CHAPTER 1

Chapter Outline

1.1 Grid Development and Interconnection

1.1.1 Basic Concepts of Grid

An electric power system is a system that involves generation, transmission, distribution, and consumption of electricity, as shown in Figure 1.1. An electrical grid is used to connect power plants and users [1].

The grid mainly consists of transmission and distribution networks. The transmission network sends the electricity produced by power plants to centers/regions of load or

Ultra-high Voltage AC/DC Grids.
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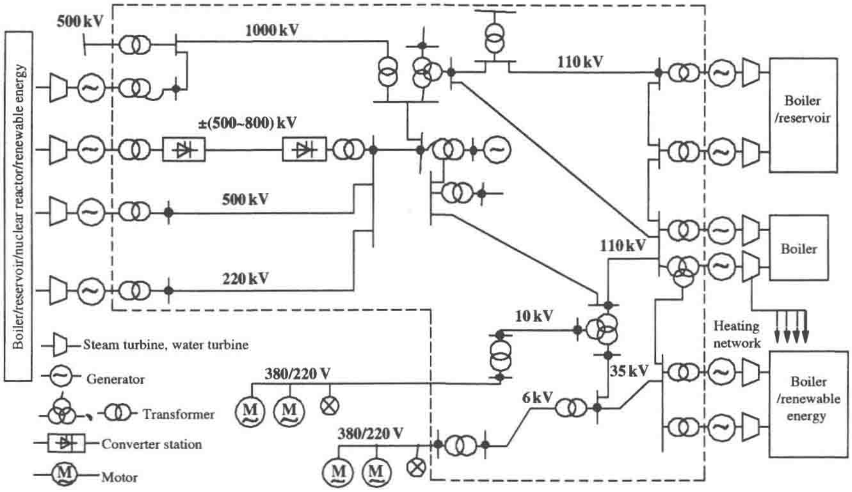

Figure 1.1
Schematic diagram of electric power system (the dotted box represents a grid).

exchanges electricity between neighboring grids through interconnection. The distribution network receives electricity from the transmission network and distributes it to urban or rural areas, including industry, agriculture, business, residence, or other special consumers.

Electricity can be transmitted and supplied in two forms: alternating current (AC) transmission and distribution, and DC transmission. The AC transmission and distribution is completed by the step-up substation, step-down substation (including primary and secondary equipment), and connected transmission lines. Transmission equipment is connected to form a transmission network, and distribution equipment is connected to form a distribution network. The DC transmission is achieved using DC transmission lines and equipment in converter stations (including primary and secondary equipment). Equipment used in substations/converter stations includes primary equipment such as transformers, reactors, capacitors, circuit breakers, grounding switch, disconnectors, surge arresters, voltage transformers, current transformers, bus, and secondary equipment such as relay protection, surveillance, monitoring and control, and power communication systems. Transmission equipment mainly includes conductors, towers, insulator strings, and grounding wires (including optical fibers). DC equipment includes converter valves, converter transformers, smoothing reactors, DC filters, DC disconnectors, grounding switches, bypass switches, DC circuit breakers, DC-measuring devices, and DC surge arresters.

Voltage classes of transmission networks are usually classified into high voltage (HV), extra-high voltage (EHV), and ultrahigh voltage (UHV). As internationally recognized for AC transmission networks, HV usually refers to voltage from 35 to 220 kV, EHV refers to voltage from 330 to less than 1000 kV, and UHV refers to voltage 1000 kV or higher.

For DC transmission, HVDC usually refers to ±660 kV or lower; UHV DC refers to ±800 kV or higher [2,3].

China has established two AC voltage series, namely, 1000/500/220/110 (66)/35/10/0.4 kV and 750/330 (220)/110/35/10/0.4 kV, and a DC voltage series of ±500 (±400), ±660, and ±800 kV. In China, HV networks refer to 110 and 220 kV, EHV 330, 500, and 750 kV, and UHV 1000 kV, which act as the backbone of the transmission network, and UHV DC systems are directly or hierarchically connected to the 1000/500 kV network. China has already constructed 1000 kV UHV AC and ±800 kV UHV DC projects, and it is currently working on ±1100 kV DC transmission technologies. The 1000-kV AC voltage proposed by China has been accepted as an international nominal voltage for UHV AC.

An electrical grid is a network to transfer electricity, like a type of logistics. The basic function of a grid is to transfer electricity from the generation side to the demand side.

Electricity is a secondary energy converted from primary energy sources, such as hydro energy (hydropower generation), thermal energy (thermal power generation), nuclear energy (nuclear power generation), wind energy (wind power generation), chemical energy (battery), and optical energy (photocell, solar cell). Electricity has several features: (i) it cannot be stored in large quantities, because generation, transmission, distribution, and consumption occur instantly; and (ii) generation and consumption must maintain a real-time balance; otherwise, the security, continuity, and quality of electricity will be undermined. Given the high synchronism of electricity, the power source, grid, and consumer must be coordinated to ensure security and quality. Notably, the grid, as the network to transmit and distribute electricity, is a hub that connects dispersed power sources and consumers. The security and quality of electricity must be ensured by properly dispatching, operating, and controlling the grid. The electrical grid plays an irreplaceable role in maintaining the power system security; therefore, it is an essential part of the energy supply system and an infrastructure indispensible to the modern economic development and social progress.

The development and wide use of smart grid technologies are bringing fundamental changes to the configuration and function of modern grids. Originally from a single-purpose means for transferring electricity, the grid is evolving into an intelligent infrastructure platform that is a powerful conduit for allocating energy resources. It is also a significant contributor to energy security, energy conservation and emission reduction, and economic and social development. In the future, the grid will become a market platform that optimizes energy allocation, a service platform that meets diverse needs of customers, and an infrastructure platform that maintains the national energy security.

The grid is a key component of a power system. The power system consists of generating equipment such as boiler, reactor, steam turbine, hydro-turbine, and generator; transforming, transmitting, and distributing equipment such as transformer and power line; consuming equipment such as motor, electric stove, and lamp; and measurement, protection, control, and energy management systems. Combined, these make the electrical power system a unified whole and a huge and complex subject to study [4].

For an electrical power system, the security and stability are the two fundamental conditions needed to operate smoothly. Security means that all the equipment in the system must operate within their permitted amplitude and limit for current, voltage, and frequency. Insecurity may lead to damage of the equipment. Stability means a state in which the power system continuously delivers electricity to the consumers [5].

In electrical power system operation, three stability requirements must be met at all times: power angle stability, frequency stability, and voltage stability. Losing power angle stability will cause system oscillation, drastic and periodic fluctuation of voltage at pilot nodes, and drastic and periodic fluctuation of current and voltage in transmission equipment. The system will no longer be able to feed the load. If poorly handled, the loss of power angle stability may cause a widespread outage. Losing frequency stability will lead to system frequency collapse, and ultimately a complete system outage. Losing voltage stability will result in system voltage collapse, causing blackouts in affected areas. Therefore, security and stability must be considered throughout the engineering, construction, dispatching, and operation of the power system.

1.1.2 History of Grid Development

In 1875, the world's first fossil-fired power plant was built in Paris, which marked the advent of the age of electricity. In 1882, Edison built the world's first commercial power station (660 kW, transmitted power over a 1.6-km-long direct current cable at 110 V) in New York, turning electricity into a commodity. According to Ohm's law, to transfer the same power, the electricity be sent over a long distance with a low loss only by increasing the voltage and reducing the current. Considering safety, the user-side voltage should not be too high, so the voltage has to be decreased after the electricity is transmitted to the users so they could consume electricity safely. If the transmission voltage is not upgraded, then the transmission loss would increase linearly when the distance further expands. With the technologies available at that time, it was difficult to increase or decrease the voltage for DC transmission; therefore, the line loss was huge for long-distance transmission. Nikola Tesla invented the AC technology, which uses voltage that can be easily and economically increased or decreased. This technology makes it possible to increase the transmission voltage and transmit electricity over longer distances through transmission lines. After arriving at the destination, the electrical voltage can be decreased to ensure its safe use [6]. In 1885–1886, Westinghouse constructed the first AC transmission system. In 1895, it built a 35-km transmission line from Niagara Falls Generating Station (with 3×3675-kW hydroelectric generating units) to Buffalo. The electricity was used for lighting and traction, and the technical barriers encountered by the power industry were overcome.

Grid development in different periods shows different technical and economic features, of which voltage class, grid size, generator unit capacity, and operating technology are the most salient. Based on these features, the development history of grid can be divided into several stages [1].

In the decades from the late nineteenth century to the mid-twentieth century, the electrical grid was featured by the use of AC in generation, transmission, and distribution. This was the initial stage that lasted until the end of World War II. At this stage, the generator unit capacity was not more than 200 MW; AC transmission at the voltage up to 220 kV was dominant. The grid was mainly small, urban, and isolated. Operation technologies were still in their infancy, with grid failure and resultant outages regularly seen. Following are the landmark events of the worldwide grid development at this stage:

1. A 35-km transmission line from Niagara Falls Generation Station (with 3×3675-kW hydroelectric generating unit) to Buffalo was built in 1895, which established the dominant role of AC transmission.
2. The 132-, 230-, and 287-kV lines were first built in the United States in 1916, 1923, and 1937, respectively.
3. The first 60-MW turbine generator was built in 1918, and the first 200-MW turbine generator was built in 1929, both in the United States.
4. The Dnieper Hydroelectric Station was put into operation in 1932 in the Soviet Union, with a unit capacity of 62 MW; in 1934, the Grand Coulee Dam Hydroelectric Power Plant was put into operation in the United States, with a unit capacity of 108 MW.

The development of electricity in China almost kept up with the world [7]. In 1879, the first electrical lamp was used for lighting in the Shanghai International Settlement. Then, in 1882, the first electric utility—Shanghai Electric Company—was set up in Shanghai. Since then, China opened the first page of its electric power industry. But the industry was sluggish before 1949. Compared with the rest of the world, it was far more backward. By the time the PRC was founded, the national generation capacity was only 1850 MW, with an annual generation of 43×10^8 kWh. Electricity was available in only a few large cities, and the grids were small but at various voltage classes. In 1908, the 22-kV Shilong Dam Hydropower Station–Kunming line was built. In 1921, the 33-kV Shijingshan Power Plant–Beijing line was built. In 1933, the 44-kV outgoing line of Fushun Power Plant was built. In 1934, the 66-kV Yanbian–Laotougou line was built. In 1935, the 154-kV Fushun Power Plant–Anshan line was built. In 1943, the 110-kV Jingpohu Hydropower Plant–Yanbian line was built. At that time, except the few 154-kV lines in the northeast, the highest voltage was only 77 kV in Beijing, Tianjin, and Tangshan, and only 33 kV in Shanghai.

After World War II, the global economy developed rapidly. Huge electricity needed for industrial production and cheap fossil energies contributed to the boom of the power industry, with unprecedented progress and innovations in grid technologies. The electrical industry was going toward higher voltage, larger generator units, and larger grids. The boom created vast benefits from economies of scale and met the increasing needs of social and economic development.

From the middle to late twentieth century, grids were expanded to form large interconnected systems. The generator unit capacity was increased to 300–1000 MW, and 330-kV (and higher) EHVAC and HVDC transmission systems emerged.

Grid interconnection in Europe and North America began to flourish in the 1950s. By the 1980s and 1990s, large cross-border and cross-region interconnections covering a wide area with large amounts of the electricity exchange took shape. In the 1950s and 1960s, low-cost, highly efficient, large-capacity generation units were introduced, which required large-capacity power grids to accommodate their operation. In the 1970s, a global oil crisis occurred, resulting in greatly increased cost of power generation. In such case, the interconnection of power grids was required to reduce the proportion of oil-based generation. In addition, more coal-based and hydro-based power sources were developed, nuclear power was introduced, the distance between the new power sources and existing load centers was increased, and the various power sources needed coordination. These also required expanding the interconnected capacity and size. In the 1980s, the world economy kept growing for many years; however, the development varied among regions and countries, and so did energy supply and demand. As environmental constraints became stringent, the risk of investing in power source construction increased. As a result, the commissioned generation capacity failed to match the demand. Many countries promoted grid interconnection to achieve higher economic efficiency. In the 1990s, the development of new remote energy bases led to long-distance, large-capacity transmission lines and interconnected lines. Landmark events at this stage include:

1. In 1952, the first 380-kV EHV transmission line was built in Sweden. It is 620 km long and has a capacity of 450 MW, sending electricity produced from Harsprånget Hydroelectric Power Station in north Sweden to the south.
2. In 1954, a 345-kV line was built in the United States, which sent out electricity from Columbia River's hydropower.
3. In 1954, an HVDC transmission line with voltage of ± 100 kV, rated power of 20 MW, and 96 km of submarine cables was constructed between native Sweden and Gotland Island. It uses mercury arc valve commutation technology and is the world's first industrial HVDC project.
4. In 1956, the 400-kV Kuybyshev–Moscow transmission line was put into operation in the Soviet Union, which is 1000 km long. The voltage of the project was upgraded to 500 kV in 1959, and it was the world's first use of 500 kV in transmission.

5. In 1965, the world's first 735-kV transmission line was completed in Canada, which transmitted power from the Manicouagan-Outardes hydroelectric generating complex to Quebec City and Montreal.
6. In 1967, a pilot 750-kV transmission line was built in the Soviet Union; in 1984, a 750-kV line from the Soviet Union to Poland was constructed.
7. In 1969, a 765-kV transmission line was built in the United States.
8. In 1972, the Eel River back-to-back DC project was completed in Canada, which was the world's first DC project to completely use thyristor valves. The DC voltage was 80 kV, and the rated capacity was 320 MW.
9. In 1985, the Soviet Union built an 1150-kV power transmission system to send electricity from the thermal power base in Kazakhstan to Europe, which, because of the collapse of the Soviet Union, was forced to enter segmented operation at a reduced voltage.

After the founding of the PRC in 1949, the voltage grade was unified to form a series. In 1952, a 110-kV transmission line was built with China's own technologies. After this, a 110-kV Beijing–Tianjin–Tangshan transmission network began to emerge. In 1954, the 220-kV Fengman–Lishizhai line was built; afterward, a number of other 220-kV lines, like Liaoning Power Plant–Lishizhai and Fuxin Power Plant–Qingduizi, were built. These lines soon formed the 220-kV backbone network in northeast China. In 1972, the 330-kV Liujiaxia–Tianshui–Guanzhong line was completed, following which the 330-kV backbone network was gradually set up in northwest China. In 1981, the 500-kV Yaomeng–Shuanghe–Fenghuangshan (Wuchang) line was built. To send the electricity produced by Gezhouba Hydropower Station, in 1983, two 500-kV circuits, Gezhouba–Wuchang and Gezhouba–Shuanghe lines, were built, which formed the 500-kV backbone network of central China. Also, 500-kV backbone networks were gradually constructed in north, east, northeast, and south China. In 1989, the ±500-kV Gezhouba–Shanghai DC transmission line was completed, which connected central China and east China network. In September 2005, China's first 750-kV pilot transmission project (Lanzhou East–Guanting (Qinghai)) was completed. After that, the 750-kV Lanzhou East–Baiyin–Yinchuan East transmission project was completed in late 2007, and the Laxiwa Hydropower Station transmission project was completed in early 2008. Based on these, the 750-kV backbone network in northwest China gradually formed. In December 2008, the 1000-kV Jindongnan–Nanyang–Jingmen UHV AC pilot project began a test run. The project connected the north China and central China network with the UHV. In 2010, Xinjiang was connected to the northwest China main grid via a 750-kV line. At the end of 2011, the Qinghai–Tibet grid interconnection project began commercial operation. In 2010, the ±800-kV Xiangjiaba–Shanghai UHV DC demonstration project and ±800-kV Yunnan–Guangdong UHV DC project were completed. In 2012, the ±800-kV Jinping–Sunan UHV DC transmission project was completed.