

Review of the development of multi-terminal HVDC and DC power grid

Y X Chen^{1,2}

¹School of Electrical and Electronic Engineering, North China Electric Power University, Beijing 102206, China

E-mail: cyx@ncepu.edu.cn

Abstract. Traditional power equipment, power-grid structures, and operation technology are becoming increasingly powerless with the large-scale renewable energy access to the grid. Thus, we must adopt new technologies, new equipment, and new grid structure to satisfy future requirements in energy patterns. Accordingly, the multiterminal direct current (MTDC) transmission system is receiving increasing attention. This paper starts with a brief description of current developments in MTDC worldwide. The MTDC project, which has been placed into practical operation, is introduced by the Italian–Corsica–Sardinian three-terminal high-voltage DC (HVDC) project. We then describe the basic characteristics and regulations of multiterminal DC transmission. The current mainstream of several control methods are described. In the third chapter, the key to the development of MTDC system or hardware and software technology that restricts the development of multiterminal DC transmission is discussed. This chapter focuses on the comparison of double-ended HVDC and multiterminal HVDC in most aspects and subsequently elaborates the key and difficult point of MTDC development. Finally, this paper summarizes the prospect of a DC power grid. In a few decades, China can build a strong cross-strait AC-DC hybrid power grid.

1. Introduction

The cross-regional and long-distance DC transmission is an important method to identify the optimal allocation of regional resources. In 1954, Sweden built the first HVDC project, and thus far the world has more than 100 HVDC projects that have been introduced into commercial operation [1]. However, most of them are double - ended HVDC system, which cannot only achieve point-to-point DC power transmission, and when using DC interconnection between the multiple AC systems, we need multiple point-to-point DC transmission lines, which will significantly improve the investment costs and operating costs. Importantly, wind power, solar, and other new energy power generations are intermittent and strongly random. In a word, they are intermittent power supplies. With the large-scale renewable energy access to the grid, the traditional power equipment, power-grid structure, and operation technology are becoming increasingly powerless. As a result, we must adopt new technologies, new equipment, and new grid structure to meet the profound changes in the future energy pattern [2]. Therefore, the multiterminal direct current (MTDC) transmission system developed on double-ended HVDC transmission system has received increasing attention.

2. Research status at home and abroad

As the DC transmission technology continuously develops and becomes increasingly perfect, it



becomes widely used. That is, many countries have become very active on the research of multiterminal DC transmission technology. At present, multiterminal HVDC projects, namely, Corsican – Sardinia (three-ended) and Quebec – New England (five-ended, actually three-terminal on operation) has been introduced into operation; Japanese Chikumagawa three-terminal DC transmission system is the world's first back-to-back system; in addition, Canada's Nelson River bipolar 1 and bipolar 2 DC transmission project and the United States Pacific interconnection DC transmission projects both have the operating mode and characteristics of four-terminal DC transmission [3].

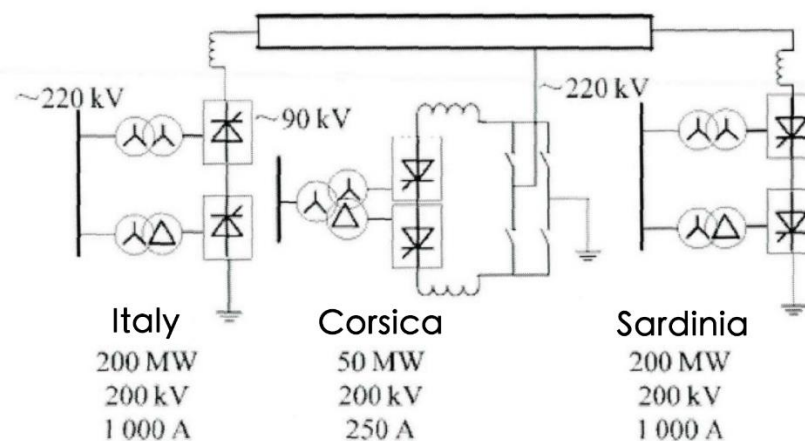


Figure 1. Italy - Corsica - Sardinian three - terminal DC transmission project connection diagram.

According to figure 1, Italy – Corsica – Sardinia three-terminal HVDC project is the world's first official operation of the multiterminal DC transmission project, of which the mode of operation is FM-based. Canada's Quebec–New England five-terminal DC system is the world's largest multiterminal HVDC project, which delivers cheap electricity from the northern Berkshire cascade to the New England power grid in the northeastern United States and the load center in southern Quebec. The project consists of five parts as follows: Radisson, Nikolai, DesCantons, Comerford, and Sundries. Whereas the converter in Radisson can only be operated as a rectifier station, the other converter stations can be operated as either a rectifier station or an inverter station; the project can vary in using two-, three-, four-, or five-terminal operation (usually three-ended operation) based on system requirements.

Japanese Shinano's three-terminal HVDC project is the world's first back-to-back voltage source converter (VSC) multiterminal DC project, which aims to achieve the interconnection of 50 Hz power grid in eastern Japan and the 60 Hz power grid in western Japan. Canada Nelson River four-terminal DC transmission is composed of two bipolar DC transmission systems (Nelson River bipolar 1 and bipolar 2). Under normal circumstances, the bipolar system is under independent operation. If necessary, bipolar line or bipolar converter can be changed to be under parallel operation, which has the characteristics of a multiterminal DC system. In 1970, the US Pacific line at both ends of the DC project was completed, and then new bipolar converter stations are added on either end in the expanded project in 1989. The new stations and old stations are operated in parallel to form a four-terminal DC transmission system [4].

3. Basic characteristics and adjustment methods

3.1. Main form and operating characteristics

In double-ended HVDC system, the two converter stations are parallel because they have a common DC voltage and the converter stations are also considered in series because they pass the same DC

current. When adding new converter stations a problem on whether maintaining a common DC voltage or maintaining the same DC current arises. Therefore, according to the different operating conditions and design requirements, a variety of topologies of the wiring can be formed. In general, wiring can be divided into parallel connection, series connection, and mixed connection, as shown in figure 2, where the parallel can be divided into radial and ring network [3]. Each type of structure has different operating control characteristics, and power allocation can be made through the control of different electricity in the converter station [1].

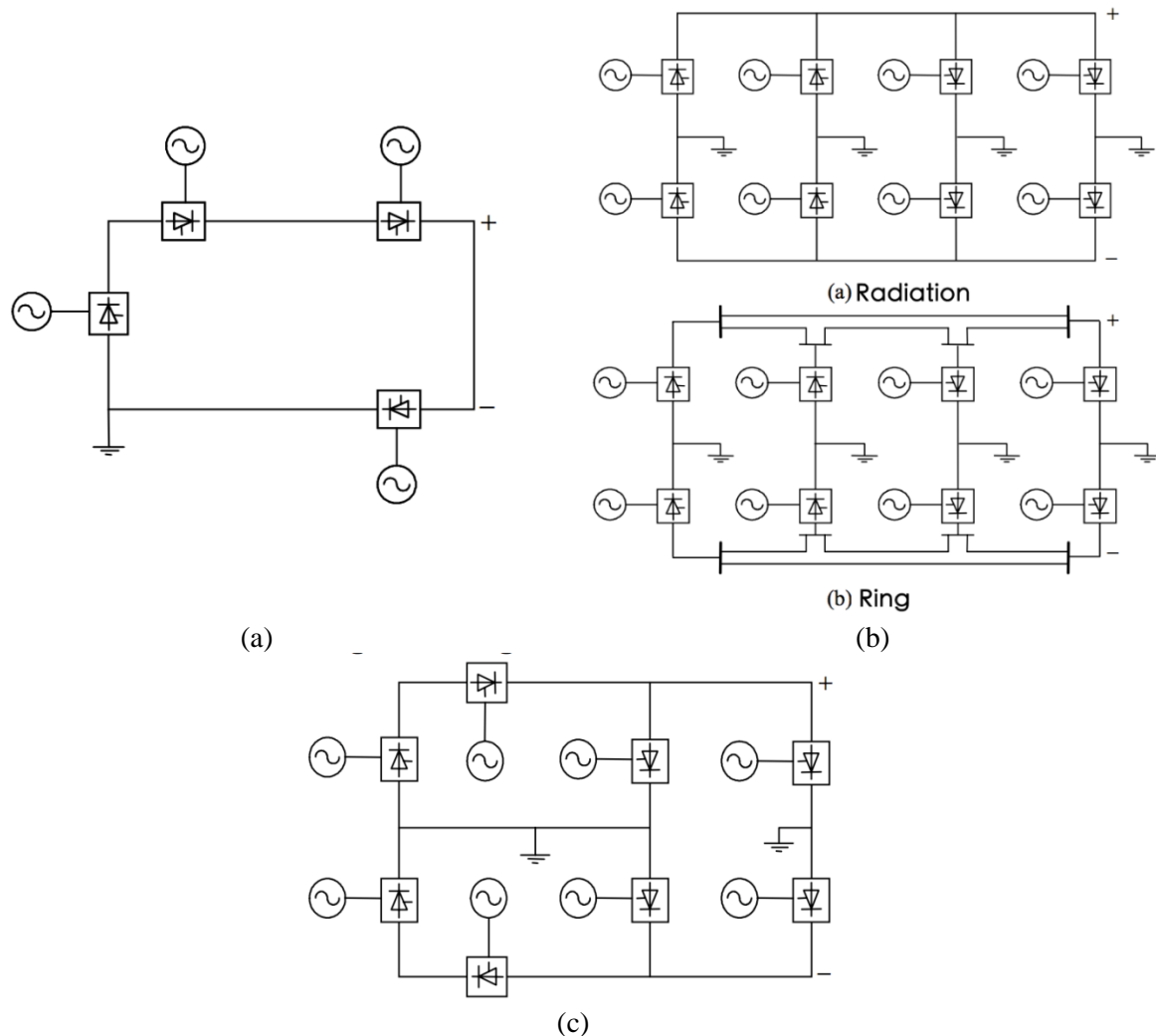


Figure 2. Topology of series, parallel and mixed connection multiterminal DC power transmission. (a) series connection, (b) parallel connection and (c) mixed connection.

The following are the different operation characteristics: parallel converter station run of the same level of DC voltage, power distribution achieving by changing the current of each converter station; series converter station run with the same level of DC current, power distribution achieving by changing the DC voltage of each converter; and mixed type increases the flexibility of the multiterminal DC connection. In the design period, wiring connection should be selected based on investment, loss, reliability, flexibility, and the specific requirements of specific projects [4].

In brief, compared with the series connection, the parallel connection has a smaller line loss, a larger adjustment range, easier to achieve the insulation with a more flexible manner of expansion and outstanding economy. Thus, the current operation of the multiterminal DC transmission project is used

in parallel connection method [1]. The detailed comparison of MTDC system of different topology are listed in table 1.

Table 1. Comparison of parallel and series connected MTDC system.

compared aspect	parallel connection	series connection
active loss	small	large
reactive power demand	small	large
Economy	excellent	not good
Fault recovery speed	fast	slow
energy flow reverse	slow	fast
Extensibility	flexible	complex

3.2. Adjustment method

When the MTDC transmission system uses different wiring methods, the adjustment methods are also different [5]. We are discussing certain basic adjustment methods in this part.

3.2.1. Adjustment of current balance control. This method is a double-ended DC transmission system constant current regulation mode extension, that is, a converter station was used to control the entire DC network's DC operating voltage, all other converter stations are regulated by constant current so that the DC system has a stable operation point.

3.2.2. Constant current and constant voltage regulation mode. As shown in figure 3, when mode I is used, the converter station, which is responsible for voltage control, is running on the constant α or constant γ feature, so that the DC voltage changes when the AC side voltage fluctuates. Although the automatic adjustment function of the converter transformer tap can reduce the range of this fluctuation to a certain extent, the adjustment speed is slow and discontinuous. If the system has strict requirements on the DC voltage, then a DC voltage regulator should be added at the control station of the control voltage and should be changed to constant voltage operating mode during normal conditions.

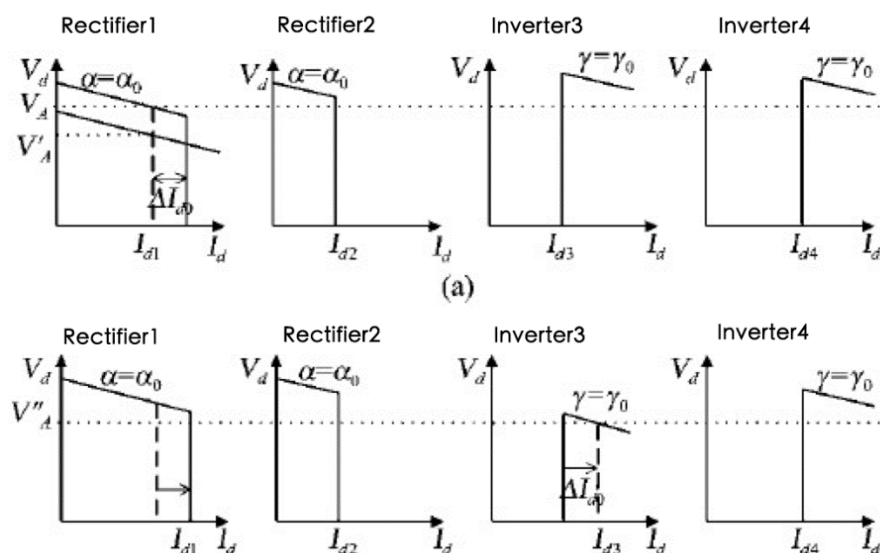


Figure 3. Current margin control [6].

3.2.3. Limited voltage regulation mode. Limited voltage adjustment mode is suitable for situations where a large number of converter stations exist, and the characteristics of the converter station are

composed of both constant voltage and constant current (inverter station also set δ) and other multi-segment composition. The voltage of the DC system is controlled by a rectifier station and is maintained at the rated value. The remaining converter stations are operated in the constant current mode. If the converter station that controls the DC voltage broke down, which leads to the decrease in the DC voltage at this end, the control of the DC voltage will be given to other station to complete, and this station is changed to the DC current control mode.

3.2.4. Basic adjustment method of series connection MTDC transmission system. Series connection multi-terminal DC transmission system is characterized by various converter stations and lines of the same DC current; the use of constant current operation mode is appropriate. To ensure that the DC system has a stable operating point, we frequently selected a converter station to be the constant current mode, with the remaining converter stations being set by constant a or constant d adjustment. This adjustment method is relatively simple, and the total amount of reactive power consumption in the converter station is also minimal.

4. Key technology overview and characteristic analysis

MTDC transmission system is a kind of DC transmission mode developed on the basis of double-ended DC transmission. Therefore, most of the technologies used in traditional DC transmission can be applied to MTDC transmission system. However, the particularity of MTDC transmission network topology and function is different from the double-ended DC transmission in the selection of circuit breaker equipment, basic control mode, coordinated control, power flow calculation, stability, and reliability analysis. This occurrence must be further explored and analyzed. The MTDC transmission technology research also focused on these aspects at home and abroad. The following will review several key issues including circuit breaker equipment, basic control and protection, coordination control and stability analysis of the domestic and foreign MTDC transmission technology.

4.1. Circuit breaker equipment

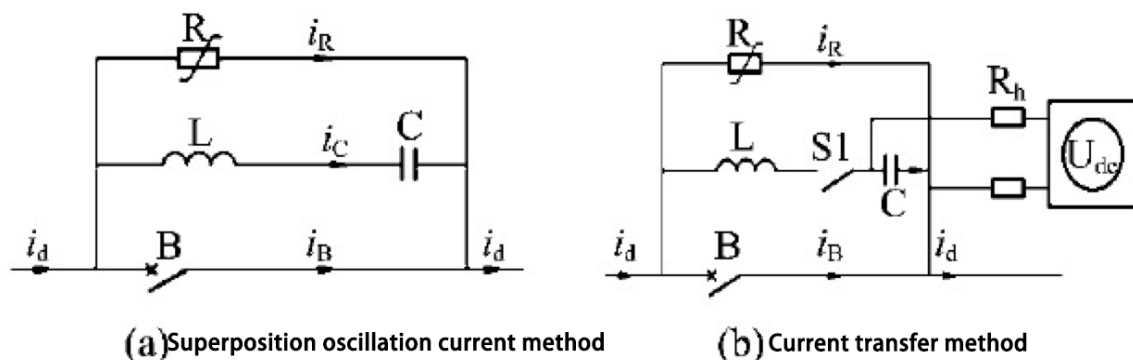


Figure 4. Principle of DC circuit breaker.

The thyristor rectifier has the ability to rapidly cut-off the current. Thus, in the double-ended DC transmission system, the DC outage can be completed through the rectifier rather than the DC circuit breaker. However, if traditional method of processing is used for multiterminal HVDC systems, we should make short-term outage of the entire multiterminal DC system to clear the fault, which will lead to its connected AC system influenced by a greater effect especially on the weak exchange system. Therefore, a high-voltage DC circuit breaker should be installed on a multiterminal DC system, similar to the AC system, to cut-off the fault current and clear the fault. This occurrence will significantly reduce the recovery time after the failure, and shutting down the entire multiterminal DC system is not necessary. However, the DC current does not have natural zero-crossing, which should be forced to zero, and at simultaneously we should consider both the arc time and system over-voltage, thus

breaking the AC current is much more difficult than breaking the DC current. High - voltage DC circuit breakers are now the bottleneck of the development and application of multi - terminal HVDC technology [4].

Two main exist for high-voltage DC circuit breaker to break the DC current [7,8] as shown in figure 4.

4.1.1. Superposition oscillation current method. The method utilizes the negative resistance characteristic of the arc and superimposes an oscillating current with increasing amplitude in the DC current to make the "artificial current zero point" to complete the DC current breaking. However, when the arc current increased to a certain extent, its negative resistance characteristics become less obvious, which cannot guarantee that the oscillation current can reach the amplitude that can make zero point. Thus, the type of circuit breaker's breaking current capacity has certain restrictions. However, it has become the most practical application of the current type of DC circuit breaker because of its simple structure and easy-to-control characteristic.

4.1.2. Current transfer method. This method produces a "manual current zero" by a precharged capacitor discharging to produce a current that is opposite to the direction of the system current. Using this principle, the circuit breaker can break the larger DC current with shorter breaking time, but the control of this type of circuit breaker is more complex, which brings less reliability.

4.2. Basic control and protection

Compared with AC transmission, DC transmission has the ability to quickly adjust the power flow distribution, single pole failure in another pole's overload conditions can induce power transfer that can be achieved provided that single pole fails with another pole's overload ability to minimize the loss of transmission power. However, this rapid adjustment characteristic cannot be separated from the controller with superior performance. The traditional DC transmission controller usually provides the converter station with a constant current controller as the main controller and is equipped with a constant α control (minimum α) as a backup control to regulate the DC current under normal operating conditions. The inverter station is equipped with a constant set-off angle or a constant voltage controller as the main controller and is equipped with a constant current controller that considers the current margin. It is used to control the DC voltage under normal operating conditions. The basic control characteristics are shown in figure 5.

In terms of protection, the multiterminal DC transmission is more complicated than the double-terminal DC transmission. This complexity is reflected in the reasonable setting of the measuring point position, the accurate judgment of the fault type and fault location, and the choice of the system running mode after failure. A good protection program should ensure that the system after the failure can ensure non-fault system to continue to run to reduce the load loss as much as possible while ensuring the impact of the equipment within the limitation [1].

4.3. Coordination control

The biggest difference between MTDC system controller and the double-ended DC transmission system is the coordinated control. Different from the pairs of converter stations of DC transmission, the control methods of MTDC system multiple converter station in the aspects of start and stop, normal operation, and accident under the coordination become a new problem. Take the parallel-connected MTDC system for example, during the process of start and stop process in synchronization of the whole station, you should consider how to meet the trigger time of all the converter stations and how to adjust the lift speed of the current setting value; in the single station start and stop processes, the power distribution problem with station stopping and the other station start and stop process not yet started. Under normal operating conditions, only one converter station controls the DC voltage, whereas the remaining stations control the DC current flowing through the station. When the DC current setting value changes, the balance of the power distribution of the whole system is necessarily

reconsidered. In the fault conditions, the reallocation of power after a station or a pole quitting should also needed be considered. The coordination of such systems is the new problem of MTDC system controller design, which should be based on a power coordination program, and a coordination controller should coordinate the station setting value and operation mode.

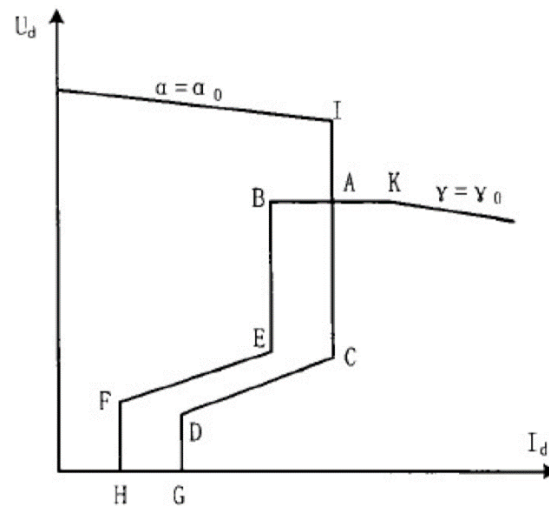


Figure 5. The basic control characteristic of double-ended DC transmission system.

Four-terminal HVDC system take two steps to transit from the outage state to the running state:

- synchronous start-up: all converter station normally unlocks simultaneously and transit to the running state;
- asynchronous start-up: a rectifier station together with an inverter station unlocks at first, when the double-ended system run into a stable state, another rectifier station or inverter station unlocks to form a three-terminal system, and finally the remaining converter station unlocks to constitute a four-terminal system.

The purpose of the system-starting control is to make the whole system start the power transmission under the minimum transient fluctuation and make the power flow of the AC system connected with the rectifier station and the inverter station increase steadily.

Valve-unlocking sequence control design: the inverter side unlocks at first, obeying the order to shift phase for 164 degrees to unlock α corner; receiving the message that the inverter side has unlocked, the rectifier side should operate similar to the inverter side, which indicates that it should place the smallest filter group and unlock α corner with 164 degrees.

Four-terminal HVDC system takes one step to transit from the running and transit into the outage state:

- multi-station asynchronous outage: a rectifier station or inverter station locks at first to form a three-terminal system, and then the remaining converter station locks to ensure that the remaining stations can work on double-ended operation. Finally, according to conventional DC system, the rectifier station and the inverter station lock simultaneously.

4.4. Stability analysis

The stability analysis method of multiterminal HVDC can be analogous to the steady-state analysis method of power system. The MTDC transmission system is linearized near the operating point, and then the nonlinear equation of state of the whole system is transformed into the state equation. The stability of the system is examined by eigenvalue analysis in algebraic equation analysis. However, this method is more of deviation; the practice use is infrequent [9].

5. Fault characteristics

5.1. DC fault characteristics

- Conducting fault location based only on local data. In the AC system, the fault location is measured by distance protection that measures the impedance value. However, the DC system fault position cannot be determined by measuring the impedance.
- For VSC-MTDC systems, the ability of the IGBT to withstand overcurrent and over-voltage is limited. At the same time, given that the DC network will also supply fault current in the AC system failure, possibly causing DC protection malfunction, which is contrary to the principle of selective characteristic.

5.2. DC fault solution

Option 1: IGBT circuit breaker with high-speed DC switch to form a DC network. In this topology, all VSCs are blocked during DC faults and are isolated from the faulty lines by IGBT circuit breakers. The DC fault is removed by high-speed DC switch, and then IGBT circuit breaker closes, VSC restarts, and the system resumes operation.

Option 2: AC circuit breaker with high-speed DC switch. The installation of costly IGBT DC circuit breakers is not required under this type of topology, but all VSCs must also be locked under DC faults. The following operation is similar to Option 1.

Option 3: Hybrid networks. A small number of IGBT circuit breakers are only installed on some of the selected DC line connection points, faulty subsystem will be isolated under DC faults to ensure the normal operation of other subsystems. This scheme is suitable for large-scale DC networks (such as large offshore wind farms). However, even if the faulty subsystem is isolated, whether the non-defective subsystem has sufficient voltage support should still be explored.

6. DC power grid

The possible topology of the future development of a multiterminal DC system is shown in figure 6, which is the simplest form of a multiterminal HVDC system. It introduces multiple converter stations out of the AC system, which connects different AC systems with multiple point-to-point DC interconnections. Multiterminal DC does not form a grid thus shows no redundancy; as a result, it is improper to be called a network. When any of the converter stations or lines in the topology malfunction, the entire line and the converter stations connected to both sides of the line will be completely out of operation, and thus the reliability will be low.

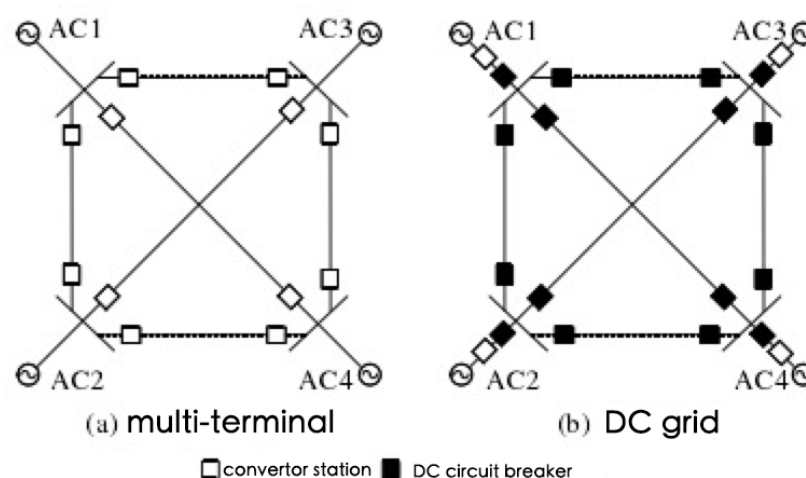


Figure 6. Topology of multi-terminal DC power transmission.

If the DC transmission line is connected in the DC side, the formation of "one-to-many" and "many-to-one" will be formed, and finally exact DC power grid is formed. As shown in figure 6(b), each AC system connects to the DC network through a converter station. Each converter station is connected to each other in multiple DC lines with high voltage DC circuit breakers. When a fault occurs, the circuit breaker can be used to selectively remove the line or converter station. The real DC power grid has the following characteristics:

- The number of converter stations can be significantly reduced. Only one converter station is required to set up at each connection point with the AC power grid, which cannot only significantly reduce the construction costs, but also reduce the overall transmission loss;
- Each converter station can separately transmit (transmit or receive) the power and can change their transmission status from transmission / reception to reception / transmission without affecting the transmission status of the other converter stations;
- More redundancy. Though in a line outage, other lines can still be used to ensure reliable power delivery.

The DC power grid will be an intelligent stable AC-DC hybrid wide-area transmission network with advanced energy management systems. In this network, different clients, existing transmission networks, microgrids, and different power supplies can obtain effective management, optimization, monitoring, control, and timely response to any power problems. It integrates multiple power supplies and transmits and distributes electrical energy over thousands of kilometers with minimal loss and maximum efficiency [2].

7. Conclusion

Compared with the double-ended DC transmission, multiterminal DC transmission system in the following occasions will be more economical and more flexible:

- From the energy base to a number of load centers in the distance;
- Connecting load or power supply to the middle of the line of the DC transmission;
- Several isolated AC systems that use DC transmission lines to achieve non-synchronous communication between the grids. In addition, with the power electronic full-controlling switching device technology and the new DC transmission technology becoming increasingly mature, multiterminal DC transmission in the distributed power generation, renewable energy power generation, and urban DC power distribution..

R & D, manufacture, and improvement of the practical DC circuit breaker in HVDC transmission project is the key problem that must be solved urgently in the development of multiterminal HVDC technology.

Multiterminal DC transmission is a phase of the development of DC grid, which helps achieve multi-power supply and multi-drop power. The DC transmission line is connected to each other in the DC side to form an exact DC power grid. The DC power grid has significantly reduced the number of converter stations that can transmit power separately, and the transmission status can be flexibly switched. In addition, the DC power grid has high reliability.

References

- [1] Hu Y R 2013 Study on some problems of multi - terminal HVDC transmission system (Zhejiang: Zhejiang University)
- [2] Tang G F, Luo X and Wei X G 2013 Proceedings of the Chinese Society for Electrical Engineering **33** 8-17
- [3] Han X 2011 Study on steady - state characteristics of multi - terminal HVDC transmission system (Beijing: North China Electric Power University)
- [4] Zhang W L, Tang Y and Zeng N C 2010 *Power System Technology* **1** 1-6
- [5] Yuan X F and Cheng S J 2006 *Power System Protection and Control* **34** 61-7
- [6] Tu Q R and Xu Z 2009 *East China Electric Power* **37** 267-71
- [7] Xu G Z 2000 Principle and Application of High Voltage Circuit Breaker (Beijing: Tsinghua

- University Press)
- [8] Zheng Z F, Zou J Y, Dong E Y and Duan X Y 2007 *High Voltage Apparatus* **42** 445-9
 - [9] Padiyar K and Geetha M 1991 Study of torsional interactions in multiterminal DC systems through small signal stability analysis *AC and DC Power Transmission* **29** 411-3