of the generators and suppress the subsynchronous oscillations (SSR) of the HVDC transmission systems.The static synchronous series compensators (SSSCs) are installed in series with the transmisision network, with the basic power electronic building blocks similar to the STATCOM systems. The dynamic voltage restorers (DVRs) are the customer power quality conditioner which are used to mitigate voltage sag and protect the sensitive load [9-13].

In the forthcoming subsections, the popular devices for smart grid applications are briefly reviewed, which includes the uninterruptible power supply (UPS), the adaptive/static var compensators (AVCs/SVCs), the static synchronous compensators (STATCOMs), active power filters (APFs) and the dynamic voltage restorers (DVRs). Next, the micro grid application is introduced, followed by the solar energy and wind power applications. Finally, the high voltage direct current (HVDC) technologies would be presented.

A. The Uninterruptable Power Supply (UPS)

Fig.11 shows the one line diagram of the uninterruptable power supply (UPS), which is fundamentally consisted of voltage source inverter (VSI) and the isolation transformer. During normal operation, the load is powered by the utility source through the closed power electronic switch (PES). The grid voltages are continuously monitored on all three phases. If a grid distrubance is obverd by the disturbance monitor, which causes the voltage to sag or swell beyond 10% of its nominal value, it sends an "open" signal to the PES, thus coincident with a "run" signal to the inverter module(s). Hence the inverter module(s) provide regulated output to the critical load within 1ms. Load is transferred to the stored-energy source in 2~4ms, which is fast enough for computers and other sensitive electronic devices to ride through without malfunction [14, 15].

When the utility source voltage returns to its normal limits, the UPS synchronizes the output voltage with that of the utility source, and sends a “close” signal to the PES along with a “stop” signal to the inverter module(s). After a few seconds, the battery chargers turn on to restore the batteries to 100% capacity [15].

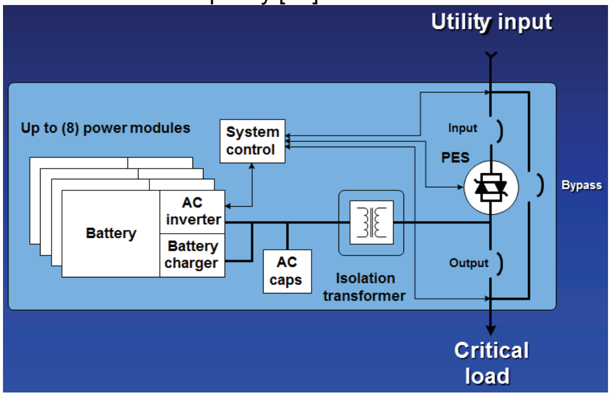


Fig.11 One line diagram of the uninterruptable power supply.

B. The Adaptive/Static Var Compensator (AVC/SVC)

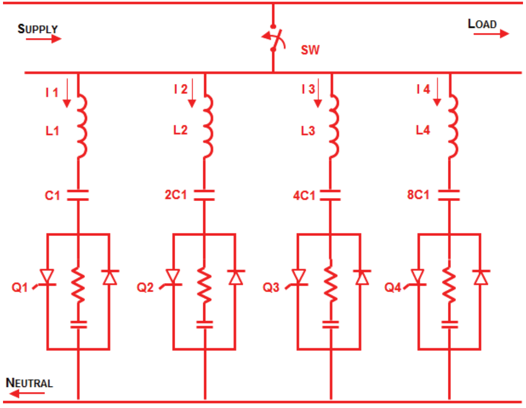


Fig.12 Diagram of the adaptive/static Var Compensator (AVC/SVC)

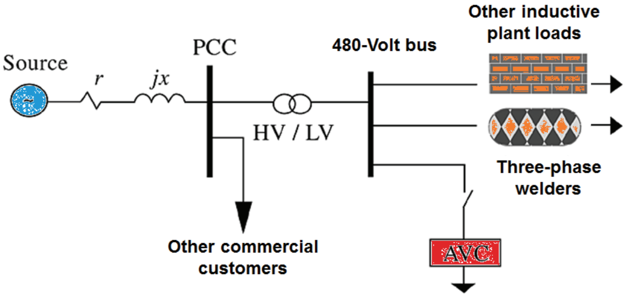


Fig.13 Single-line diagram of the AVC/SVC application.

Fig.12 shows the diagram of the adaptive/static var compensator, which is an economical, distribution var compensator that provides dynamic reactive compensation and power-factor correction. By using the AVC systems, the problem of voltage fluctuations can be reduced, system stability and reliability can be enhanced, and the system capacity is increased, and light flicker is eliminated.The AVC can enable problem loads to coexist on the same feeder as more sensitive loads, eliminating the need for separate feeders [16, 17].

Fig.13 shows the single-line diagram of the AVC/SVC system. Normally, the AVC systems are installed in parallel with the dynamic load, which continuously monitors line-to-neutral voltage and current on each phase of the feeder serving the load. By measuring the inductive component of the current, the microprocessor-based controller of the AVC determines the needed capacitive compensation. The required reactive power is then injected into the system by closing the appropriate power electronic switches. By using an array of sophisticated algorithms, a response time close to 1⁄2 cycle can be achieved. Notably, the capacitors are always pre-charged and ready until the triggering signal is applied to the switches [16].

Besides, switching is synchronized to occur at peak of the grid voltage, i.e., the zero crossing of the capacitor current, when voltage across the power electronic switch is nearly zero. As a result, the transients associated with capacitor switching are eliminated. The micro-processor controller updates the capacitor switching patterns up to every half-cycle and sets the optimum firing sequences. Notably, the de-tuning reactors are inserted in series with the capacitors to eliminate undesirable system resonance.

C. The Static Synchronous Compensator (STATCOM) for the Distribution System (DSTATCOM)

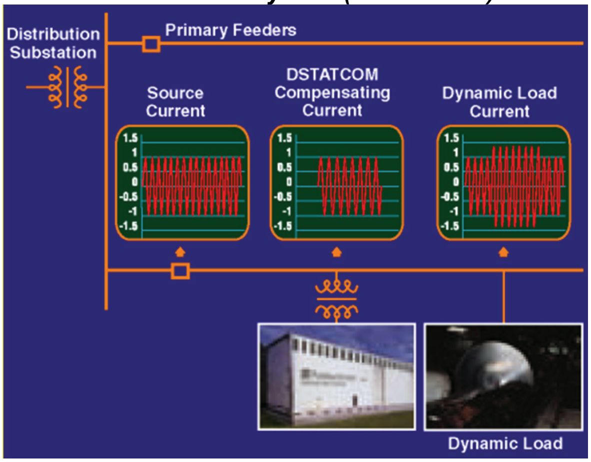


Fig.14 Distribution static synchronous compensator (DSTATCOM).

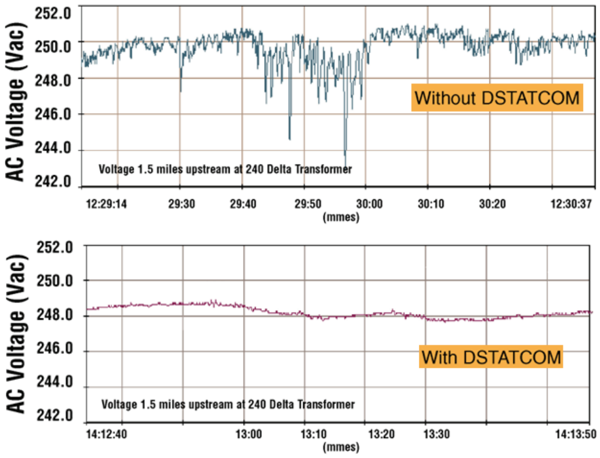


Fig.15 Field tests of the DSTATCOM for flicker mitigation.

Fig.14 shows the circuit diagam of the DSTATCOM in a typical distributon network. The basic electronic block of a DSTATCOM is the voltage source converter (VSC), which in general converters an input dc voltage into three-phase output voltage at the fundamental frequency, with rapidly controllable amplitude and phase angle. In adddition, the controller has a coupling transformer and a dc capacitor. The control system is designed to maintain the magnitude of the bus voltage constant by controlling the magnitude or phase shift of the VSC output voltage [18-20].

For the distribution system application, the STATCOM is controlled to inject or absorb reactive power to the grid, in order to support the dynamic load variations. From Fig.14, it can be observed that the currents supplied by the grid is pure sinusoidal waveform. Hence, the DSTATCOMs are widely utilized for dynamic compensation of the fluctuating loads, such as arc furnaces or other flicker producing loads. Fig.15 shows the typical experimental waveforms recorded in the field. It shows that the flicker effect in the dynamic load causes fluctuating grid voltages without compensation. However, when the DSTATCOM is used for compensation, the fluctuation in grid voltage is eliminated.

D. The Active Power Filter (APF)

The growing problems of power quality contamination also originated from the proliferation of nonlinear loads such as power converters in the distribution systems. For instance, voltage harmoincs result from current harmonics produced by nonlinear loads, e.g., variable ac motor drives, arc furnaces and household appliances.These nonlinear devices result in a significant increase in the line losses, instability and voltage distortion, which corrupts the electric distribution systems. The active power filters (APFs) have been recognized as the most effective techniques for harmonic compensation. Their objective is to suppress the current currents and to correct power factor, especially in the fast-fluctuating nonlinear loads. In addition to their performances, APFs can favorably be widely used in the existing power systems and thus has a wide application. A lot of recent research work tries to improve the APFs by developing new topologies or control laws [21-26].

Fig.16 shows the circuit diagram of shunt active power filter, which has the similar power-stage configuration as the DSTATCOM. However, by exploiting a sophisticated control algorithm to the power electronic switches, the shunt APF is capable to generate the nonlinear current to cancel the load harmonics, hence making the grid currents free of harmonics. On the other hand, the series APFs are used for compensating voltage source type harmonics, as shown in Fig.17. In the series APF, each output phase leg is connected to the grid by series connection of coupling transformer, which serves the purpose of isolation and turn ratio adjustment between the inverter and the grid.

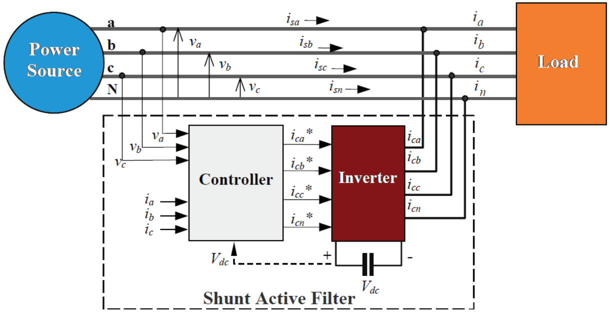


Fig.16 The circuit diagram of the shunt active power filter.

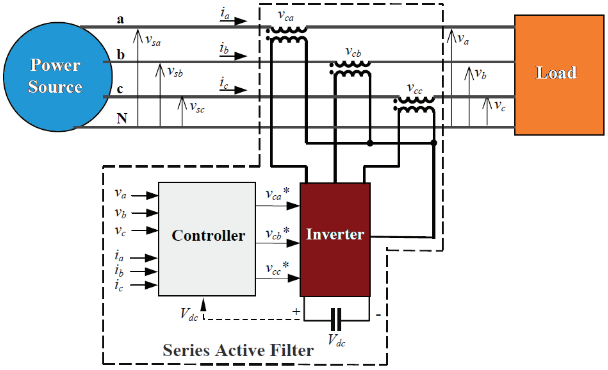


Fig.17 The circuit diagram of the series active power filter.

E. The Dynamic Voltage Restorer (DVR)

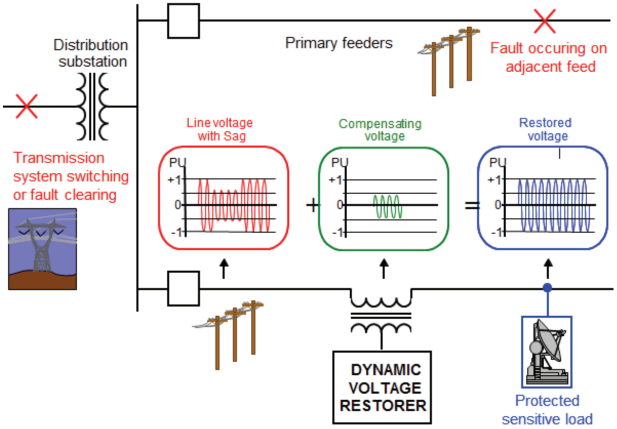


Fig.18 The circuit diagram of the dynamic voltage restorer (DVR).

The modern industrial plant is subjected to abnormal shutdown or malfunction due to the voltage sag problems. The dynamic voltage restorer (DVR) is considered as the best choice to protect the industrial facilities from voltage sag and other other voltage disturbances. Fig.18 shows the typical circuit diagram of the DVR in a distribution system. It demonstrates that voltage sag may be incurred by the fault from the adjacent feeder or the fault from the transmission network. Therefore, the DVRs can be applied to protect the sensitive loads of high-tech industries with adjustable speed drives and other power electronic based loads. For the industries with a high penetration of the induction motors, the energy storage might be used and a sophisticated controller must be adopted due to the inherit inertia of induction motors and their capability to withstand short duration, shallow sags and phase jumps [27,28].

F. The Unified Power Quality Conditioner (UPQC)

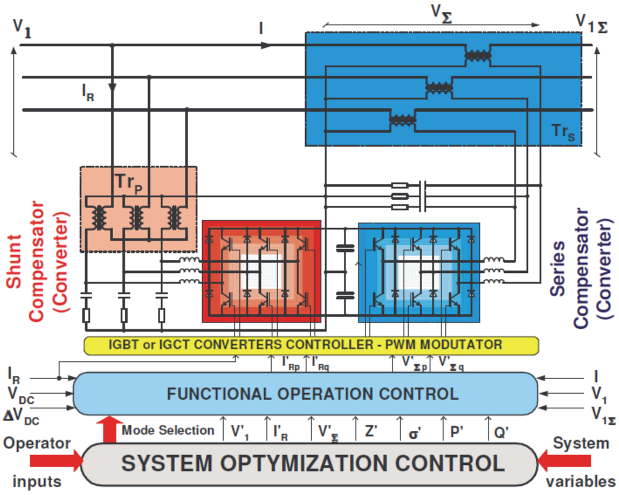


Fig.19 The circuit diagram of the unified power quality conditioner.

Fig.19 shows the circuit diagram of the unified power quality conditioner (UPQC), which is composed of shunt compensator and series compensator. The UPQC can be used for the simultaneous compensation of the currents and voltages, which provides a comprehensive solution for the harmonic and sag sensitive loads. The series APF is used for harmonic isolation between the load and the grid, which has the capability of voltage fliker and unbalance compensation as well as voltage regulation and harmonic compensation at the utility consumer side. The shunt APF is used to absorb current currents, compensate reactive power and negative-sequence current, and regulate the dc link voltage between two voltage source converters [29].

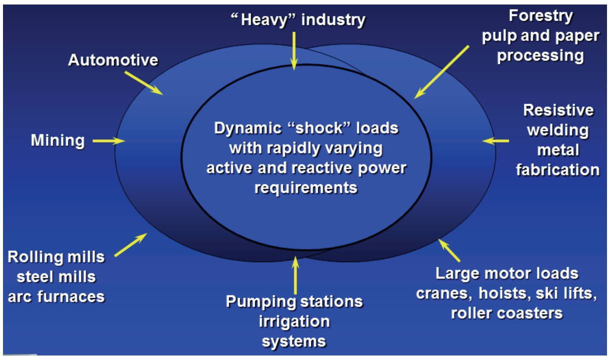


Fig.20 The application issues of the power quality conditioners.

Fig.20 shows the application areas of the power quality conditioners, such as STATCOM, APF, DVR and UPQC. These devices can be used for the dynamic 'shock' loads with rapid varying active and reactive power requirement. For instance, the heavy industries such as the automotive, mining systems, rolling mills, steel mills, arc furnaces, the pumping stations, the irrigation systems, large motor loads, cranes, hoists, ski lifts, roller coasters, resistive welding, and the metal fabrication industries, forestry pulps, paper processing industries, etc. These power quality conditions are the fundamental devices for the premium power quality and improving energy efficiency [30-39].

G. *The Micro-Grid Applications*

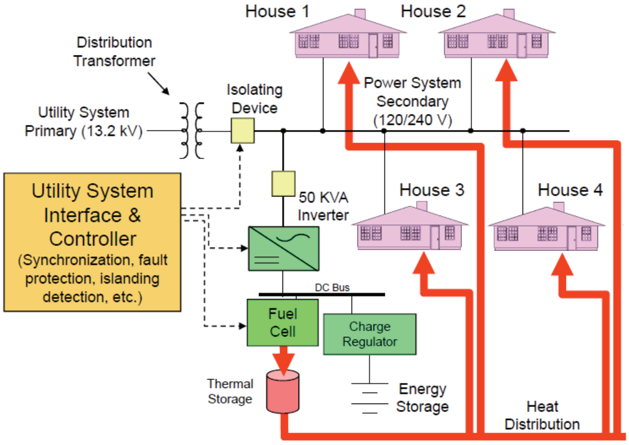


Fig.21 The configuration of the smart city with four houses.

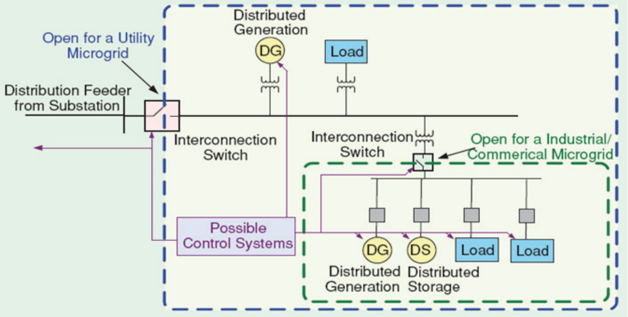


Fig.22 The circuit diagram of the micro-grid.

Fig.21 shows the configuration of the smart city with four houses, where the energy storage systems are indicated. It shows that fuel cell and battery are designed to share the common dc bus, which is charged by using the 50kVA inverter with bi-directional power flow capabilities. During normal conditions, the four customers are supplied from the utility power system. In case of grid fault, the controller sends the islanding signal to the isolating device, and grid is isolated and the fuel cell or battery provide the enery to the four customers by the dc/ac inverter. At the same time, the thermal storage system is capable to provide heat to each house. In the smart city scenario, the major technique consideration includes the grid synchronization, grid fault detection, islanding detection and remote control, etc [40].

Fig.22 shows the circuit diagram of the micro-grid, which is similar to the configuration of the smart city. Notably, the distributed generation (DG) systems are indicated and their circuit diagrams are denoted, which include the solar enery, wind power generation, etc. The micro-grid can work in the grid-connection manner or islanding mode. In case of grid fault or abnormal conditions, the micro-grid works in the islanding mode thus the DG supplies the electricity to the load from the same feeder. In case of grid connected mode, bidirectional energy flow is achieved hence the abundant energy generated by the DGs can flow into the grid.

H. *The Solar Energy Applications*

The photovoltaic (PV) system is appreciated for its ease of fabrication and declining cost in recent decades, which is most of the major driving forces for renewable enrgy. A lot of industrialized contries have put forward ambitious plan for developing solar energy as alternative for the fossil power generators, such as the US and Japan. Fig.23 shows the demonstration of Japan's solar eneryg roadmap toward the year 2020. It shows that the total capacity of solar energy was only 1.4M kW in 2005, and a ten times increase of capacity is targeted in 2015 and the capacity would reach up to 28 M kW in 2020 based on the current plan. It is suggested that 5.3 million houses would install the solar pannels in 2020 [41-45].

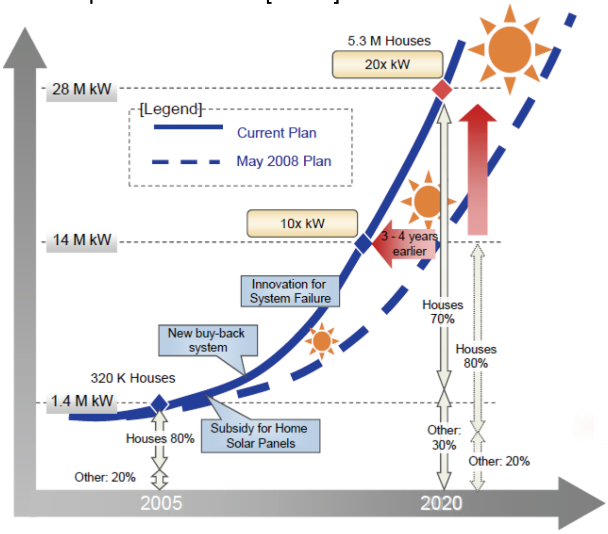


Fig.23 A demonstration of Japan's solar energy roadmap.

However, the fast development of solar pannels also face significant technique barriers owing to large unstable solar power connected to the grid. For instance, the solar pannels face problems of devidation from voltage range by voltage rise of distribution grid, and the ac grid frequency regulation. Besides, the energy storage devices due to the excessive power generation is also crucial for the practical systems. The anti-islanding control and fault ride through abilities are also critical for high reliability applications.

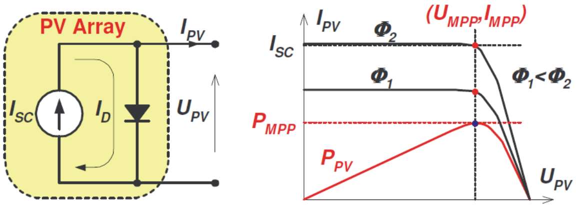


Fig.24 The equivalent of PV array and its V-I characteristics.

Fig.24 shows the equivalent of the PV array and its V-I characteristics. Normally, the PV pannel is modelled using a current source in parallel with a diode, the output current of the PV pannel I_{PV} is affected by the solar intensity. To maximize the efficiency of the PV pannels, the maximum point point tracking (MPPT) algorithm must be adopted at the output stage of the PV pannel, using a dc-dc converter.

Fig.25 shows the configuration of the PV pannels with the electric distribution network. Generally, there are three types of circuit topologies, as illustrated in Fig.25. The first one is the conventional PV system based on the central converter ranging from 1~5 kW power rating. And the PV pannels are connected in series to synthesize the output dc voltage, and the dc/ac inverter is adopted to connect the PV systems with the network. The string PV systems are based on the modular converter ranging from 0.5~1 kW to connect a string of PV pannels to the network. Another type of PV system is named the integrated PV systems, which is based on the individual dc/ac converter integrated with each PV pannel, which provides flexible solution and higher reliability with tradeoff of the increased cost.

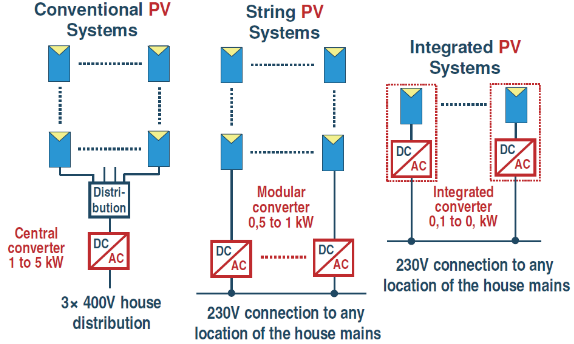


Fig.25 The configuration of PV arrays with the electric network.

I. *The Wind Power Generation*

The increasing concerns over environmental issues and the depletion of fossil fuel demanded the search for more sustainable electrical sources. The wind power generation is the most effective solution that converts the energy contained by the wind into electricity. The wind is a vast and mainstream energy source and an important player in the world's energy markets, with the 2008 market for wind turbine installation worth about 36.5 billion euros [46, 47].

The majority of current turbine models make best use of the constant variations in the wind by changing the angles of the blades through 'pitch control', by turning or 'yawing' the entire rotor as wind direction shifts and by operating at variable speed, which enables the turbines to adapt to varying wind speeds and increases its ability to harmonise with the operation of the electricity network [48-53].

Fig.26 shows the circuit diagrams of the wind generation systems, which can be classfied as the induction generator type and the synchronous generator type. Fig.26(a) shows the induction generator with reactive compensation. The gear box is controlled to regulate the active power output. Fig.26(b) shows the scheme of induction generator with both reactive compensation and the resistance control. Fig.26(c) shows the scheme of the synchronous generator based wind generation system by using ac/dc and dc/ac inverter structures. Fig.26(d) shows the circuit diagram of the induction or permanent magnetic (PM) synchronous generator. Fig.26(e) shows the circuit diagram of the wind generation system using double-fed induction generator.

Modern wind technology is able to operate effectively at a wide range of sites, with low and high wind speeds, in the desert and in the freezing arctic climates. Clusters of turbines collected into wind farm operate with high speed, are generally well integrated with the environment. The main design drivers for the current wind technology are:

- Reliability;
- Grid compatibility;
- Offshore expansion;
- High productivity for low wind speeds;
- Acoustic performance (noise reduction);
- Maximum efficiency and aerodynamic performance.

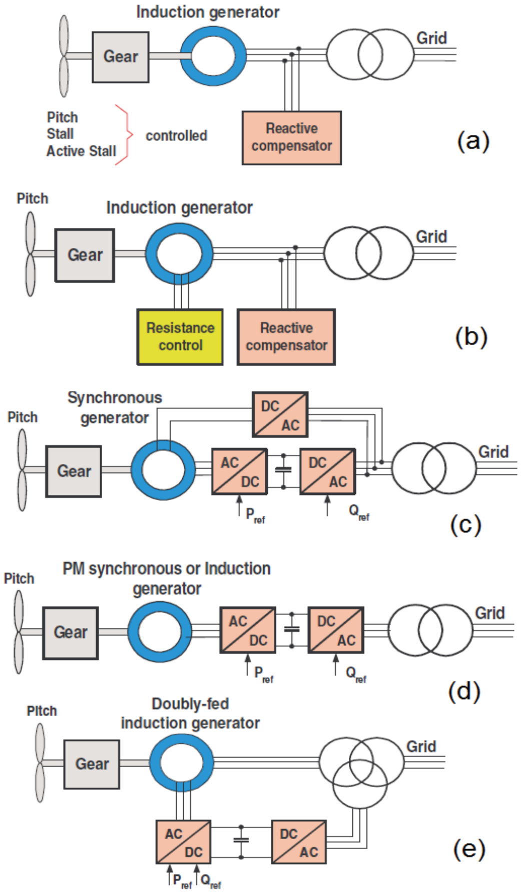


Fig.26 The classification of wind generation systems.

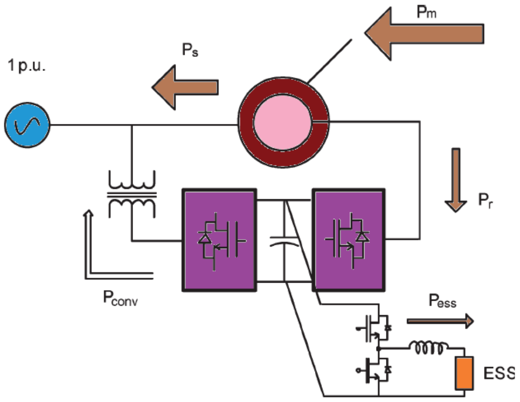


Fig.27 Supercapacitor energy storage for wind energy applications

Fig.27 shows the circuit diagram of the supercapacitor energy storage for wind power applications. Notably, there is an increasing interest in both large scale storage system at transmission level, and smaller scale dedicated storage embedded in distribution networks. For large-scale storage, pumped hydro accumulaton storage is best-known, which can also be implemented underground. On a decentralized scale storage opertions include flywheels, batteries, and possibly in combination with the electric vehicles, fuel cells, the electrolysis and super capacitors [48, 49, 50].

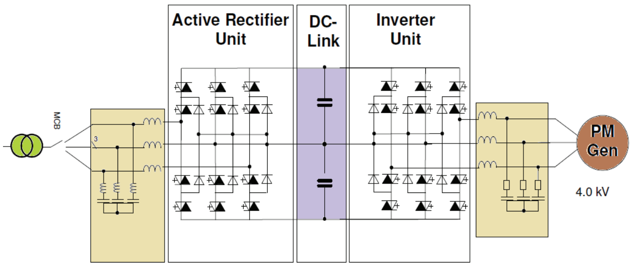


Fig.28 The circuit diagram of the MV wind generator using tri-level converter and permanent magnetic (PM) generator.

Fig.28 shows the circuit diagram of the medium voltage (MV) wind generator suing tri-level inverter and permanent magnetic (PM) generator. The tri-level inverter topology is widely used in medium voltage high power applications. The power rating of the wind turbine is normally 3~5 MW and the tri-level inverter has the minimum components requirement for the power electronic switches hence result in high reliability. Moreover, the IGCTs are normally used to meet the requirement of high current and efficiency.

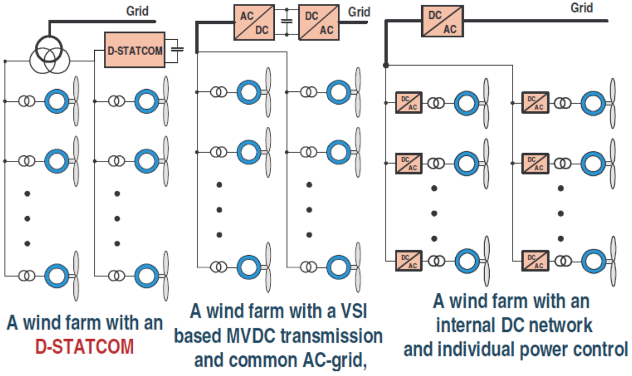


Fig.29 The configurations of the wind generators with the network.

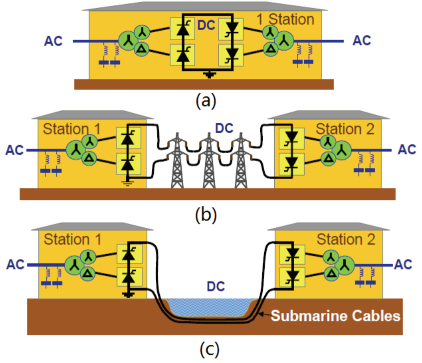
Fig.29 shows the circuit configuration of the wind power generators with the electric distribution network. In the first case, the wind farm is integrated with a shunt DSTATCOM for dynamic reactive power compensation. In the second case, the wind farm is made of multiple wind generators with a common ac grid, followed by the ac/dc and dc/ac converters to connect the wind farm to the grid. The third case denotes that the output of the invididual wind power generator is connected to the grid through modular ac/dc converter, and a large capacity dc/ac converter is applied to convert the dc-link voltage into ac voltage [51, 52].

The technical requirements within grid codes vary from system to system, but the requirements for the generators normally concern tolerance, control of active and reactive power, the protective device and power quality. Specific requirements for the wind power generators are changing as penetration increases and as wind power is assuming more and more plant capabilities, i.e., assuming active power control and delivering grid support services [53].

In response to the increasing demands from the network operators, for example to stay connected to the grid during a fault event, the most recent wind turbine designs have been substantially improved. The majority of the MW-size turbines being installed today are capable of meeting the most severe grid code requirements, with advanced features including the fault ride-through capabilities. This enables them to assist in keeping the power system stable when disruption occur. In the past, the common practice was to disconnect the wind turbine generator unit during network disturbances. However, disconnection from the grid may deteriorate a critical grid situation and threaten the network stability and security with a high penetration of wind generators.

Furthermore, the fluctuating nature of wind arises issue of power quality such as flicker, voltage fluctuation, etc. At present, the variable voltage variable frequency converters are utilized for the wind generators. However, it introduces the problems of harmonics into the network and there is also high possibility of resonance effect due to reactance of wind turbine generator system electrical unit. Hence, most grid code will request wind power plant to maintain voltage fluctuations, flickers and harmoinc currents in the desired range.

For secure grid operation, the frequency of the power system should be maintained to its rated value. However, in case of power imbalance between supply and demand, the undesirable frequency deviation occurs. The frequency control is a requirement for generating units to be able to increase or decrease output power with the falling or rising frequency. Besides, the wind power generator should be capable of automatically regulating its terminal voltage according to the given set point.



(a)

(b)

(c)

Fig.30 The schemes of HVDC transmision system.

J. *The HVDC Technologies*

The high voltage direct current (HVDC) transmission is widely recognized as being advantageous for long distance, bulk power delivery, asynchronous interconnections and long submarine cable crossings. HVDC lines and cables are less expensive and have lower losses than those for three-phase ac transmission. Owing to their controllability, the HVDC links offer firm capacity without limiation due to network congestion or loop flow on parallel paths. Hence, higher power transfer is possible without distance limitation.

Fig.30 shows the illustration of the HVDC transmission system. Fig.30(a) shows the scheme of the back to back connection, which is utilized for frequency changing, or synchronous connection. Fig.30(b) shows the scheme of the point-to-point overhead line for bulk transmission and overland construction. Fig.30(c) shows the scheme of the point-to-point submarine cable transmission for bulk power transmission [54, 55].

For the underground or submarine cable systems, there is considerable savings in the intalled cable costs and cost of loss with HVDC transmission. Depending on the power level to be transmitted, these savings can offset the high converter station costs at distance over 40km. Besides, there is a rapid drop-off in the cable capacity with ac transmission over distance due to the reactive component of charging current. Although it can be compensated by the shunt compensators for the conventional schemes, for the underground cables, it is not practical for submarine cables. For a given cable conductor area, the line loss with HVDC cables can be less than half those of ac cables due to the skin effect and induced currents in the sheath and armor.

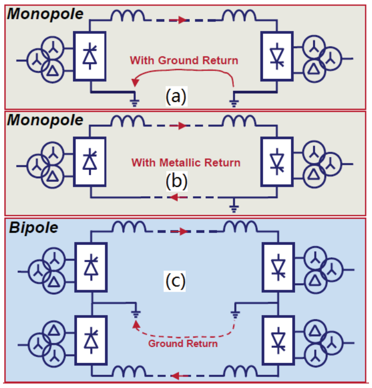


Fig.31 The circuit diagrams of monopolar/bipolar HVDC systems.

Fig.31 shows the circuit diagram of monopolar/bipolar HVDC systems. For very long distances and in particular for very long sea cable transmissions, a return path with ground/sea electrodes will be the most feasible solution, as shown in Fig.31(a). In many cases, existing infrastructure or environmental constraints prevent the use of electrodes. In such cases, a metallic return path is used in spite of the increased cost and power losses, as depicted in Fig.31(b).

A bipolar scheme is a combination of two poles in such a way that a common low voltage return path, if available, will only carry a small unbalance current during the normal operation conditions. During the maintenance or outages of one pole, it is possible to transmit part of the power. More than 50% of the transmission capacity can be utilized, limited by the actual overload capacity of the remaining pole. The advantages of a bipolar solution over a solution with two monopoles are reduced cost due to one common or no return path and lower losses [54, 55].

As shown in Fig.31(c), this bipolar configuration provides a high degree of flexibility with respect to operation with reduced capacity during contingencies or maintenance. Upon a single-pole fault, the current of the sound pole will be taken over by the ground return path and the faulty pole will be isolated. Following a pole outage caused by the converter, the current can be commutated from the ground return path into a metallic return path provided by the HVDC conductor of the faulty pole.

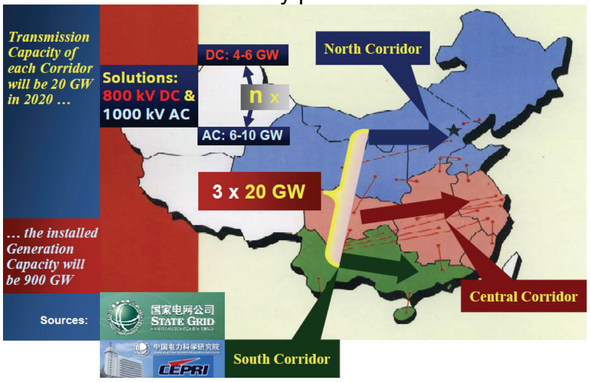


Fig.32 Perspectives of grid development in China-The AC and DC bulk power transmission from West to East via three corridors.

Fig.32 depicts the perspectives of the grid development in China using the AC and DC bulk power transmission from the western regions to the eastern economy centers. The focus is on the inter-connecton of 7 large provincial grids of the northern, central and southern systems via three bulk corridors which built up a redundant 'backbone' for the whole grid. The north corridor is aimed to send bulk power from the fossil power plants in the inner-mongolia and northern provinces to the capital. The central corridor is aimed to send bulk power from the three George's hydro power plant to Shanghai. The south corridor is aimed to send the bulk power from the southwestern provinces to Guangdong and HongKong. Each corridor is planned for a sum of a bout 20 GW transmission capacity which shall be realized with both AC and DC transmission line with ratings of 4~10 GW each (at +/-800kV DC and 1000 kV AC). With these ideas, China investigated a total amount 900 GW installed generation capacity by 2020. The benefits of such a large hybrid power system interconnection are:

- Increase of transmission distance;
- Sharing of loads and reserve capacity;
- Flexible renewable energy integration;
- Reduction of power losses using ultra-high voltage;
- Utilization of cheap resources far from load center;
- Serves as stability booster and firewall against blackout.

IV. Conclusions

This paper presents a critical survey of the smart grid technologies, including the backgound, motivation and the technique issues. Driven by the energy crisis and financial crisis, the smart grid provides the best solutions to improve the grid efficiency, reliability, flexibility and also provides interactive activities for consumers. The popular devices of smart grid and their application issues are reported, such as the UPS, AVC, DSTATCOM, APF, UPQC, micro-grid, the solar and the wind generation as well as the HVDC transmisision systems. This paper can be used as useful reference for the engineers in the smart grid research and implementation field.

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