

1

Power Grid Development and Interconnection

1.1 Overview

The power grid is an important infrastructure needed for the development of national economies and electrical power transmission, and it is an important platform for the optimal allocation of energy resources. In particular, with the accelerated development of clean energy and the promotion and application of smart grid technology, the function of power grids has become increasingly prominent. The world's primary energy resources and energy consumption are generally reversely distributed where energy production is far away from power load centers. In order to meet the growing electricity demand needed for economic and social development, it has become more and more urgent to strengthen the interconnection of power grids, and achieve flexible control of large power grids and their capability to optimize the allocation of energy resources. For this purpose, the major countries and regions in the world are accelerating the development of large power grids, and some have realized cross-border power grid interconnection. Existing large interconnected power grids in the world include those in North America, Europe, and the Russia-Baltic Sea. Countries in the Gulf, South America, Southern Africa, and other regions are also developing cross-border interconnected power grids. With rapidly growing energy and electricity consumption, China is under more pressure from energy and electricity development. Therefore, China has made great effort to develop and deploy Ultra High Voltage (UHV) transmission technology for AC 1000 kV, DC ± 800 kV, and DC ± 1100 kV, focusing on constructing strong and smart power grids with UHV as the backbone network and characterized by coordinated development of power grids at all voltage levels. Grids of this kind are expected to form a new energy development pattern by connecting large energy bases and major load centers with power grids all over China closely interconnected with the "West-East and North-South power flow" [1–3]. Both for China and the rest of the world, there is an urgent requirement to accelerate the development and application of power grid interconnection technology. As a new power grid interconnection device and piece of flexible AC transmission system equipment, the variable frequency transformer (VFT) will play a positive role in the future power grid development in China and in the world.

This chapter introduces the prominent problems in current as well as future trends for world energy development. World energy development is divided into three important stages; namely, the first generation, the second generation, and the third generation of power grids. Based on China's power grid development, the structure, functions, and technical features of power grids in each stage have been compared comprehensively

[4]. The trends for UHV grids, smart grids, and clean energy are discussed in detail. In addition, the important functions of large power grids interconnection and four different modes of grid interconnection method are analyzed and compared: these are synchronous AC, asynchronous DC, AC/DC parallel, and VFT asynchronous [5]. Finally, based on the development of the electrical power systems and the research results from VFTs, the main content of each chapter in this book will be briefly introduced.

1.2 Energy Reform and the Third Generation of Power Grids

1.2.1 Objectives of Energy Reform and the Mission of Power Grid Development

Energy is an important material base for economic and social development. Since 1965, the world's energy demand has been increasing rapidly. The world's primary energy consumption has grown from 5.4 billion tons of standard coal in 1965 to 18.7 billion tons of standard coal in 2015; nearly a 2.5-fold increase. As the world's second largest economy, China has witnessed more rapid energy consumption growth in recent decades. China's primary energy consumption has increased from 2.6 billion tons of standard coal in 2005 to 4.3 billion tons of standard coal in 2015: up 70% in the last 10 years. Figure 1.1 shows global energy consumption in the past 50 years. Figure 1.2 shows China's energy consumption in the past 35 years.

Global energy development has gone through a course of evolution from firewood to coal and further to oil and gas. At present, over 80% of the world's energy consumption relies on coal, oil, natural gas, and other fossil energy resources. Figure 1.3 shows the trend of energy consumption structure through history. Figure 1.4 compares the world's energy consumption structure in 1980 and 2015. Figure 1.5 shows the world's primary energy consumption structure by region in 2015.

The imminent exhaustion of fossil energy resources and the pollution and emission caused by the use of fossil resources places tremendous pressure on energy supply and ecological environment. The predicted shortage and exhaustion of fossil energy resources, current threats of global climate change and environmental pollution

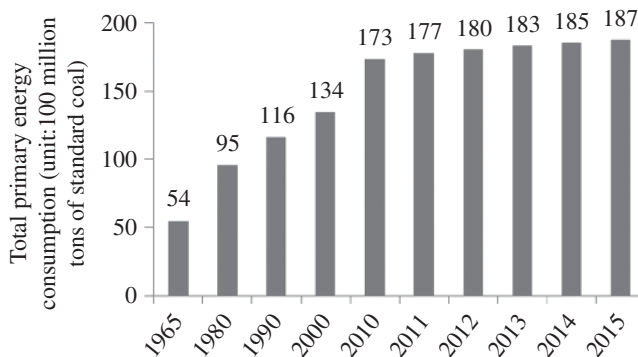


Figure 1.1 World primary energy consumption growth. Data source: BP, Statistical Review of World Energy 2016.

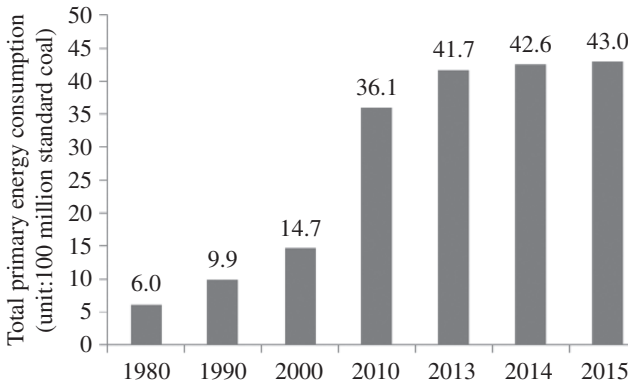


Figure 1.2 China's primary energy consumption growth. Data source: National Bureau of Statistics of China, *China Statistical Yearbook 2016*.

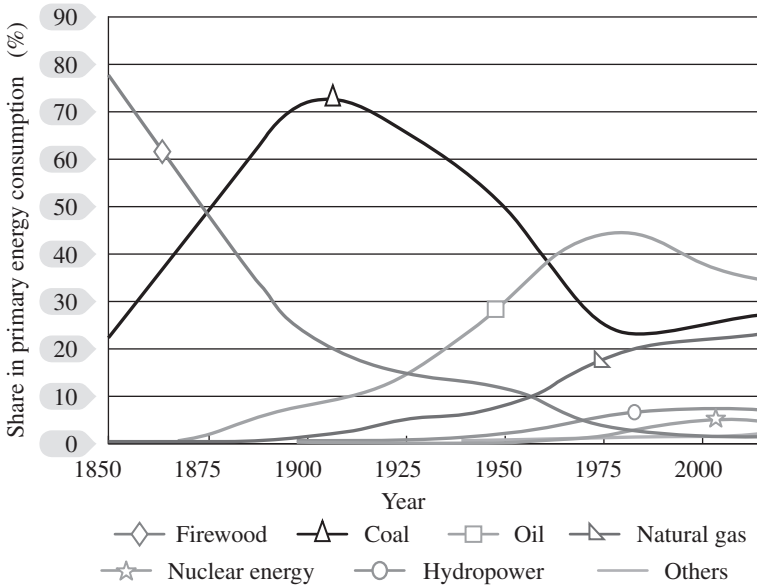


Figure 1.3 Changes in the composition of world energy consumption [36].

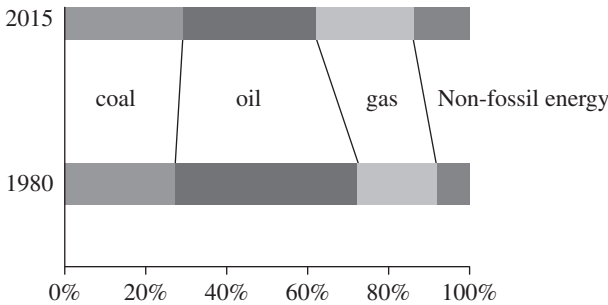


Figure 1.4 Structure of global primary energy consumption in 1980 and 2015. Data source: IEA energy balances of non-OECD countries 2016.

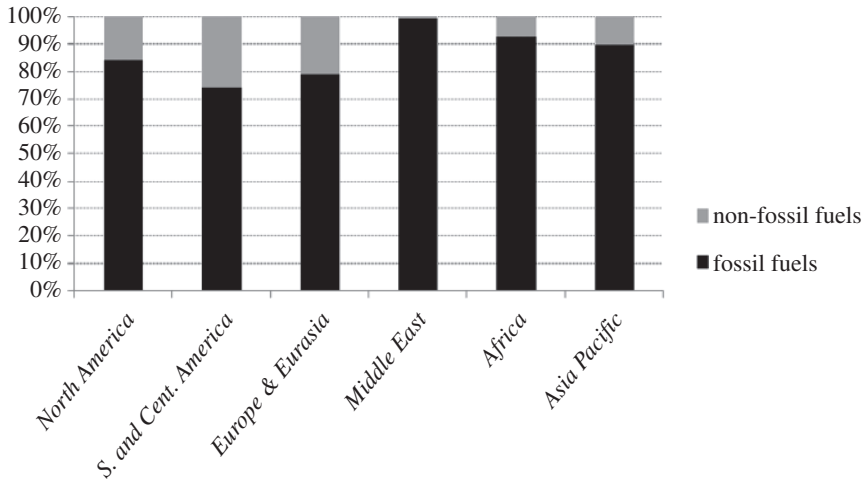


Figure 1.5 2015 Primary energy consumption structure by region. Data source: BP, Statistical Review of World Energy 2016.

have become the main driving force of new energy reform. On the one hand, the shortage of fossil energy resources has become increasingly prominent. By the end of 2015, the world’s proved recoverable oil reserves was 239.4 billion tons and the reserves-to-production ratio was 51 years; the world’s proved recoverable natural gas reserves was 186.9 trillion m³ and the reserves-to-production ratio was 52.8 years; the world’s proved recoverable coal reserves was 891.5 billion tons and the reserves-to-production ratio was 114 years [6]. Figure 1.6 shows the reserves-to-production ratio of fossil energy both for the world and that of China.

On the other hand, large-scale consumption of fossil energy resources leads to high emissions of carbon dioxide and other greenhouse gases. Greenhouse gases in the atmosphere can make solar energy reach the Earth via shortwave radiation while the energy radiated by the Earth in the form of long wave radiation cannot penetrate the

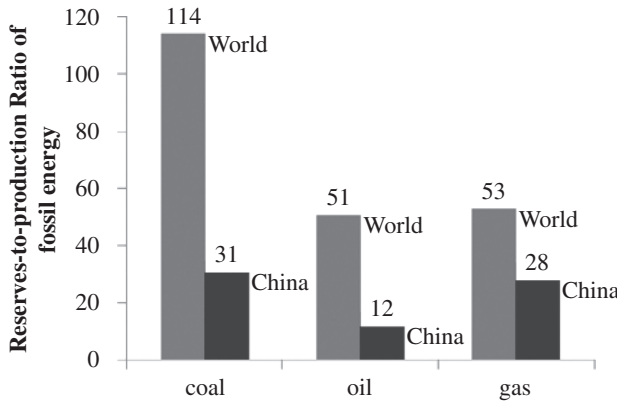


Figure 1.6 Reserves-to-production ratio of fossil energy. Data source: BP, Statistical Review of World Energy 2016.

greenhouse gas layer, resulting in the greenhouse effect that causes global warming and other abnormal changes in global climate. Research shows [7] that 60% of greenhouse gas emissions are from energy consumption. At the same time, if the average temperature rises over 2°C compared to that of pre-industrial times, this will have a disastrous impact on the Earth. To prevent the atmospheric temperature from rising by no more than 2°C , the corresponding atmospheric carbon dioxide concentration cannot exceed 450 ppm ($1 \text{ ppm} = 1 \times 10^{-6}$). To solve the problem of greenhouse gas emissions, the key is to optimize the energy structure and control the use of fossil energy resources. Figure 1.7 shows the amount of global carbon dioxide emissions from 1980 to 2014. Figure 1.8 shows the evolution of atmospheric carbon dioxide concentration.

Coordinated development of energy, ecology, environment, and economy is a major issue related to sustainable development of human society. Since the 1990s, the call for use of clean energy has become increasingly louder and its purpose is to gradually replace fossil energy with new energy sources (such as nuclear power) and renewable energy (including hydropower, biomass energy, solar energy, wind energy, geothermal

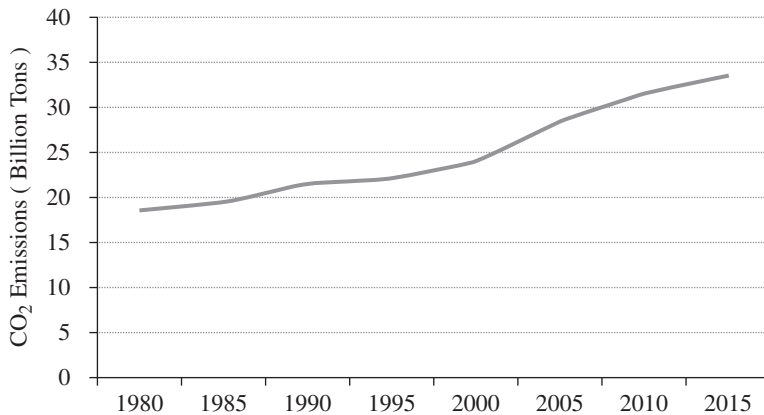


Figure 1.7 Total CO₂ emissions (1980–2014). Data source: BP, Statistical Review of World Energy 2016.

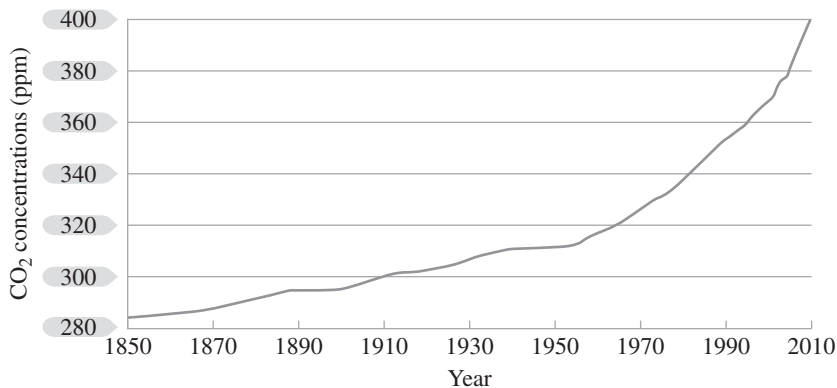


Figure 1.8 Atmospheric carbon dioxide concentrations [36]. Source: www.globalcarbonproject.org/activities/AcceleratingAtmosphericCO2.htm.

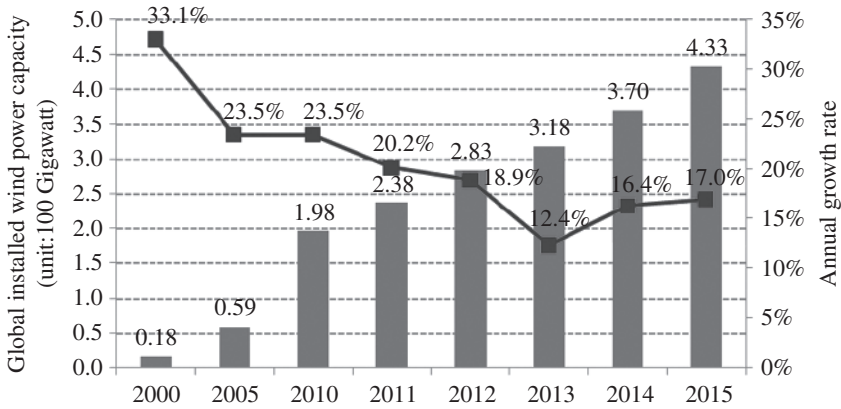


Figure 1.9 Global installed wind power capacity and growth rate. Data source: GWEC global wind report 2016.

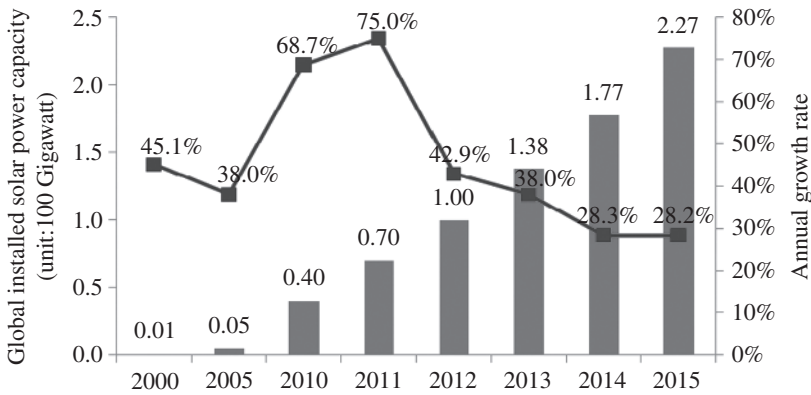


Figure 1.10 Global installed solar power capacity and growth rate. Data source: REN21 renewables 2016 global status report.

energy, ocean energy, and hydrogen) to ensure a sustainable supply of energy for human beings. This trend is called *new energy reform* and its main goal is to gradually decrease the proportion of fossil energy, improve clean and efficient use of fossil energy, and make renewable energy and nuclear energy account for a larger share in primary energy consumption. Figures 1.9 and 1.10 show the global installed wind and solar power capacity. Figures 1.11 and 1.12 show the installed wind and solar power capacity in China. Figure 1.13 shows per capita electricity consumption.

At the United Nations Conference on Environment and Development held in Rio de Janeiro, Brazil, in June 1992, the *United Nations Framework Convention on Climate Change* was formulated; in December 1997, the *Kyoto Protocol* on reducing greenhouse gas emissions was adopted at Kyoto. At the United Nations Climate Change Summit held in September 2009, the Chinese government promised that by 2020 China's non-fossil energy consumption would account for 15% in primary energy consumption and energy consumption per unit of GDP would drop by 40–45%. Vigorously developing clean energy is an effective way to solve the world's energy security and climate change

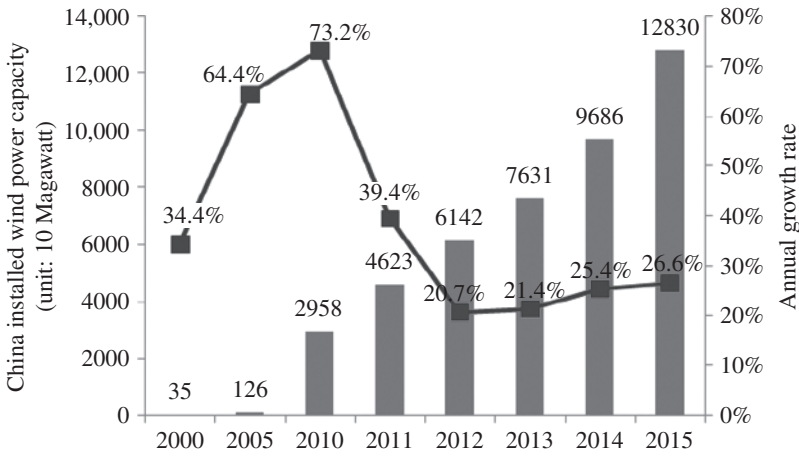


Figure 1.11 China's wind power capacity and growth rate. Data source: China Electricity Council.

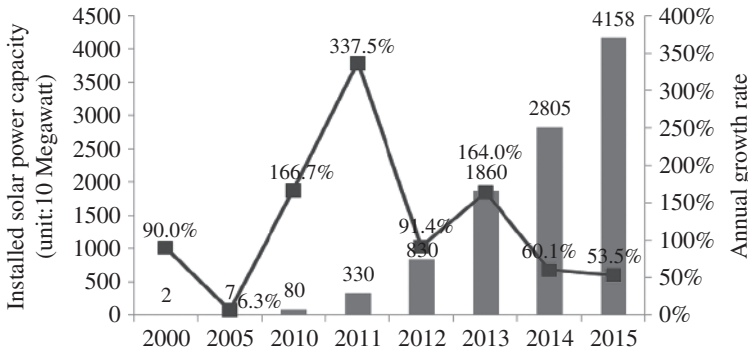


Figure 1.12 China's solar power capacity and growth rate. Data source: China Electricity Council.

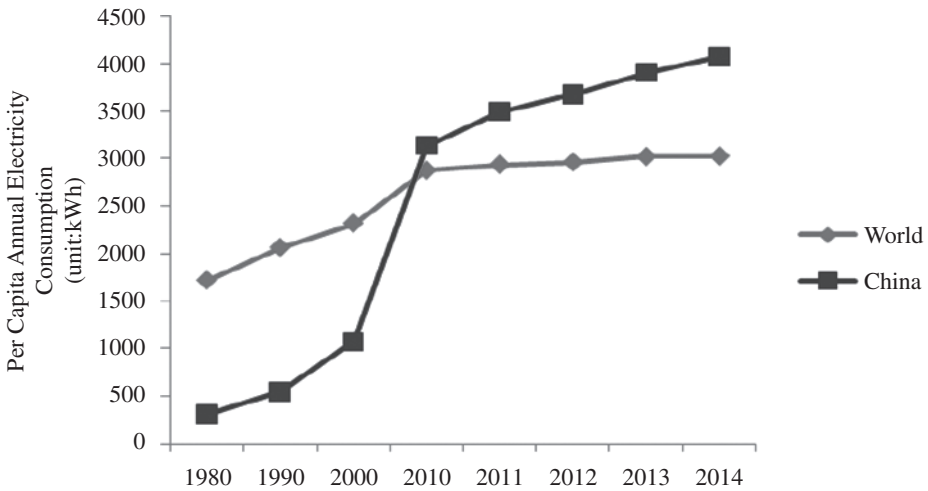


Figure 1.13 Comparison of per capita electricity consumption. Data source: China Electricity Council.

problems and play an irreplaceable role in meeting energy demand, improving energy structure, and reducing environmental pollution. It is also an important direction for world energy development and the main characteristic of new energy reform.

At present, the world energy development shows a trend for diversification, cleanliness, efficiency, globalization, and marketing. Diversification is reflected in the change from an over-reliance on fossil energy to vigorously developing hydropower, nuclear energy, wind energy, solar energy, and biomass energy in energy development. Cleanliness is reflected in gradually increasing the proportion of clean energy, actively deploying clean coal combustion technology, desulfurization technology, and denitrification technology, reducing carbon, and sulfur emissions to deal with haze, climate change, and other problems. Efficiency is reflected in improving the efficiency of energy development, allocation and utilization by technical innovations, improving the utilization of low calorific coal, inferior quality oil fields, and other primary energy resources. Globalization is reflected in the fact that world energy resources are allocated to an increasingly larger range of areas and transmitted farther and farther, representing an important part of economic globalization. Marketing is reflected in the regulation of global energy production and flow through price mechanisms, and world energy marketing levels are increasingly higher. Figures 1.14–1.16 show the global coal, oil, and natural gas trade.

The key to achieving sustainable energy development is to build a platform for efficient energy development, allocation, and utilization. An important measure is to construct an efficient and intelligent modern power grid system. In Reference [1], the development concept of comprehensive energy view is proposed, namely the view of taking electric power as the center, giving overall consideration to energy production, transportation, and consumption, giving full attention to the important role of power grids in the optimal allocation of energy resources in a large areas in order

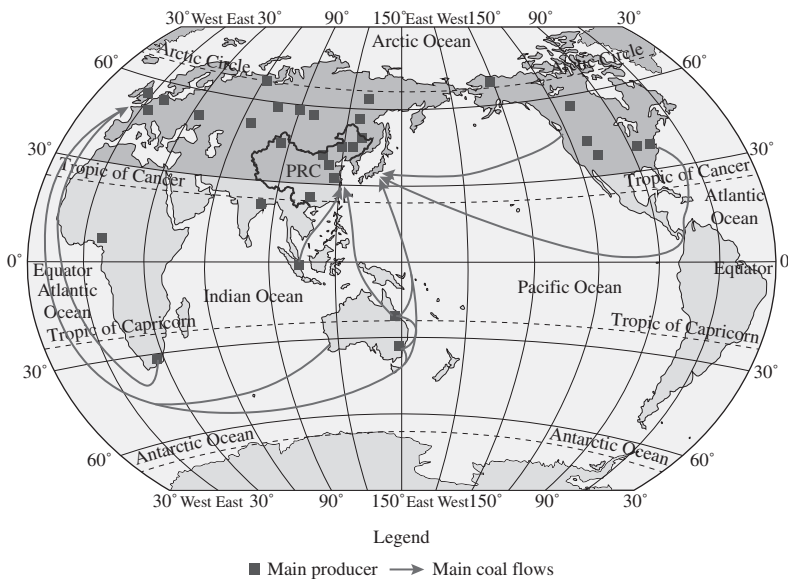


Figure 1.14 Global coal trade. Source: BP, Statistical Review of World Energy 2016.

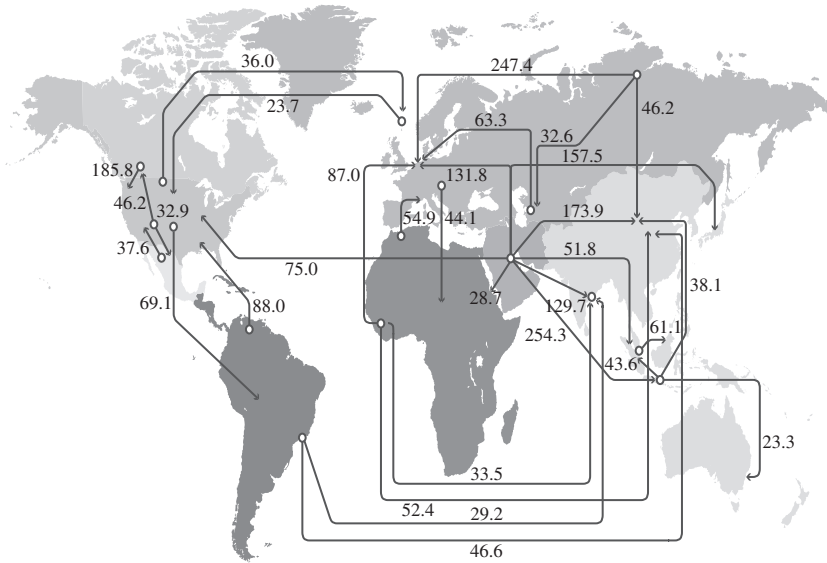


Figure 1.15 Global oil trade 2015 (million tonnes). Picture source: BP, Statistical Review of World Energy 2016.

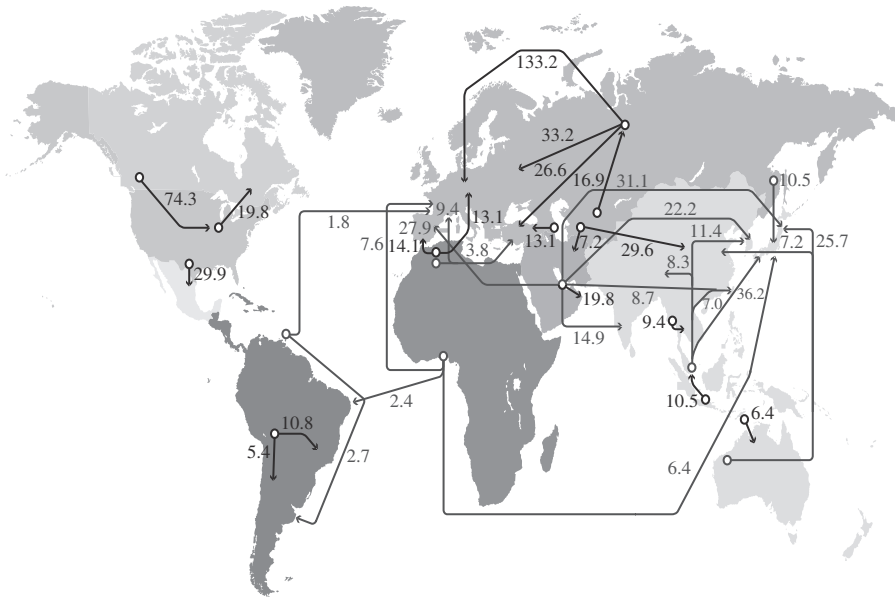


Figure 1.16 Global natural gas trade in 2015 (billion cubic meters). Picture source: BP, Statistical Review of World Energy 2016.

to ensure safe, economical, efficient and green development, and utilization of energy. In Reference [37], the development idea of “two replacements” is proposed, namely in the energy development process, to speed up the development of clean energy such as solar power, wind power, and hydropower, replacing fossil energy with clean energy alternatives and increasing the proportion of non-fossil energy in primary energy; and in the energy consumption process, to replace coal and oil with electricity to increase the proportion of electricity consumption in final energy consumption.

The role of electricity and power grids in future energy development is obvious and irreplaceable. On the one hand, not only hydropower, nuclear power, wind power, and solar power, but also fusion power and hydrogen power being studied must be transformed into electric energy and delivered to users to achieve efficient application. On the other hand, as a clean and efficient secondary energy, electricity can meet the demands for many industries such as lighting, power, heating, and transportation. In particular, the economic output of equivalent electric power is 3.22 times that of oil and 17.27 times that of coal. As a result, without electricity and power grids, it is difficult to achieve the diversified, clean, and efficient energy development.

In the new round of energy reform, the importance of the power grid has become increasingly prominent. China’s successful development and application of UHV AC and DC transmission technology [2] as well as the maturation of large power grid security and stability control technology has laid a good foundation for large-capacity, long-distance, low-loss transmission, and large-scale optimal allocation of electric power. Meanwhile, it will provide an effective platform for distributed generation and micro-grid integration. In order to adapt to the energy reform, new requirements have been made for power grid development [4, 8].

1. The ability to accommodate large-scale renewable energy. Particularly, it must adapt to the random and intermittent characteristics of wind and solar power generation, and increase clean energy integration capacity.
2. Realize the organic integration of demand side response, distributed source, energy storage devices, electric vehicle charging and discharging power stations, energy comprehensive utilization systems with power grids, greatly improving end energy utilization efficiency.
3. High power supply reliability to effectively avoid power grid chain reaction accident and basically eliminate the risk of large area blackout.
4. Extensive and in-depth combination with the communication information system and modern intelligent technology to achieve an integrated energy, electricity, and information service system covering urban and rural areas.

1.2.2 Development and Upgrading of Power Grids

In 1831, the British physicist Michael Faraday discovered the law of electromagnetic induction. On this basis, the original AC generator, DC generator, and DC motor soon emerged. Early motor manufacturing and power transmission technologies were mainly for DC and power lines were 100–400 V low-voltage DC lines characterized by short transmission distances and small capacities. Then, with the application of alternating current and continuously improved grid voltage levels and through more than 100 years of development, power grid technology innovations, scale expansion,

and function improvement have been constantly achieved. The world's power grid development can generally be divided into three stages; the first, second, and third generations of power grids [4].

The first generation of power grids are referred to as AC-dominated power grids that were developed from the end of the nineteenth century to the end of the Second World War. Transmission voltage reached 220 kV and stand-alone capacity was no more than 100–200 MW. Major milestone events: in 1882, Edison built the world's first commercial power plant (using the 1.6 km 660 kW, 110V DC cable for power transmission) in New York; between 1885 and 1886, Westinghouse built the first AC power transmission system, and built the 35 km AC transmission line from Niagara Falls (three 3675 kW hydropower units) to Buffalo in 1895. From then on, AC transmission has dominated the world's power grids. In 1916, the United States built the first 132 kV AC transmission line, built and began to use the 239 kV AC transmission line in 1923, and built the 287 kV AC transmission line in 1937. In 1918, they made the first 60 MW turbine generator and, in 1929, the first 200 MW turbo generator. In 1932, the Soviet Union built the Dnieper Hydropower Station with a unit capacity of 62 MW. In 1934, the United States built the Grand Coulee hydropower station with a unit capacity of 108 MW and in 1935, they built the Hoover Hydropower Station with a unit capacity of 82.5 MW.

Since the 1950s, with large hydropower development, developed countries in Europe and America have begun to develop large-capacity units, EHV, and large interconnected power grids that characterize the second generation. Major milestone events include: in 1952, Sweden built the first 380 kV EHV AC transmission line with a total length of 620 km and transmission power of 450 MW. In 1954, the United States built the 345 kV AC transmission line. In 1956, the Soviet Union put into operation the Kuibyshev-Moscow 400 kV AC transmission line with a total length of 1000 km. In 1959, the voltage was increased to 500 kV and it was the first time 500 kV AC transmission line was used. In 1965, Canada built the first 735 kV AC transmission line. In 1969, the United States achieved 765 kV EHV transmission. In 1985, the Soviet Union built the 1150 kV UHV transmission line that underwent industrial trial operation for about 5 years and later on adopted reduced-voltage operation due to dissolution of the Soviet Union. By the end of the twentieth century, all developed countries had built a second generation of power grids characterized by EHV AC and DC power transmission and large interconnected power grids. Major equipment and hardware technology in the second generation of power grids include: supercritical and ultra-supercritical coal-fired units (600 MW and 1000 MW), 1000 MW nuclear power generating units, 700–800 MW hydropower units; EHV transmission and transformation equipment as well as line technology; high-speed relay protection and automatic safety devices; and optical fiber communication. The main system technologies involved include: overvoltage, insulation coordination, reactive power balance, secondary arc current, electromagnetic interference, and other EHV transmission system technologies; low-frequency oscillation of interconnected power grids/dynamic stability, transient stability, voltage stability, power system stability control, SCADA/EMS dispatching automation and other large power grid technologies; power system analysis and simulation technology such as detailed dynamic modeling, electromechanical/electromagnetic transient analysis, and reliability analysis.

For the third generation of power grids, in the 1990s, developed countries began to study distributed power generation, renewable energy, microgrids, and the power

system market. Technologies such as the application of power electronic devices in electric power systems, high-speed optical fiber communication, 1000 kV UHV AC transmission, ± 800 kV (and above) UHV DC transmissions, and smart grid equipment were studied. The development and construction of the third generation power grids is characterized by higher voltage level, large-scale utilization of renewable energy, and high intelligence techniques. The third generation power grids involve innovative change in five major areas:

1. New materials and new elements and devices. These form the basis of the development of modern power grids providing efficient, energy-saving, and environment-friendly equipment.
2. New power transmission technology. Large capacity, low loss, environment-friendly transmission technology (UHV transmission, superconducting transmission, underground cable transmission, etc.) are the main goals of R&D.
3. Large-scale renewable energy (centralized and distributed) integration is the key technology of modern power grids.
4. Smart dispatching and operation control based on advanced sensing, communication, control, computation, and simulation technology ensures the construction of efficient and reliable power grids.
5. A smart power distribution and consumption system helps realize demand side response as well as the integration of distributed sources, electric vehicles, and energy storage devices, forming a comprehensive energy, electric power, and information service system covering urban and rural areas.

China began to construct first generation of power grids in 1882 (Shanghai Electric Power Company). In 1949, China's capacity of power generation was 1.85 GW with an annual electricity generation level of 4.31 billion kWh. In 1966, China's generation capacity reached 17.02 GW with 82.5 billion kWh of electricity generation and the maximum voltage level of the power grids was 220 kV. China began to build the second generation of power grids in the 1970s, 20 years later than developed countries. In 1971, the Liujiaxia Hydropower Station and Liujiaxia-Guanzhong 330 kV AC transmission line (535 km; 420 MW transmission capacity) were completed, forming China's first inter-provincial power grid (Gansu, Shaanxi, Qinghai). In 1981, China built the first 500 kV AC transmission line (Pingdingshan-Wuhan), heralding the start of construction of large regional power grids with 500 kV as the backbone. Between the end of the twentieth and beginning of the twenty-first century, the completion of the Three Gorges Power Transmission Project accelerated national power grid interconnection. In 2005, the Northwest Power Grid 750 kV AC transmission line was put into operation. In January 2009, China's Southeastern Shanxi-Nanyang-Jingmen 1000 kV UHV AC test and demonstration project was completed and put into operation within just 28 months. It was the first commercial UHV AC transmission project in the world (see Figure 1.17). In July 2010, China's Xiangjiaba-Shanghai ± 800 kV UHV DC demonstration project was put into operation within just 30 months. It is 1891 km long and has a rated transmission power of 6.4 GW. In Dec. 2012, China's Jinping-Sunan ± 800 kV 7.2 GW UHV DC project (see Figure 1.18) was put into operation.

Since the founding of new China, China's power grid has developed into one of the world's largest interconnected power grids and has become the most important energy transmission and distribution network in the country. Between the 1970s and



Figure 1.17 Shanxi-Nanyang-Jingmen 1000 kV UHV AC transmission line. Picture source: SGCC.

the beginning of the twenty-first century, based on the construction of the 330, 500, and 750 kV power transmission systems as well as the practice of large regional power grids and national grid interconnection, China has achieved rapid development and progress in technology (such as equipment, power system, control, protection, safe and stable operation, and simulation analysis) and comprehensively grasped the technology of second generation power grids, reaching the international advanced level. Since the beginning of the twenty-first century, with the development and construction of the UHV AC and DC transmission and smart grids, China has started the construction of the third generation power grids and gradually joined the top ranks of the world, catching up with developed countries. Table 1.1 compares the main characteristics of the first, second, and third generations of power grids.

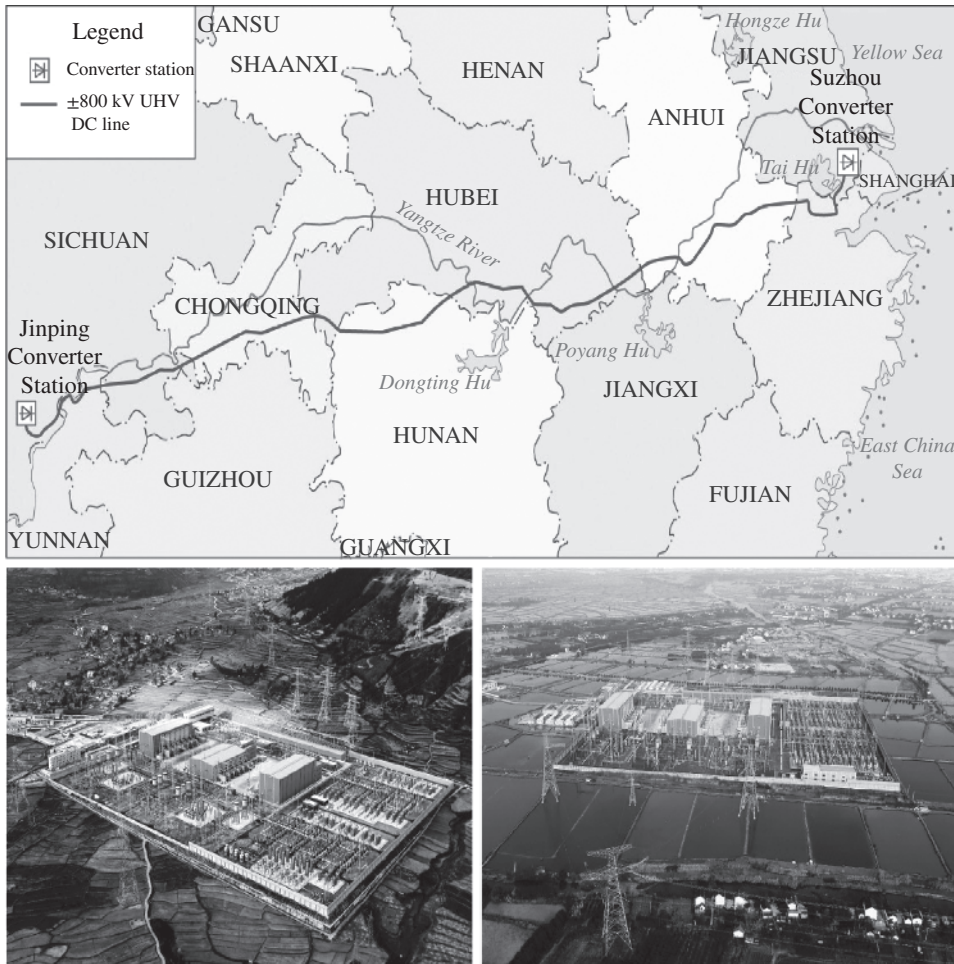


Figure 1.18 China’s Jinping-Sunan ±800 kV UHV DC transmission line. Picture source: SGCC.

1.3 Large-Scale Power Allocation and Large Power Grid Interconnection

1.3.1 The Necessity and Importance of Large Power Grid Interconnection

With the increase in power grid voltage level and the expansion in scale, the installed capacity, load level, transmission distance, and allocation efficiency of power grids are greatly improved. Since the discovery of electricity more than 100 years ago, the world’s power grids have undergone development from small power grids, isolated power grids, and urban power grids to large-scale interconnected power grids. Large-scale interconnection and formation of the layered and zoned power grids are the basic features of the second generation of power grids. On this basis, the third generation of power grids will form the power grid mode of organically combining backbone grids, local grids, and microgrids. This grid development mode is commensurate

Table 1.1 Comparison of characteristics between the first, second, and third generations of power grids.

	First Generation	Second Generation	Third Generation
<i>Energy form</i>	Dominated by low efficiency small coal-fired generating units and small hydropower generating units.	Efficient fossil energy, nuclear power and large hydropower (large hydropower development promotes the EHV transmission and grid connection) account for a large proportion.	Non-fossil energy generation accounts for a large proportion (e.g., 40~50% or above); combination of large centralized and distributed clean energy power.
<i>Transmission mode</i>	220 kV and below power transmission and distribution.	330 kV and above EHV AC and DC transmission, mainly in the overhead transmission mode.	Large capacity, low loss and environment-friendly transmission mode (UHV, superconducting power transmission, etc.).
<i>Unit scale</i>	Small units with the stand-alone capacity below 200 MW.	Large units with the stand-alone capacity between 300 MW and 1 GW.	Large units with unit capacity between 300 MW and 1 GW including large thermal power, hydropower, nuclear power, wind power generator clusters.
<i>Grid model</i>	Small power grids, urban power grids, isolated power grids, and small power grids.	Large-scale interconnected power grids, layered, and zoned power grids	Combination of backbone power grids, local power grids, and microgrids.
<i>Control and protection</i>	Simple protection and discrete relay protection.	Fast protection and optimal control; rapid removal of power transmission and transformation equipment fault; microcomputer-based protection.	Smart control and protection of grid; self-healing of power transmission, and transformation equipment and network; intelligent protection.
<i>Dispatching mode</i>	Empirical dispatching.	Analysis-based dispatching; power supply side energy management system that can adapt to the load changes.	Intelligent dispatching; integrated energy management system that can adapt to the changes of renewable energy power and load.
<i>Power consumption mode</i>	Passive power consumption.	Passive power consumption; single power service.	Active power consumption; widespread participation of users in power grid regulation; providing users with integrated energy and information services.

(Continued)

Table 1.1 (Continued)

	First Generation	Second Generation	Third Generation
<i>Management model</i>	Extensive management.	Vertical centralized management of power generation, transmission and distribution; introducing the power market mechanism.	Market oriented management model, fully mobilizes the initiative of power grids, users, and other participation parties.
<i>Efficiency of electrical energy</i>	Power plants' energy consumption rate and line loss rate are high.	Both power generating efficiency and power grid efficiency have been gradually improved.	Efficiency of power generating, grid, and consumption has been greatly improved.
<i>Environmental impacts</i>	High pollutant discharge of power plants.	Conventional pollutant emissions (SO _x , NO _x , etc.) are basically solved.	Pollutant and carbon emissions have been well controlled.
<i>Reliability</i>	Low power grid security and low power supply reliability.	Power grid security and power supply reliability have been significantly improved, but large power grid accident risks still exist.	Power supply reliability has been significantly improved; users' unexpected power outage risk has been basically ruled out.
<i>Economic efficiency</i>	Small units and small power grids have low economic efficiency and poor resource optimization allocation capacity.	Making full use of the scale economy of large units and large power grids; the ability to optimize the allocation large-scale resources.	Making full use of the scale economy of large units and large power grids; the ability to optimize the allocation large-scale resources; sustainability of high efficiency and adaptability of smart grids.
<i>Sustainability</i>	It is difficult for power supply to adapt to the needs of rapid economic development.	Highly dependent on large-scale use of fossil energy and nuclear energy resources; in the face of the two major challenges: exhaustion of fossil energy resources and global warming, this model of power grid is non-sustainable.	Fossil energy consumption is greatly reduced and carbon emissions are greatly reduced. It is a sustainable development model of power grids.

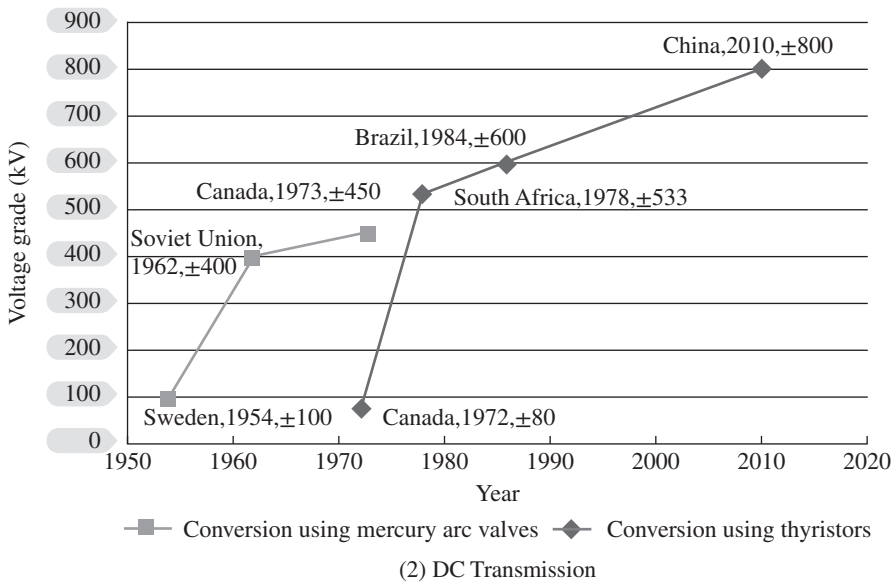
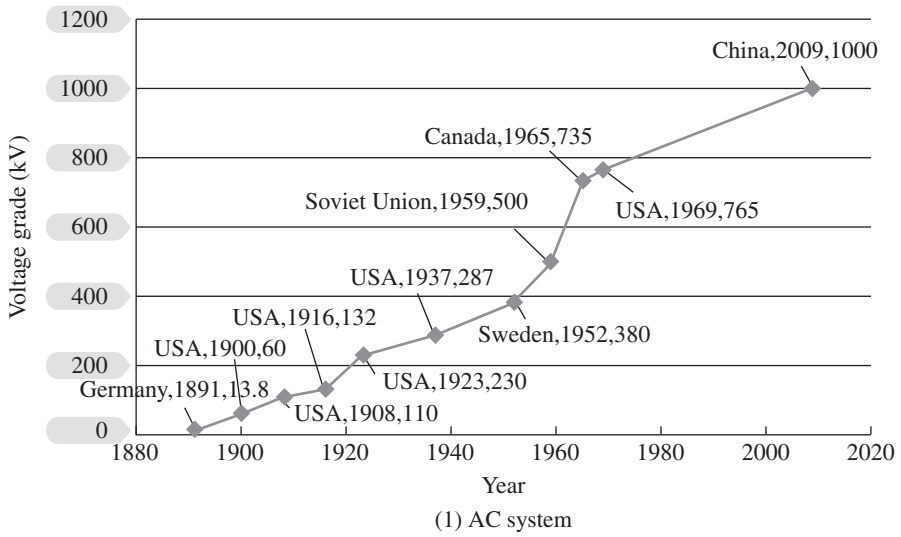


Figure 1.19 Voltage level of power system.

with the basic attributes of power grids and realistic demands of economic and social development. Figure 1.19 shows the development of AC/DC transmission voltage grades in the world. Figure 1.20 shows the interconnection of power grids in the world.

1.3.1.1 Power Grid Attributes

The power grid is a closely linked physical network that has a strong natural monopoly attribute. Strengthening the interconnection of large power grids can significantly improve the economic efficiency, security, and market competitiveness of power grids.

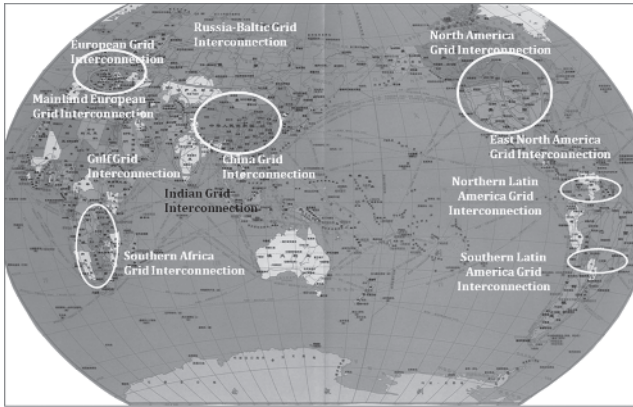


Figure 1.20 Interconnected power systems in the world.

Economically, larger-scale power grids can help better utilize power plants connected to power grids and make the operation mode of various power plants more efficient and flexible. For example, by giving the role of base load to nuclear power and coal-fired power and the role of load regulation to hydropower, the system can better adapt to the random characteristics of wind and solar generation. As larger power grids have more users, it is beneficial to make full use of the load characteristics from all kinds of users, forming complementary advantages and improving the efficiency of load management. Meanwhile, with the increase of power grid capacity, the average cost of per unit transmitted power will be reduced and benefits such as peak load shifting and averting, mutual aid of hydropower supply and thermal power supply, inter-basin complementation, and reduction of reserve capacity of power grids can be achieved.

From the prospect of security, compared with small power grids, large power grids have stronger anti-disturbance ability, higher reliability, and supply better quality power. When system faults occur, power support can be provided through the interconnected power grids. Power shortage can be balanced adaptively by the active frequency characteristics of large power grids that reduce the impact of large units or large capacity transmission channels' faults on system load. Judging from the world's and China's grid operation practices, the reliability of power supply is always improved with the expansion of scale of power grids.

At the market level, with the expansion of the grid coverage and the improvement of the large-scale resource allocation ability, more extension and reliable platforms will be provided for all kinds of power sources and loads to take part in competition, promoting fair trade in the electric power market. Therefore, large power grid interconnection has become the common trend in the world's power grid development and gradually the interconnection of local, regional, national, and even transnational and intercontinental power grids has been achieved.

1.3.1.2 Grid Interconnection

Adapting to the large-scale optimal allocation of electric power requires a lot of power grid interconnection. From a worldwide perspective, due to geological formation and for historical reasons, energy resources and energy consumption are unevenly distributed. Primary energy resources including hydropower, coal, and wind power are usually far

away from the load center, which makes large power grid interconnection highly necessary. At present, more than 70% of the world’s oil and natural gas resources are located in Middle East, Europe, and the former Soviet Union. To be specific, 57% of oil resources are located in the Middle East; 40 and 34% of the natural gas resources are located in Middle East, Europe, and the former Soviet Union, respectively; coal resources are distributed in North America, Asia Pacific, Europe, and the former Soviet Union [6]. At present, some developed countries, especially large cities, have a great demand for energy, but energy resources in the surrounding areas of these countries or cities have been exhausted. As a result, it is a matter of urgency to introduce energy and power from other areas. Figure 1.21 shows the fossil energy distribution around the world.

In China, 76% of the coal resources are distributed in North China and Northwest China; 80% of the hydropower resources are located in Southwest China; most land-based wind energy and solar energy resources are concentrated in Northwest China, Northeast China, and northern areas of North China. On the other hand, more than 70% of the energy demand is concentrated in East and Central China. Coal reserves and wind energy in Xinjiang account for 40 and 20.4% of China’s total, respectively.

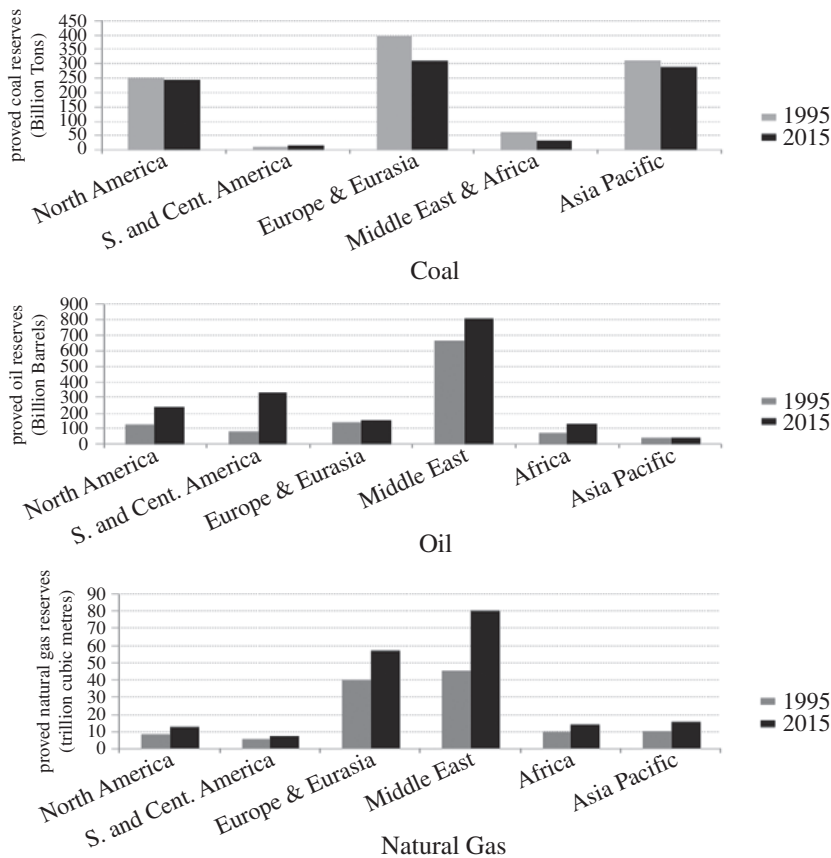


Figure 1.21 Distribution of proved fossil energy reserves in 1995 and 2015 (percentages). Data source: BP, Statistical Review of World Energy 2016.

Judging by China's future energy demand growth forecast, the load growth in East and Central China will still account for two-thirds of China's total energy demand growth. As a result, East and Central China will form China's energy consumption center. It can be seen from it that China's energy bases and load centers are 800 ~ 3000 km and even farther away from each other. With the shifting of China's future energy development focus westward, speeding up the large grid interconnection and long-distance power transmission will become more urgent [9–12].

From the perspective of solving the problem of environmental pollution, it is difficult to maintain China's long-term electric power development mode focusing on local balance. At present, the installed thermal power capacity in East and Central China has reached 630 million kW. The pollutant emissions are very high and the SO₂ emission per unit land area is 5.2 times that in West China. The SO₂ emission per unit land area in the Yangtze River Delta is even 20 times as much as China's national average. Therefore, due to the restrictions of land, environmental protection, transportation, and other factors, large-scale development of coal-fired power plants in East China is no longer suitable. Particularly, in order to solve the problem of PM_{2.5}, we must optimize the layout of power sources, control the installed capacity in East China and reduce the emissions of pollutants. Meanwhile, we should vigorously develop the electricity replacement industry to replace oil and coal use with electricity: for example, by vigorously developing electric vehicles and reducing vehicle exhaust emissions. At the same time, due to the lack of coal resources in East China, the contradiction between coal and electricity transportation has become increasingly tense. The downtime due to coal shortages caused by rising coal prices, difficult transportation, and natural disasters has increased over the years. In order to meet China's continued growth in demand for electricity, long-distance and large-scale power transmission as well as an optimal allocation of energy resources all over China is required. See Figure 1.22 for the distribution of coal resources in China.

1.3.1.3 Clean Energy and Grid Interconnection

The rapid development of clean energy leads to urgent requirements for the interconnection of large power grids. Vigorously developing clean energy such as wind power and solar energy is an important part of current world energy development as well as a permanent solution to carbon emissions and ensuring a sustainable energy supply. The world's theoretical reserves of hydropower resources are about 39 trillion kWh/a, of which 16 trillion kWh/a, or 42%, were technically exploitable hydropower resources. The technically exploitable hydropower resources in Asia are about 7.20 trillion kWh/a, accounting for 46% of the world's total; the technically exploitable hydropower resources in South America are about 2.87 trillion kWh/a, accounting for 18% of the world's total; the technically exploitable hydropower resources in North America are about 2.42 trillion kWh/a, accounting for 16% of the world's total; the technically exploitable hydropower resources in Europe are about 1.04 trillion kWh/a, accounting for 7% of the world's total. Global wind energy resources are abundant and the theoretical reserves of wind energy resources are about 2000 trillion kWh/a. Affected by the atmospheric circulation, topography, land, and water and other factors, the world's wind energy resources are unevenly distributed. In terms of wind energy resource distribution in various continents, the theoretical reserves of wind energy resources in Africa, Asia, North America, South America, Europe, and Oceania account for 32, 25, 20, 10, 8,



Figure 1.22 Distribution of coal resources in China. Picture source: SGCC.

and 5% of the world's total, respectively. Solar energy is derived from solar radiation and is the most abundant and widest distributed resources in the world. The annual solar radiation in the world equates to about 116 trillion tons of standard coal, which is equivalent to 6500 times of the world's total primary energy consumption (18.19 billion tons of standard coal) in 2013; higher than the world's reserves of fossil energy resources. The distribution of world's hydropower resources are shown in Table 1.2. See Figures 1.23 and 1.24 for the distribution of world's wind and solar resources. Global distribution of hydro, wind, and solar resources is shown in Figure 1.25.

China has the world's richest hydropower resources. There are more than 3800 rivers with theoretical reserves of hydropower resources of 10,000 kW and above in China. China's theoretical annual power generation totals about 6.08 trillion kWh; the technically exploitable installed capacity reaches 570 million kW, equivalent to annual power generation of 2.47 trillion kWh, which is mainly attributed to the huge hydropower resources in the Yangtze River, Yarlung Zangbo River, and Yellow River. The technically exploitable hydropower resources in these three rivers account for 47, 13, and 7% of China's total, respectively. By the end of 2017, China's installed hydropower capacity was 340 million kW, accounting for about 60% of China's technically exploitable hydropower resources. As a result, there are great potentials for hydropower development in the future. China also has a land area of about 200,000 km² where the wind power density 10 m above ground is 150 W/m² and above, and theoretical reserves of wind power are above 4000 GW. According to the results of wind energy resource assessment [13] released by the China Meteorological Administration (CMA) at the beginning of 2010, China's potential exploitable wind energy resources above Grade 3 and 50 m above ground in onshore areas are about 2400 GW; China's potential exploitable offshore wind energy resources above Grade 3, 50 m above the ground

Table 1.2 Distribution of the world's hydropower resources.

Region	Nation	Theoretical Reserves	Technologically Developable Capacity (TWh/year)
Asia	China	6080	2470
	Russia	2300	1670
	India	2640	660
Europe	Norway	600	240
	Turkey	430	220
	Sweden	200	130
North America	USA	2040	1340
	Canada	2070	830
	Mexico	430	140
South America	Brazil	3040	1250
	Venezuela	730	260
	Columbia	1000	200
Africa	Democratic Republic of Congo	1450	780
	Ethiopia	65	260
	Cameroon	29	120
Oceania	Australia	270	100
	New Zealand	210	80
	Papua New Guinea	180	50

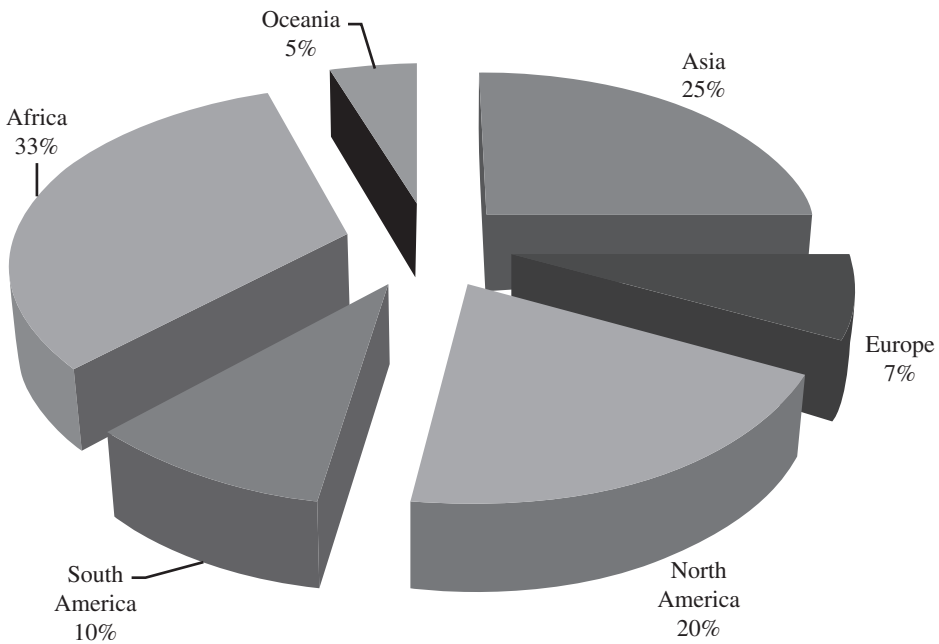


Figure 1.23 World wind power resource distributions [37].

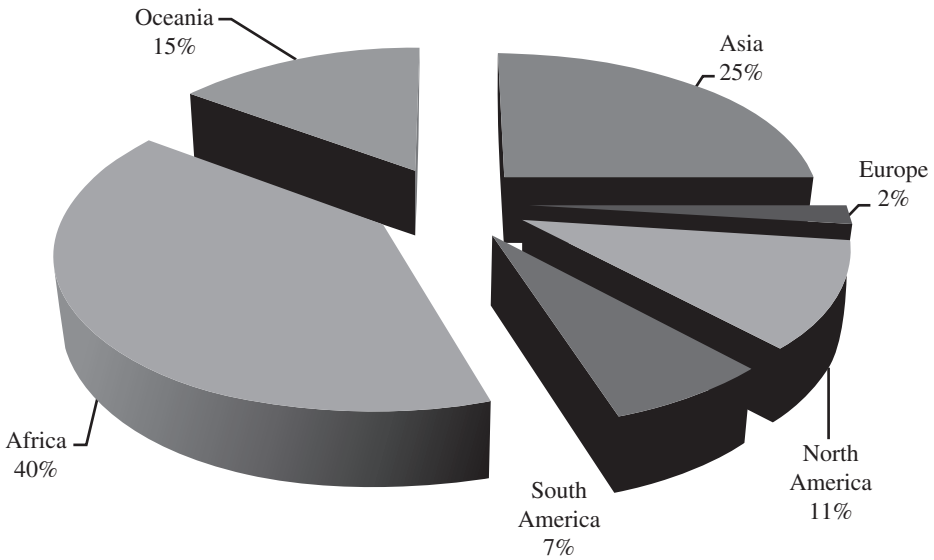


Figure 1.24 World solar power resource distributions [37].

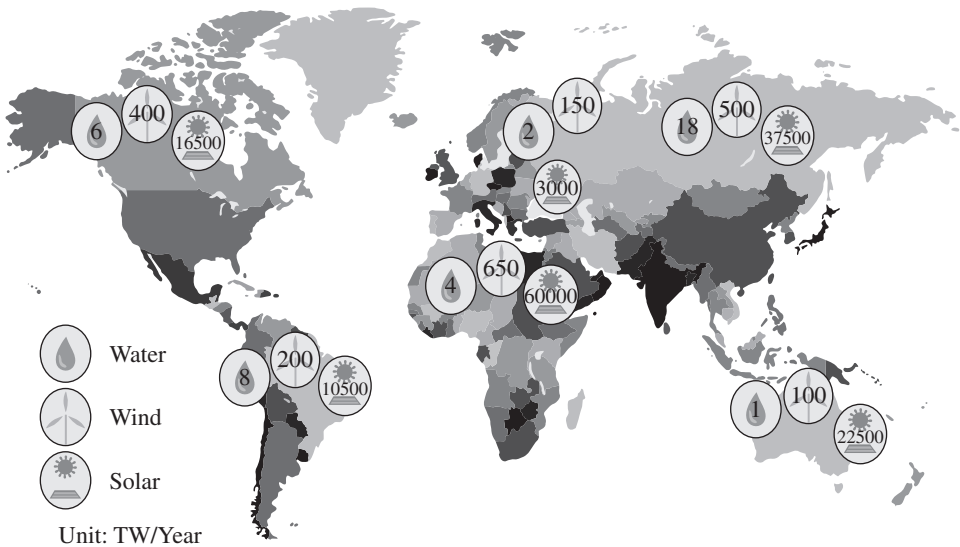


Figure 1.25 Global distributions of hydro, wind and solar resources [37].

and 5~25 m in depth are about 200 GW. In addition, China's solar energy resources are very rich and theoretical reserves reach 1700 billion tons of standard coal per year. According to planning by the National Energy Administration (NEA), China has plans to construct nine 10-GW wind power bases in Jiuquan, the Gansu province, coastal areas in the Jiangsu province, Inner Mongolia, Hebei, and other areas to create the "Wind Power Three Gorges Project" and develop large-scale photovoltaic power



Figure 1.26 Distributions of hydropower bases in China. Picture source: SGCC.

generation in Northwest China. See Figures 1.26–1.28 for the distribution of China’s Hydropower, wind power, and solar power resources.

Meanwhile, wind and solar power generation are characterized by randomness and intermittency. Measurement of the wind power output from the Gansu Jiuquan Wind Power Base indicates the probability of the wind power output change rate per minute within 1.5% is about 99%. The measured data in some southern cities also show that the power change of solar energy per minute reaches 70% of the rated power. The uncertainty of these power sources will pose great challenges to power balance, reactive power, and voltage control of the electrical power systems [14–18]. See Figure 1.29 and Figure 1.30 for the intermittency of wind power and solar power.

In the European Blackout on November 4, 2006, wind turbines were disconnected and reconnected in a disorderly manner during fault and recovery periods, respectively, which made fault control more complex [19–21]. In the first half of 2011, wind turbines in Gansu Jiuquan Wind Power Base experienced two large-scale disconnection accidents and security issues of wind power grid integration attracted attention from all parties. Judging from the analysis results, the problem was attributed to non-unified wind turbine standards and inadequate low-voltage ride through capability, but weak interconnection of the power grid will also affect the full utilization of wind power. Due to these characteristics of new clean energy, the interconnection of large power grids



Figure 1.27 Distributions of wind power bases in China. Picture source: SGCC.

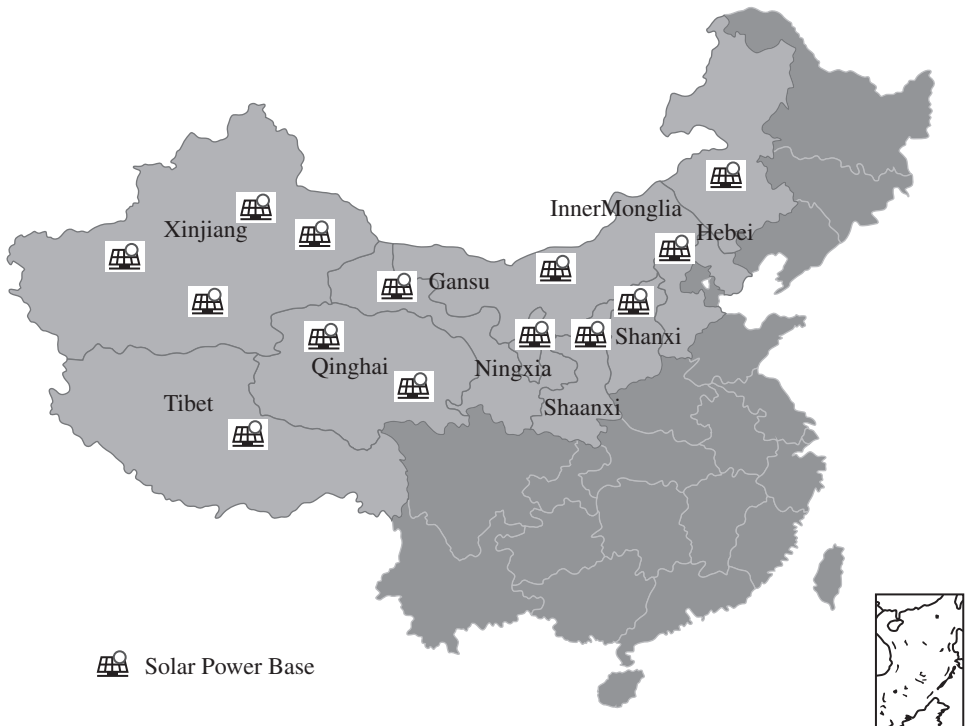


Figure 1.28 Distributions of solar power bases in China. Picture source: SGCC.

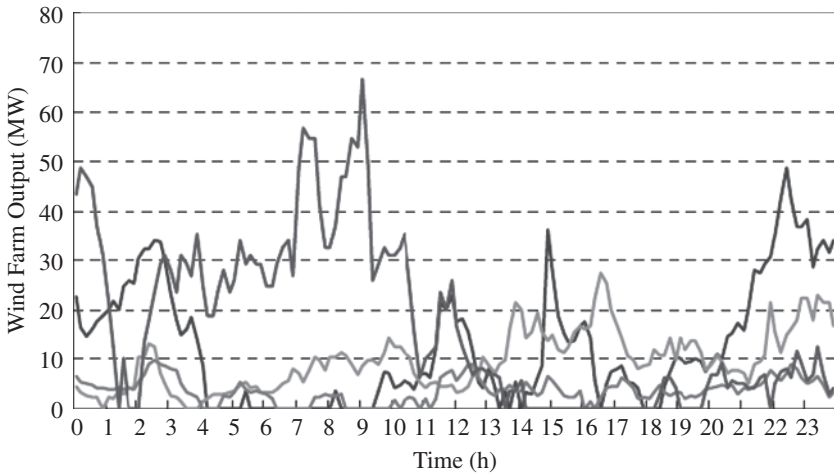


Figure 1.29 Intermittency of wind power. Picture source: SGCC.

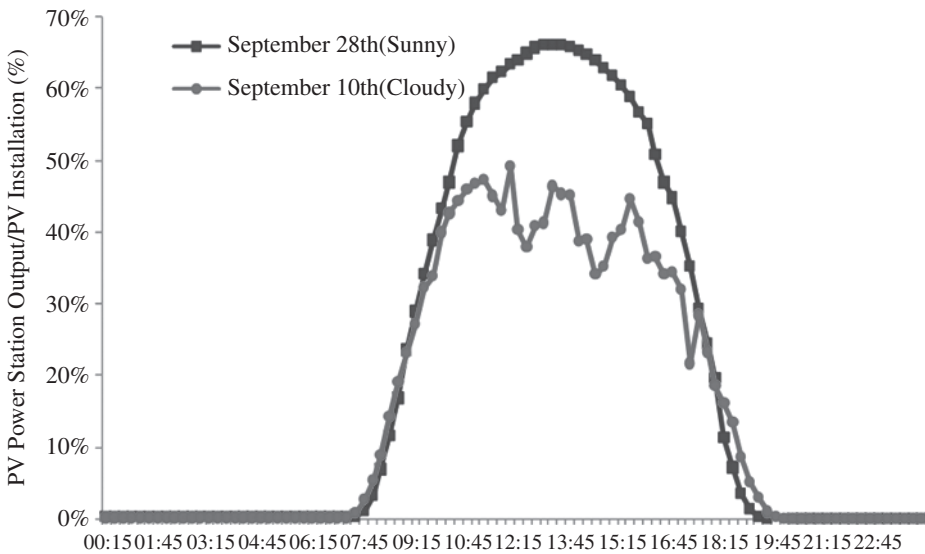


Figure 1.30 Intermittency of solar power. Picture source: SGCC.

is required as well as control of the proportion of wind and solar power in the total installed capacity. In addition, there is a requirement to improve the ability of power source integration through mutual coordination of power sources. Measures such as bundled outward transmission (consumption) of wind power, hydropower, photovoltaic power, and coal-fired power through large power grids can better facilitate the effective utilization of clean energy. In addition, the rapid development of electric vehicles, the connection of distributed power at the consumers’ side, and the application of the micro-grid technology and the form of power grids (especially the form of distribution grids), will be quite different to that of existing power grids. The operation mode of

power grids will also undergo significant changes. Therefore, this poses new challenges to the construction, operation, and management of power grids. What is more, the development of large power grids must speed up to satisfy consumers' demand and ensure grid security and the economic efficiency of grid operation.

1.3.1.4 Large Power Grid Interconnection is Required to Adapt to the Needs of Development of the Third Generation of Power Grids

To further strengthen the interconnection of power grids and improve their ability to optimize the allocation of energy resources is an important part in the construction of the third generation of power grids [22–27]. The national condition that China's energy resources and productivity are reversely distributed means that China must speed up the interconnection of power grids all over China and even on a larger scale. At present in China, with the expansion of the scope of the optimal allocation of energy resources, the scale of power grids has been expanded from small urban power grids, provincial power grids, and regional power grids to interconnected national power grids. In the 1950s, China's highest voltage level was 220 (110) kV and hundreds of small regional power grids gradually came into being. Between the 1970s and the 1980s, with continuous growth of power demand and installed capacity, almost 30 provincial power grids with 220 kV as the backbone network were gradually formed. Between 1970s and the 1990s, with the emergence of 330 and 500 kV voltage levels, inter-provincial power grids developed rapidly and finally formed six regional power grids; the Northeast China Grid, North China Grid, East China Grid, Northwest China Grid, and South China Grid. Between the end of the 1990s and the beginning of the twenty-first century, regional power grids such as the Central China Grid and East China Grid, Central China Grid and South China Grid, Central China Grid and Northwest China Grid achieved asynchronous interconnection through HVDC transmission projects (including back-to-back DC transmission system). Meanwhile, the Northeast China Grid and North China Grid, Central China Grid, and North China Grid achieved synchronous interconnection through AC transmission projects. In 2010, Xinjiang Grid and Northwest Power Grid were interconnected through the 750 kV AC power transmission project; in 2011, the Tibet Grid was interconnected with the Northwest Power Grid through the Qinghai-Tibet ± 400 kV DC transmission project and the supporting 750 kV AC transmission project. Meanwhile, the Hainan Grid was interconnected with the South China Grid through submarine cables. Figure 1.31 shows the synchronous grids in China by 2015. At present, except for the Taiwanese province, all China's power grids are basically interconnected with each other.

In January 2009 the world's first 1000 kV UHV AC demonstration project, the Southeastern Shanxi-Nanyang-Jingmen transmission line, was completed and put into operation; in July 2010, the ± 800 kV Xiangjiaba-Shanghai UHVDC demonstration project was completed and put into operation; in December 2012, the ± 800 kV Jinping-Southern Jiangsu UHV DC demonstration project was completed and put into operation. With the rapid development of the UHV transmission technology, by 2020 SGCC will have built a backbone network consisting of five vertical and five-horizontal UHV AC transmission lines and 27 inter-regional UHV DC power transmission projects connecting large energy bases and main load centers to form the energy distribution pattern of large-scale "West-East electricity transmission" and

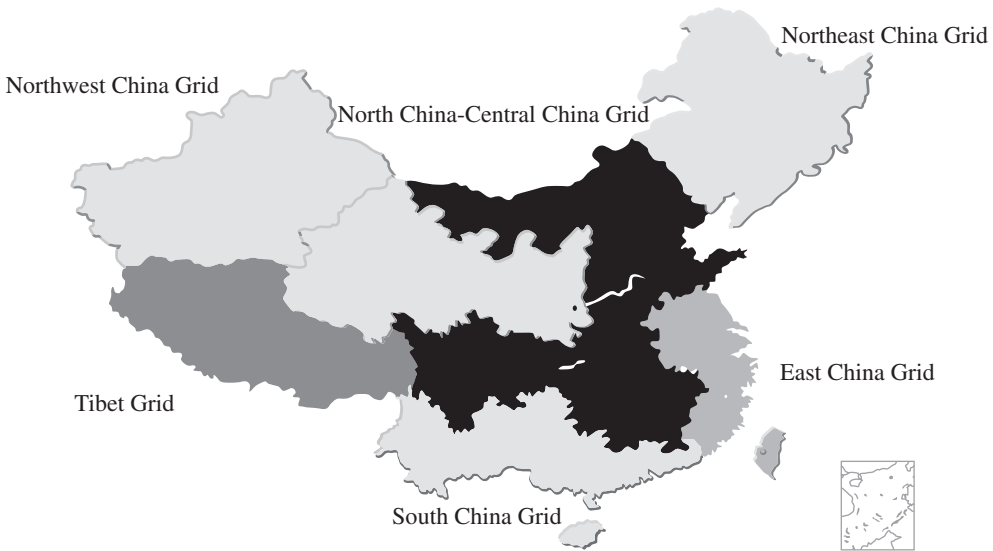


Figure 1.31 Schematic diagram of the interconnection of China's power grids in 2015. Picture source: SGCC.

“North-South electricity transmission.” Figure 1.32 shows a schematic diagram of the interconnection of China's power grids in 2020 [1].

1.3.1.5 Large Power Grid Interconnection is an Important Trend in World Power Grid Development

The scale of interconnected synchronous power grids in most areas in the world is gradually expanding. At present the total installed capacity of the synchronous power grids in eastern North America exceeds 760 GW, covering an area of about 5.2 million km². With 500 kV as the backbone network and containing some 750 kV power grids, the synchronous power grids in eastern North America have the largest installed capacity in the world. Figure 1.33 shows a schematic diagram of interconnected power grids in North America. The installed capacity of synchronous power grids in Western Europe reaches 690 GW, covering an area of about 4.5 million km². The synchronous power grids are dominated by 400 kV power grids, but also have a few 330 kV power grids. After the American Blackout in 2003, the USA accelerated the development of grid technology and put forward the concept and idea of Grid2030, a super-power grid; namely, constructing the national backbone network [28], connecting the East and West Coast of the USA with Canada and Mexico. Figure 1.34 shows a schematic diagram of America's Grid2030 Plan. In order to meet the needs of clean energy development, European countries proposed to construct a “Europe-Mediterranean-Middle East” super-power grid by 2050 to connect renewable energy power generation bases in North Africa, the Middle East, and areas along the coast of the North Sea in Europe. Figure 1.35 shows a schematic diagram of the European SuperGrid Plan. Figure 1.36 shows a schematic diagram of the Desertec plan. Figure 1.37 shows a 2050 projection of the major powerhouses and super producers in Europe and North Africa. According to the plan, by 2020 at least 35% of the power in Europe will be supplied by distributed and



Figure 1.32 Schematic diagram of the interconnection of China's power grids in 2020. Picture source: SGCC.

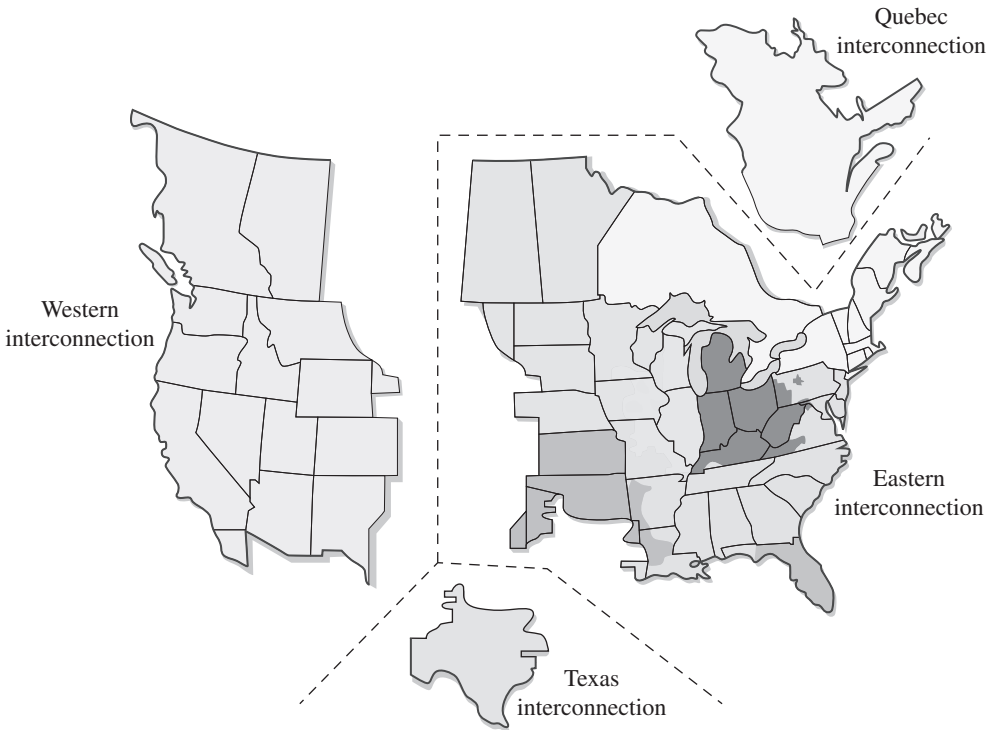


Figure 1.33 Schematic diagram of interconnected power grids in North America in 2012. Picture source: EIA.

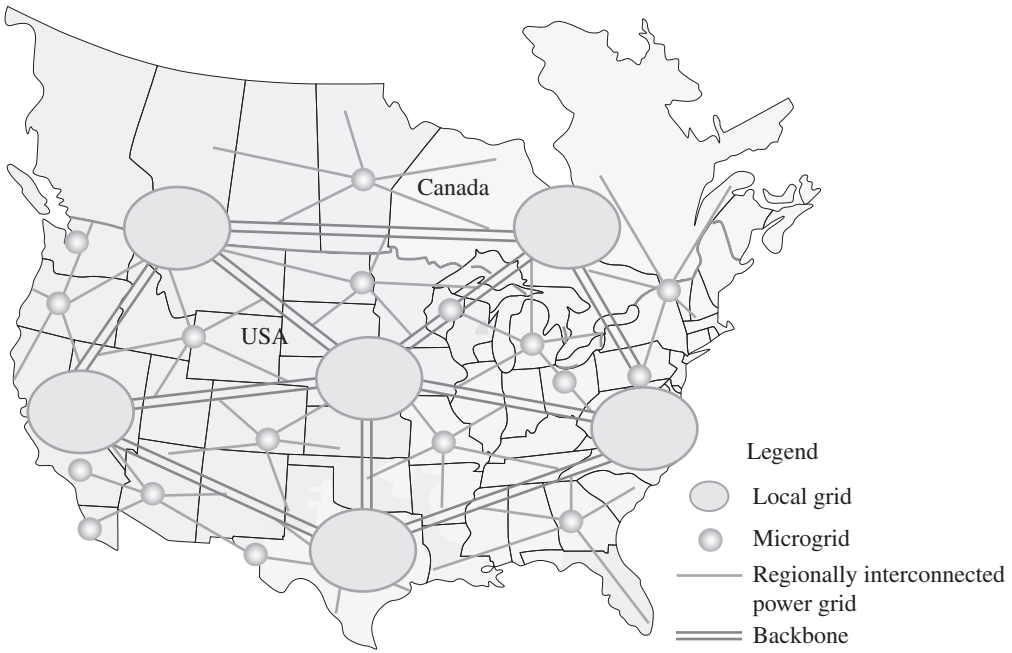


Figure 1.34 Schematic diagram of America's Grid2030 plan. Picture source: United States Department of Energy.

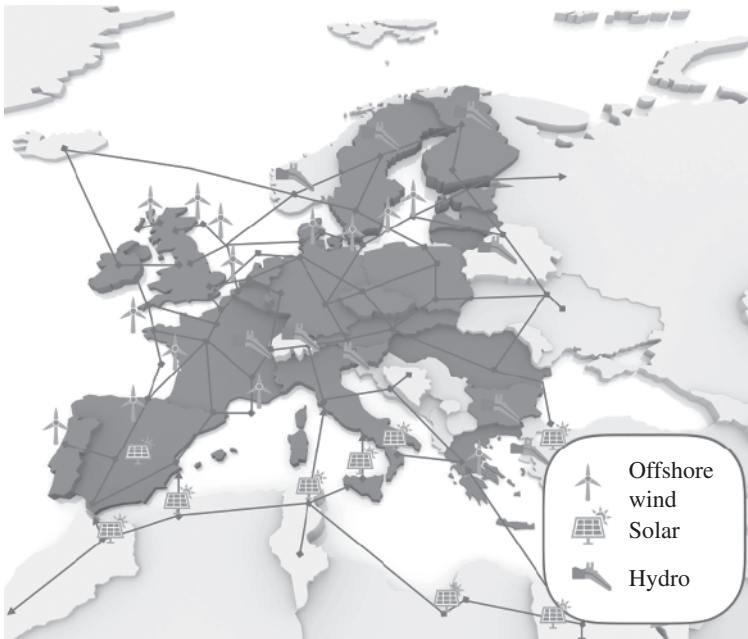


Figure 1.35 Schematic diagram of European SuperGrid plan. Picture source: Europagrid.

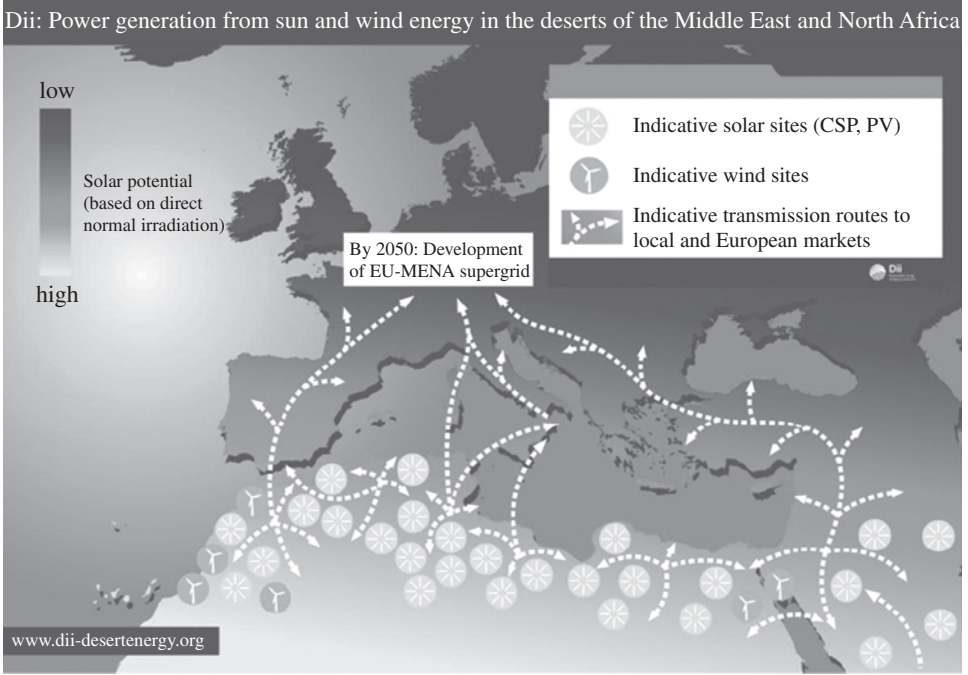


Figure 1.36 Schematic diagram of desert planning. Picture source: Dii-desertenergy.

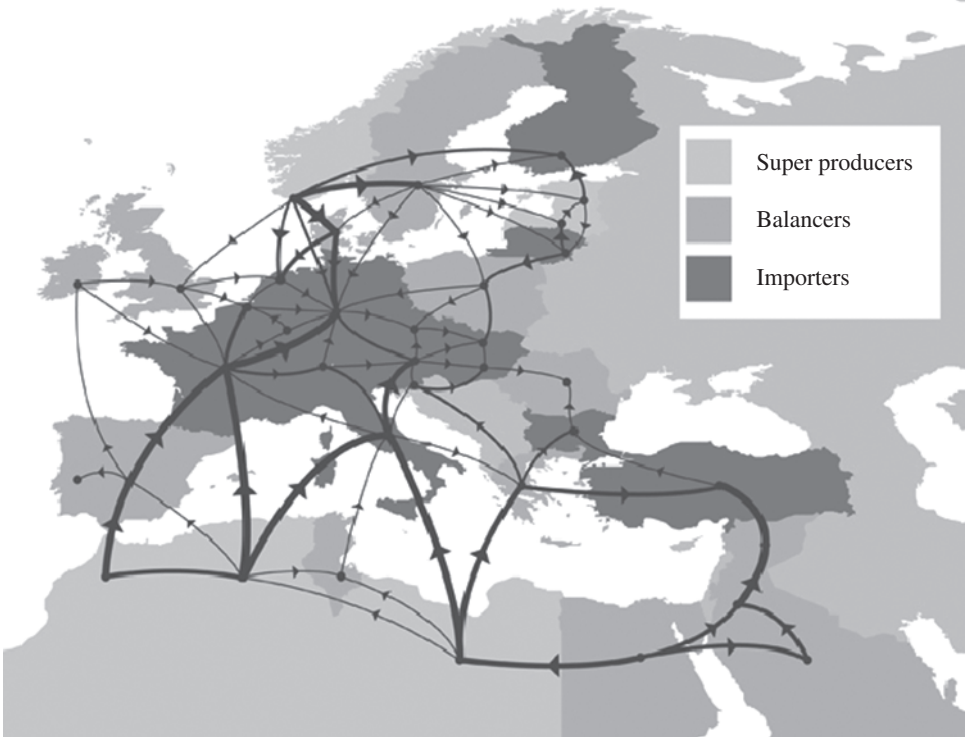


Figure 1.37 North and South – EUMENA’s Powerhouses in 2050. Picture source: DESERTEC [38].



Figure 1.38 Schematic diagram of the Europe, Asia, and Africa intercontinental UHVDC Asynchronous grid interconnection vision. Picture source: SGCC.

centralized renewable energy. By 2050, Europe will achieve decarbonized production of all power. Driven by these new demands, the smart grid will come into being [29, 30].

Faced with the common worldwide problem of energy security, at the G-SEP Leaders' Summit held in 2012, the SGCC proposed the vision of building an intercontinental power grid – namely integrating the coal-fired power in Central Asian countries like Kazakhstan and China's Xinjiang, hydropower in Yarlung Zangbo River, hydropower in Russian Far East, solar energy in Sahara Desert in Africa and onshore as well as offshore wind power in Eurasian areas – into a Eurasian intercontinental energy allocation system through UHV transmission lines to comprehensively improve energy supply security. Figure 1.38 shows an intercontinental UHV DC asynchronous interconnection plan: namely, building a ± 800 or ± 1100 kV multi-terminal DC transmission system covering Asia, Europe, and Africa with all kinds of power sources including wind power, photovoltaic power, and coal-fired power in order to connect major energy bases and load centers. Figure 1.39 shows a schematic diagram of the global grid interconnection vision based on HVDC transmission and connection of all kinds of clean energy [31]. Figure 1.40 shows a schematic diagram of the global super-grid that was proposed by Professor Jielingth of the Electric Power Research Institute in the USA (EPRI).

1.3.2 Development of Grid Interconnection Technology

At present, the main means of large grid interconnection deployed in the world include AC synchronous interconnection, DC asynchronous interconnection, AC/DC parallel operation, and VFT asynchronous interconnection, which have different characteristics and advantages.

1.3.2.1 AC Synchronous Interconnection

Two separated systems are linked together through the AC transmission line that is generally called the network tie line (see Figure 1.41). The power flow of the tie line

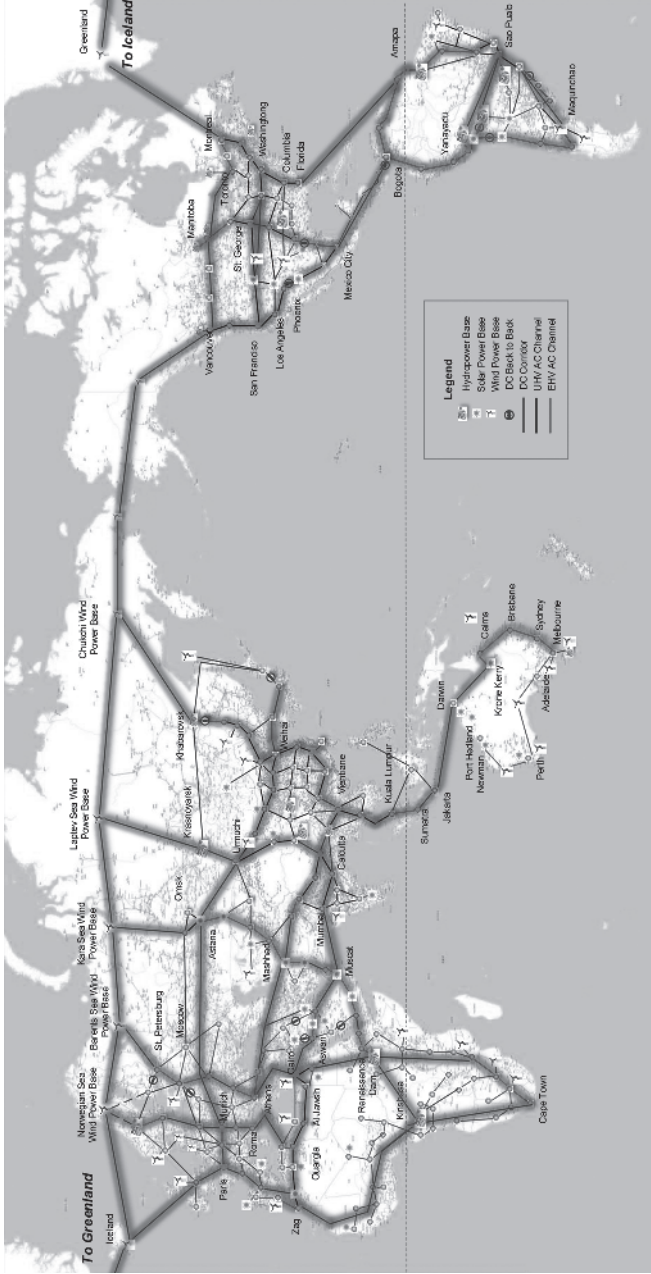


Figure 1.39 Schematic diagram of the global grid interconnection vision based on HVDC transmission and connection of all kinds of clean energy.



Figure 1.40 Schematic diagram of the global super-grid. Picture source: Clark W. Gellings, Global Supergrid.



Figure 1.41 Typical AC synchronous interconnections in a power system.

is determined by the law of the AC circuit. In order to control the power of the tie line, the control strategy of regional automatic generation control (AGC) is generally adopted. Through AC interconnection, the systems on both sides in a synchronous power grid must control the power-angle of generator in the whole system to ensure safe and stable operation and to prevent the tie line power from exceeding the limit and becoming unstable; AC synchronous interconnection can not only achieve active power exchange, but also reactive power exchange. In addition, when the fault occurs in the system, a short-circuit current will be increased on the other side.

From the perspective of the world power grid development history, the scale and scope of the AC interconnection depends on the power grid voltage level and the load growth needs. The transmission capacity and distances of AC lines of different voltage levels are shown in Table 1.3. The higher the voltage level is, the longer the AC transmission line length and the larger the scale of the interconnected power grid. The success of China's 1000 kV UHV AC transmission demonstration project not only provides technical support for the construction of Central China-North China-Eastern China UHV synchronous power grid, but also provides a reference for other countries and regions in the world in power grid interconnection. A strong transmitting end grid or receiving end grid is built through the AC interconnection. The greater the number of generators

Table 1.3 Transmission capacity and distance of AC lines at different voltage levels.

Voltage Level (kV)	Natural Power (10 MW)	Transmission Capacity (10 MW)	Transmission Distance (km)
110	3	3–6	30–120
220	16	10–20	100–250
330	36	20–50	200–500
500	95	40–100	250–800
750	230	100–250	500–1200
1000	500	200–600	1000–2000

connected with the synchronous power grid, the larger the inertia of the synchronous power grid, which can significantly enhance the synchronous power grid's ability to deal with faults and accommodate external inflow.

At the same time, with the expansion of the scale of the synchronous power grid, the risk of low-frequency oscillation and accident diffusion has attracted much attention. For example, there is a low-frequency oscillation risk in China's "long chain" AC interconnected system of Central China-North China-Northeast China, which restricts the exchange power level of regional power grids and results in a small transmission scale of the Central China-North China, North China-Northeast China 500 kV AC tie line. In order to ensure the safe operation of large power grids, we need to construct AC synchronous power grids in a scientific way. On the one hand, we need to adopt safe and stable automatic control, PMU, other technologies, and measures to improve the large power grid state perception and controllability; on the other hand, in the power grid construction process, we should reasonably design the grid architecture to ensure a clear interface of the interconnected system, in order to effectively control key lines and important sections as well as actively prevent the risk of cascading failures caused by an electromagnetic loop network.

1.3.2.2 DC Asynchronous Interconnection

Two separate AC systems are linked through the HVDC transmission project (see Figure 1.42). This HVDC project can be a conventional HVDC project, a back-to-back DC project, or a flexible DC device. A DC project generally includes a DC line and converter stations on both sides of the line. The converter station mainly consists of a converter transformer, converter valve, AC filter, DC filter, smoothing reactor, overvoltage protection facilities, and other devices. The DC transmission power is decided by the DC control system and generally the constant power control mode or constant current control mode is adopted. Through DC interconnection, the systems on both sides can be asynchronous grids or even power grids of different frequencies, and there is no requirement for the power angle of generator in the interconnected systems. DC interconnection can only transmit active power, thus the systems on both sides need to provide a certain proportion of reactive power support. DC asynchronous interconnection can effectively isolate the interaction between the interconnected power grids and realize the effective and controllable transmission of active power. However, large-scale DC power exchange requires the support of

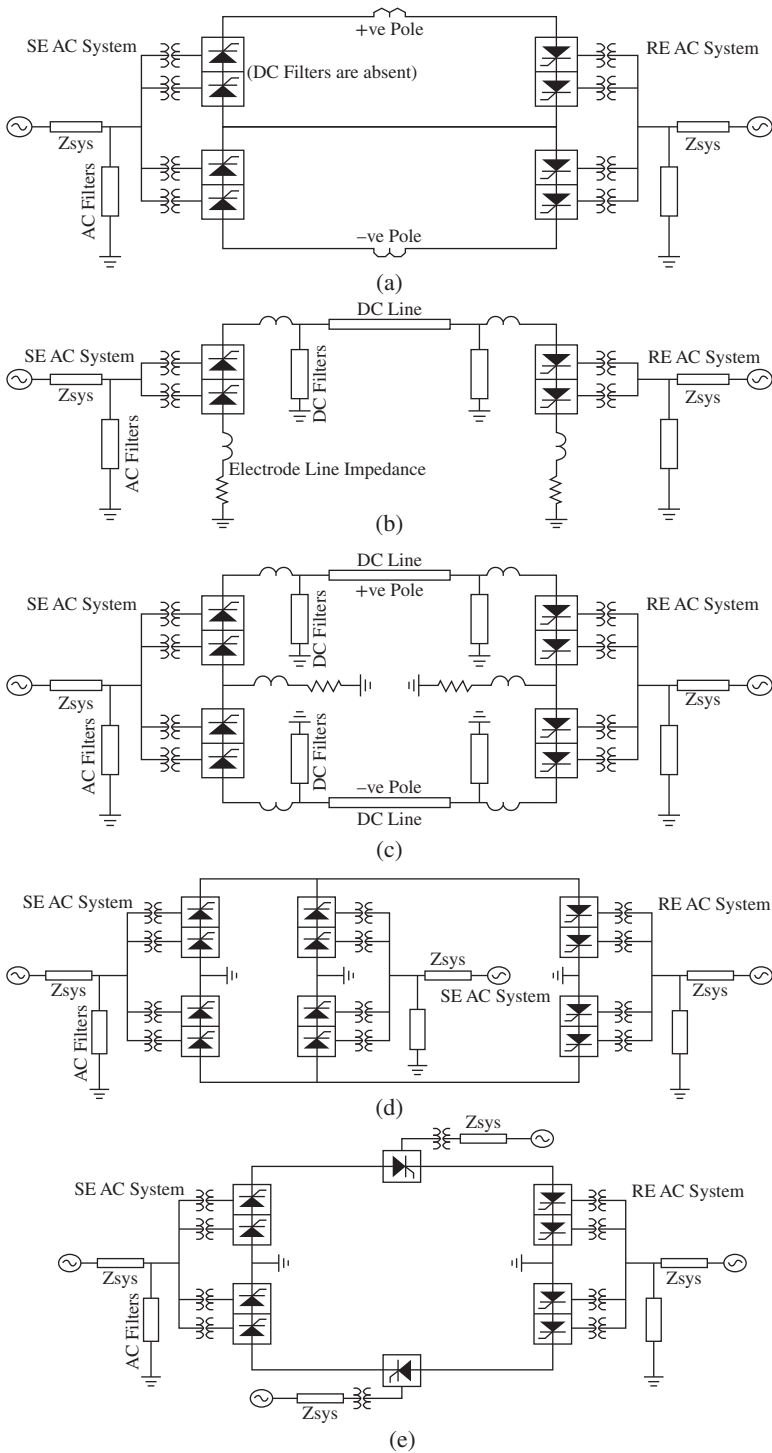


Figure 1.42 Typical DC asynchronous interconnections. (a) Back-to-back, (b) monopolar HVDC, (c) bipolar HVDC, (d) multi-terminal in series, and (e) multi-terminal in parallel.

strong AC grids; otherwise DC faults will lead to power supply accidents, and AC system faults may also cause DC commutation failures and even unipolar or bipolar blocking. Due to the limitation of the DC transmission characteristics, the normal operation of the conventional DC system (including back-to-back DC system) needs the support of the voltage of the systems on both sides to achieve normal commutation and rectification. Therefore, in supplying power to a weak power grid, the conventional DC connection has some limitations. In addition, as the DC transmission system will lead to certain harmonics, it should be equipped with a filter of a certain capacity.

1.3.2.3 AC/DC Parallel Operation

To be specific, there are both DC transmission channels and AC tie lines between two systems. This kind of interconnection, in essence, is an AC synchronous interconnection. The DC transmission power is determined by the DC control system; the power flow of the AC tie line is determined by the law of the AC power grid. The systems on both sides in a synchronous power grid must control the generator power angle of the whole system to ensure safe and stable operation and to prevent the tie line power from exceeding the limit and becoming unstable. The AC/DC parallel operation and control can significantly improve the transmission efficiency, safe, and stable performance of the interconnected systems and effectively suppress the low-frequency oscillation of interconnected systems. Figure 1.43 shows a AC/DC parallel operation power grid. In Reference [32] the operation and control of the AC/DC parallel system is studied and some control methods as well as ideas for flexible AC/DC parallel power transmission are proposed.

1.3.2.4 VFT Asynchronous Interconnection

Two separate AC systems are linked together through the VFT and step-up transformers on both sides (see Figure 1.44). Specific information about the VFT will be introduced in subsequent chapters. The power flow of the VFT is determined by its control system. Interconnection through the VFT has a similar effect as a back-to-back DC project. The

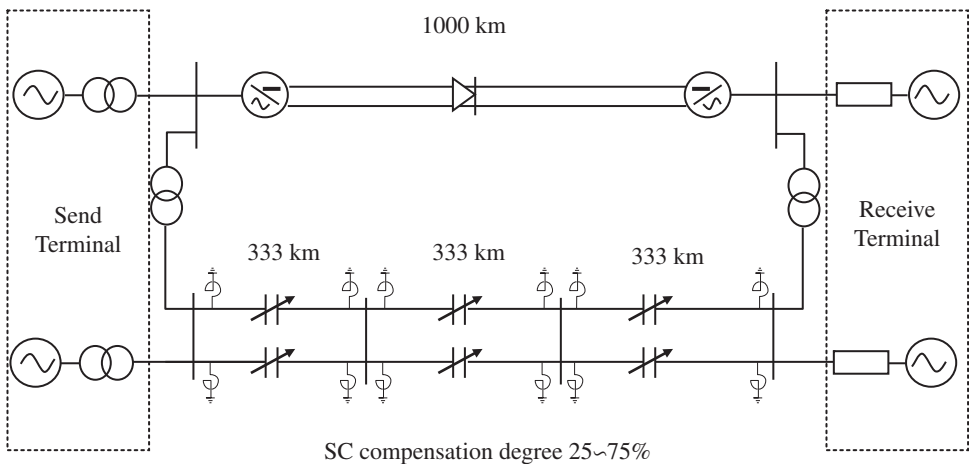


Figure 1.43 Schematic diagram of an AC/DC parallel operation power grid [32].

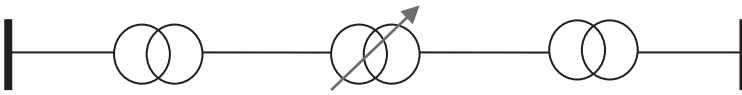


Figure 1.44 Typical VFT asynchronous interconnection.

systems on both sides can be asynchronous power grids and have no requirement for the power angle of generator. The VFT transmits active power as well as reactive power. In addition, in case of a system fault, this limits the increment of a short-circuit current. The VFT can also run in parallel with the AC channel. In this operation mode, the VFT is equivalent to a phase shifter capable of continuous and large-scale regulation.

These four kinds of interconnection methods have different characteristics and can be applied on different occasions. Generally speaking, the AC interconnection is applicable to countries and regions with the same management subject or unified management conditions and abilities. The interconnection scale depends on the voltage level and scale of energy exchange demand. The DC interconnection, to some extent, can isolate the systems on both sides and prevent their mutual influence on each other. So it is applicable to occasions when the systems on both sides belong to different management subjects or different countries, when the interconnected power grids have different voltage frequencies, and when power of an ultra-large capacity is transmitted over an ultra-long distance. The VFT is suitable for the marginal interconnection between large power grids and the interconnection of weak or small power grids to main grids. It can play an important role to achieve an organic combination of the backbone power grids and local power grids as well as microgrids.

At the same time, in order to ensure safe and stable operation of power grids, flexible power flow control, and development of the power market, there must be a clear interface between interconnected power grids, which is even more important to AC synchronous interconnection. Otherwise, once an interconnected line fails, this may lead to large-scale power transfer and affect the safe operation of the whole interconnected system. A similar situation occurred in the USA and Canada Blackout of 2003 and led to serious consequences. Therefore, the safety of large power grids has attracted attention from various parties [33–35]. In strengthening the interconnection of power grids, we must select suitable interconnection modes based on the actual situation of the power grids to ensure the safe operation of the interconnected power grids.

1.4 Main Content of this Book

Starting from the development features of modern power grids, in this book we carry out comprehensive research on VFT theory, control and simulation, and engineering applications. Problems are solved, such as VFT simulation analysis tools, operation control strategy, and large system low-frequency oscillation. A comparative study is made here on the technical economy of VFT and phase shifter as well as the back-to-back DC transmission system leading to systematic and innovative research results [5]. This book is divided into eight chapters. The main content of each chapter is as follows:

Chapter 1: Power Grid Development and Interconnection. On the basis of analyzing the development trend for world energy, electric power, and the power grid development

trend, we summarize the basic characteristics of the first, second, and third generations of power grids. Starting from the needs of large-scale optimal allocation of electric power, we introduce the development of the power grid interconnection technology and compare the characteristics and performance of different types of interconnection.

Chapter 2: Proposal and Application of VFTs. In this chapter, we focus on the physical composition, technical characteristics, basic functions, foreign research, and engineering applications of VFTs, discuss the necessity of developing them and their application prospects in China, and elaborate on the problems related to research on VFTs that have to be solved urgently.

Chapter 3: Basic Equations and Simulation Models of VFTs. Based on the principle of general motors and circuits, we derive and establish the power flow steady-state equation, electromechanical transient equation, and electromagnetic transient equation that can effectively represent the static and dynamic characteristics of the VFT. These equations reflect the relationship between the main parameters of the VFT such as rotor speed, transmission power, driving torque, voltage and current of the main circuit, control driving circuit ignition angle, and the electromagnetic coupling and power exchange law of VFTs. We reveal the basic principle of asynchronous grid interconnection transmission and flexible operation control by using VFTs, and prove that the VFT can improve the stability level of an interconnected electric power system. On this basis, based on the derived basic equations of the VFT and the basic functions provided by programs such as the Power System Analysis Software Package (PSASP), EMTP, and PSCAD/EMTDC, we study and establish the digital simulation model of VFTs, which are applicable to power flow calculation, electromechanical transient analysis, and electromagnetic transient research of electric power systems. Simulation modules in relevant simulation programs of electric power systems are realized so as to create conditions for analysis of VFTs in a large electric power system.

Chapter 4: VFT Control System Research and Modeling. In this chapter, we study the overall control strategy of VFT, construct the DC driving circuit model, and put forward and establish block diagrams and parameters of various control systems that can realize functions such as frequency control, power angle control, synchronous grid connection control, power control, reactive power voltage control, system power flow optimization, and suppression of low-frequency oscillation. These control modules are mainly based on PID control, have strong robustness, and can adapt well to different system conditions and operation modes providing support for the implementation of various control targets of VFT.

Chapter 5: Analysis of Operation Characteristics and Application of VFTs in the Electric Power System. We use the simplified electric power system, a typical four-generator power system, and a complex practical system to build the all-digital simulation system including VFTs based on software such as PSASP, EMTP, and PSCAD/EMTDC and carry out an all-digital simulation including processes such as VFT startup, grid integration, power regulation, reactive voltage control, fault response, power supply to weak systems, system frequency regulation, and damping low-frequency oscillation. Simulation results show that the developed VFT simulation model and control system are effective; the VFT can be used to achieve power bidirectional transmission and smooth regulation between asynchronous

power grids, effectively prevent the impact of the fault on the interconnected power grids, realize basic functions such as system frequency adjustment, power flow optimization, damped oscillation, power support, and power supply to islands. With the power step response time being about 400 ms, the VFT can meet the needs of power control and regulation and has sound system stability.

Chapter 6: Design of an Adaptive Low-Frequency Oscillation Damping Controller Based on a VFT. We study the low-frequency power oscillation problem of a large interconnected electric power system and propose the self-adaptive low-frequency power oscillation damping control method based on the VFT and Prony method. This method can actively identify the system oscillation mode and adjust the damping controller parameters. The simulation of the typical four-generator power system and complex practical system simulation proves this method can better adapt to the system changes and fault interference so as to effectively suppress low-frequency power oscillation of the synchronous interconnected systems.

Chapter 7: Technical and Economic Characteristics of VFTs. We compare the differences and similarities of VFT and different types of power phase shifter, DC power transmission devices, and other devices. Characteristics and advantages of VFT are analyzed. Compared with a phase shifter, a VFT can realize asynchronous interconnection as well as flexible and smooth power regulation of two power grids with different frequencies, it has better adaptability, controllability, and flexible regulation performance, and it does not produce harmonics. Compared with the back-to-back system, the VFT has advantages such as simple structure, fewer components, low loss, high reliability, small footprint, easy maintenance, lower reactive power configuration needs, strong system adaptability, convenient expansion, and no harmonics. It can be used as an alternative technique for asynchronous interconnection and has broad development and application prospects.

Chapter 8: Summary and Prospects. In this chapter, we summarize the main conclusions of VFT research and propose key issues to be studied next.

1.5 Summary

1. At present, human society is facing the threat of imminent fossil energy depletion and global climate change. In the new energy reform characterized by clean energy and smart grids, the energy structure will undergo dramatic changes in the future and electric power is expected to become the most important energy form. As a result, there are higher requirements for safety, adaptability, interaction, and ability to optimize the allocation of energy resources of the power grid.
2. Power grids and grid interconnection technology have entered the era of the third generation power grids characterized by the large-scale utilization of renewable energy and smart power grids. In the next 40 years, the world will complete the transition from the second to third generation power grids. Therefore, the promotion and application of new technologies and new devices will become more urgent.
3. Third generation power grids will gradually evolve to the network pattern of combining large power supplies with distributed generation and backbone power grids with microgrids. As a new smart grid device, the VFT can play a positive role in large power grid interconnection.

4. In the new round of world energy reform, particularly driven by the large-scale optimal allocation of electric power, we must accelerate the innovation and development of grid technology. The VFT is an innovative technology for future grid interconnection and has broad prospects in the future.

References

- 1 L. Zhenya. *Electric Power and Energy in China*. Beijing: China Electric Power Press, 2012.
- 2 L. Zhenya. *UHV Grid*. Beijing: Economic Press, 2006.
- 3 S. Yinbiao. Research and application of 1000 kV UHV AC transmission technology. *Power Grid Technology*, 2005, 29(19): 1–6.
- 4 Z. Xiaoxin, C. Shuyong, L. Zongxiang. Review and prospect of the development of power grid and power grid technology. *Proceedings of the CSEE*, 2013, 33(23): 1–11.
- 5 C. Gesong. *Modeling and Control of VFT for Power Systems*. D. Phil Thesis, Beijing: China Electric Power Research Institute, 2010.
- 6 BP Statistical Review of World Energy, 2012.
- 7 D. Archer. *The Global Carbon Cycle*. Princeton, NJ: Princeton University Press, 2010.
- 8 Z. Xiaoxin. The development prospects of power grid and its technology during the new energy revolution era. *Annual Meeting of the Chinese Society of Electrical Engineering*, 2010.
- 9 National Bureau of Statistics. *China Energy Statistics Yearbook 2008*. Beijing: China Statistics Bureau Press, 2009.
- 10 State Grid Energy Research Institute. *Handbook of International Energy and Power Statistics (2009)*. Beijing: SGCC, 2009.
- 11 SGCC. *Research on the Energy Base Construction and Medium and Long Term Development Plans for Electric Power*. Beijing: SGCC, 2006.
- 12 Chinese Academy of Engineering. *Research on the Medium and Long Term Development Strategy for Energy*. Beijing: Chinese Academy of Engineering, 2010.
- 13 Wind Energy Resource Assessment Center of China, Meteorological Administration. *Assessment of Wind Energy Resources in China (2009)*. Beijing: Meteorological Press, 2010.
- 14 L. Feng, L. Yichuan. Influences of large-scale wind energy converters on transmission systems. *China Electric Power*, 2006, 39(11): 80–84.
- 15 H. Dongsheng, L. Yongqiang, W. Ya. Study of the shunt-connected Wind Power Generation System. *High Voltage Engineering*, 2008, 34(1): 142–147.
- 16 Z. He, X. Jianyuan, Z. Mingli, et al. Status and key issues of wind power technology development. *East China Electric Power*, 2009, 37(2): 314–316.
- 17 A. Vladislav. *Analysis of dynamic behavior of electric power systems with a large amount of wind power*. Dissertation. Denmark: Technical University of Denmark, 2003.
- 18 T. Geetha, V. Jayashankar. Stability assessment of power system models for higher wind penetration. *Power System Technology and IEEE Power India Conference*, 2008.

- 19 G. Rui, D. Yu, L. Yaochun. Analysis of large-scale blackout in UCTE power grid and lessons to be drawn to power grid operation in China. *Power System Technology*, 2007, 31(3): 1–6.
- 20 L. Chunyan, C. Zhou, X. Mengjin. Analysis of large-scale blackout in Western Europe Power Grid on November 4 and relevant suggestion to Central China Power Grid. *High Voltage Engineering*, 2008, 34(1): 163–167.
- 21 S.K. Salman, A.L.J. Teo. Improvement of fault cleaning time of wind power using reactive power compensation. *IEEE Power Tech Conference*, Porto, Portugal, 2001.
- 22 Z. Xiaoxin, G. Jianbo, S. Yuanzhang. *Basic Research on the Operational Reliability of Large-Scale Interconnected Power Grids*. Beijing: Tsinghua University Press, 2008.
- 23 Z. Baosen, G. Ricai. On development of interconnection of power networks in China. *Power System Technology*, 2003, 27(2): 1–7 [in Chinese].
- 24 H. Zhenxiang, X. Yusheng, Q. Jiaju. A review of CIGRE-2000 on power system interconnection. *Automation of Electric Power Systems*, 2000, 23(24): 1–4 [in Chinese].
- 25 Y. Yongkang. Research on inter-provincial power system interconnection and the electric power exchange project. *Power System Technology*, 1996, 20(7): 14–18 [in Chinese].
- 26 P.A.S. Pegado. Large international interconnections in South America and Brazil. *2000 CIGRE 37*, Paris, France, 2000.
- 27 J.P. Dresbrosses. International interconnections of power systems: trends for the next decade. *2000 CIGRE 37*, Paris, France, 2000.
- 28 L. Zongxiang, J. Jinfeng. Interpretation of the vision of the United States “Grid2030.” *China Electric Power Enterprise Management*, 2004.
- 29 A.S. Massoud, B.F. Wollenberg. Towards smart grid. *IEEE Power & Energy Magazine*, 2005, 3(5): 34–41.
- 30 M. Vadari. Demystifying intelligent networks. *Public Utilities Fortnightly*, 2006, 145(11): 61–64.
- 31 GEIDCO. Global Energy Interconnection Backbone Grid Research. *International Conference on Global Energy Interconnection*, 2018.
- 32 C. Gesong. Discussion on the flexible AC/DC power transmission mode. *National Conference on Power System Technology*, 2001.
- 33 Z. Xiaoxin. Power system burst disaster and risk of blackout. *Power Industry Summit*, 2007.
- 34 Z. Xiaoxin, Z.J. Chao, S. Guorong, X. Yusheng. Draw lessons from the Northeast America-Canada power grid blackouts accident. *Power System Technology*, 2003, 27(9): 1.
- 35 B.G. Gher, P. Dusan, R. Dietmar, T. Erwin. Lessons learned from global blackouts lessons from the Northeast, 2007, 40(10): 75–81.
- 36 R.A. Hefner III, *The Grand Energy Transition* [Yuanchun M, Boshu L, Trans.]. Beijing: China Citic Press, Citic Publishing House; 2013.
- 37 L. Zhenya. *Global Energy Interconnection*. Beijing: China Electric Power Press, 2015.
- 38 S. Mludi, I.E. Davidson, Dynamic analysis of the southern Africa Power Pool (SAPP) Network, presented at *2017 IEEE PES-IAS Power*, 2007.