Research and Simulation Analysis of Systematic Voltage Fluctuation in DC Commutation Failure

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Abstract: The failure of high-power DC commutation leads to large fluctuations in the voltage of the transmitting end grid, which brings great harm to the safe and stable operation of the transmitting end grid. In this paper, the detailed analysis of PMU data is carried out for the voltage fluctuation events of the transmitting end caused by the frequent DC commutation failure in recent years. By constructing a simulation model in BPA and RTDS, the fault back-tracking of the voltage fluctuation of the power supply with the commutation failure is carried out. The simulation results show that the main cause of the fluctuation is caused by the timing coordination and the delay of the rectification side AC filter. This is of great significance for reducing voltage fluctuations in the case of subsequent DC system commutation failure, and it also has great significance for maintaining safe and stable operation of the power grid.

1. Introduction
In order to reduce the risk of large-scale power outages in the power grid and enhance the controllability of the impact of large-scale power grid accidents, in 2016, China Southern Power Grid proposed to use Yunnan Power Grid as a separate transmitting power grid in the medium- and long-term grid planning, and implemented the main network of China Southern Power Grid. Asynchronous networking operation [1-3]. The problem of DC transmission line after asynchronous networking has become a major problem that plagues the safe and stable operation of China's power grid.

In recent years, voltage fluctuations have often added a lot of trouble to industrial production, scientific research and daily life, sometimes damaging equipment and causing accidents. With the rapid development of modern science and technology, the increasing popularity of electronic computers and various electronic devices, the quality of supply voltages in factories, mines, scientific research, post and telecommunications, and hospitals are getting higher and higher. However, due to the large amount of impact load, intermittent load, and various short-circuit faults in the power supply system, attempts to cause the system voltage to change rapidly and rapidly, that is, voltage fluctuations. DC voltage fluctuation is one of the difficulties that plague the safe and stable operation of the DC transmission system of the Southern Power Grid. Through a large amount of research and practice [4-6], the operation and maintenance unit has gradually mastered the abnormal causes and possible effects, not only taking the action. Effective improvement measures to avoid the adverse effects of DC voltage fluctuations on the operation of the system as much as possible, and also to develop corresponding maintenance plans. A large number of practices have proved that these overhauls can quickly and accurately identify and eliminate fault points under the conditions of system operation, which is of great significance for maintaining safe and stable operation of the power grid.

Literature [4-6] has confirmed the root cause of the abnormal fluctuation of high-voltage DC voltage caused by the failure of the photoelectric sensor in the high-voltage DC voltage measurement loop through a lot of research and practice. The literature [4,7] carried out simulation analysis on the abnormal voltage fluctuations of Tianguang and Niu Cong from the DC transmission system, and analyzed the causes of abnormal voltage fluctuations. In the literature [8], a DC voltage fluctuation suppression method suitable for modular multilevel converter HVDC transmission system (MMC-HVDC) is proposed for the defects of the DC voltage fluctuation suppression algorithm in flexible DC transmission systems. Thus, the MMC AC side current remains symmetrically operated while the DC side voltage, current and power remain constant. Literature [9] analyzed the phenomenon of several outages caused by the action of the valve protective triggering function caused by the high voltage DC voltage fluctuation of the rectifier side of a DC transmission system. It is proposed that the DC line voltage measurement system needs to be modified to solve this problem. In [10], the mechanism of voltage fluctuation was studied and verified by constructing a high-voltage DC actual control protection device in RTDS. The change in internal resistance at the time of sensor failure is the direct cause of DC voltage fluctuations.

In August 2018, a DC system of Yunnan Power Grid failed to commutate, which led to fluctuations in the voltage of Yunnan Power Grid. This incident caused great concern of relevant personnel. In this paper, the voltage fluctuations after this commutation failure are simulated and analyzed in RTDS and BPA respectively, and compared with the PMU observation data. The main reason leading to this voltage fluctuation is the timing matching and the rectifier side AC filter triggered by the delay.

2. Voltage fluctuation

The ideal state of the power supply system is that the three-phase AC power supply should be symmetrical, the voltage rms value is constant, and the load characteristics are independent of the system voltage level. This requires ensuring that the user's load is distributed in three-phase balance, and that the power is absorbed at a constant power. At the same time, it is necessary to ensure that the common connection point has an infinite short-circuit capacity, and the equivalent reactance of the system is zero. However, in the actual operation process, it is impossible to meet such conditions. Generally, the voltage of the power supply system changes from time to time. Therefore, the voltage rms value cannot be kept constant [11], or the actual voltage and system. The phenomenon in which the nominal voltage deviates is collectively referred to as voltage fluctuation. Its value d is often expressed as a percentage of the ratio of the difference ΔU between the two adjacent extreme values U_{max} and U_{min} (which are the root mean square values) to the nominal value U_N. which is

$$d = \frac{\Delta U}{U_{\mathrm{N}}} \times 100\% \tag{1}$$

The number of voltage fluctuations per unit time is usually called frequency, expressed in r, and the unit is min^{-1} or s^{-1}. There are various reasons for voltage fluctuations. Short circuit faults in power systems or switching of large rectifier devices and reactive power compensation devices may cause fluctuations in plant voltage.

Since the volatility load frequently uses the rapidly changing electric energy from the power distribution system during the operation, the impact power change occurs, causing the voltage of the common connection point to fluctuate rapidly in a short time and obviously deviate from the nominal voltage. value.

Voltage fluctuations are an important indicator of power quality. Rapid voltage fluctuations can degrade the performance of electrical equipment, the length of time that automatic remote devices and electronic equipment work, the inferior quality of products, and the long-term flashing of lighting. With the development of production automation and intelligence, the level of electrification continues to increase, and voltage fluctuations have caused widespread concern.

3. Data Analysis

This paper builds a schematic diagram of the grid structure of a DC system in Yunnan Power Grid as shown in the Figure 1.

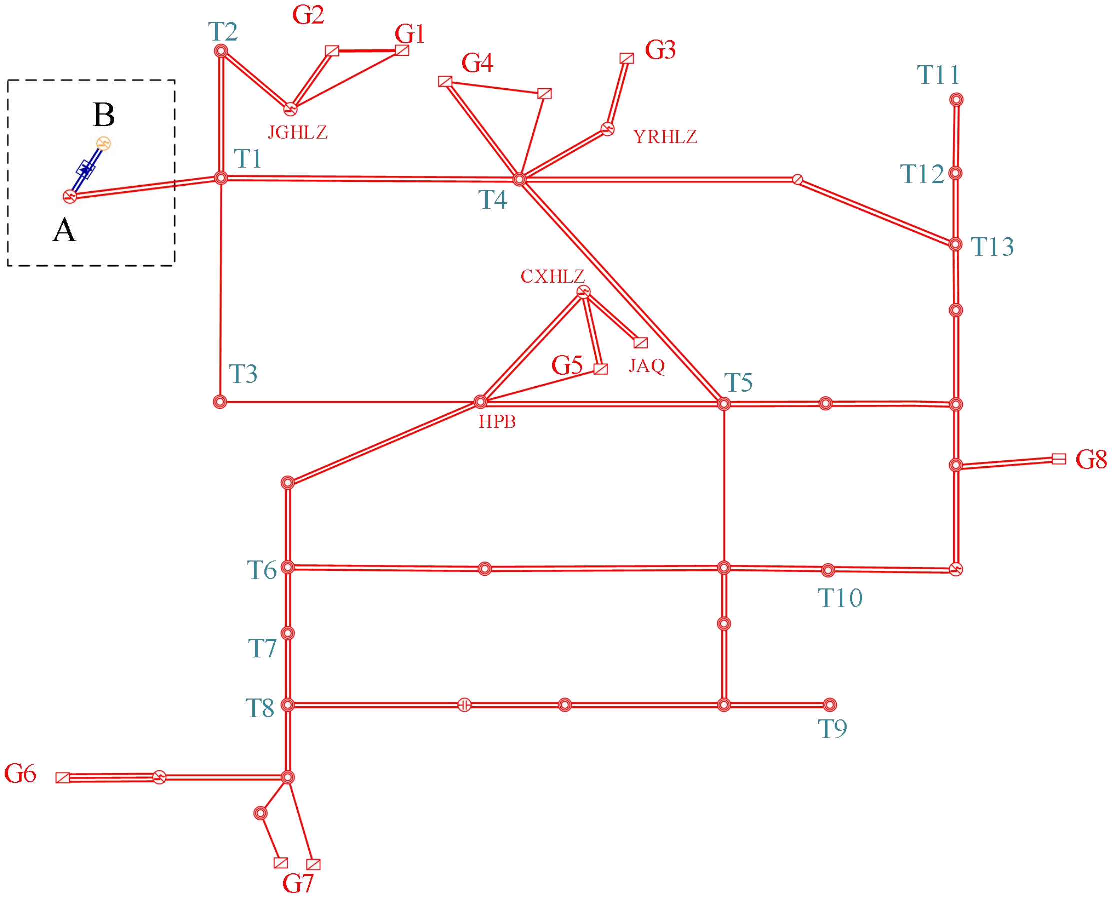

Figure 1. Yunnan power grid structure diagram.

Among them, G1-G8 is a power plant, and T1-T13 is a substation. This paper compares the voltage changes of these stations and the subsequent analysis of the voltage fluctuations of these plants in the case of commutation failure through BPA and RTDS. The main reason for voltage fluctuations is obtained.

3.1. Power Plant Voltage Fluctuation Analysis

By reading the PMU data, the voltage fluctuations of the DC power supplies are as follows.

Table 1. Power plant voltage fluctuations.

Measuring point	Us（kV）	U_{min}	T_{min}（s）	U_{max}	T_{max}	ΔU
G1	310.30	285.8	29.39	331.8	29.45	46.0
G2	309.95	281.7	29.39	333.3	29.45	51.6
G2	312.82	294.3	29.39	324.2	29.45	29.9
G4	303.26	288.2	29.38	317.2	29.44	29.0
G5	311.64	295.6	29.38	318.3	29.44	22.7
G6	309.79	302.6	29.38	316.0	29.98	13.4
G7	308.26	302.6	30.38	313.3	30.95	10.7
G8	310.09	299.5	29.37	316.3	29.43	16.8

The voltage fluctuation ΔU is the difference Us between U_{max} and U_{min} is the steady state value of the voltage, the unit is kV, U_{min} is the voltage minimum value, U_{max} is the voltage maximum value, T_{min} is the voltage minimum time, and T_{max} is the voltage maximum time, the unit both are seconds, and the starting time of voltage fluctuations of each power plant is basically the same, between 209.34-209.37.

It can be seen from the above table: (1) It can be seen from the table that the power point close to the DC line has a significant voltage amplitude, and the voltage fluctuation amplitude is relatively small from the power point far from the DC line. (2) The voltage reaches a minimum value after 0.02 seconds (corresponding to time 29.38), and reaches a maximum value after 0.06 seconds (corresponding to time 29.44), indicating that the voltage adjustment is basically synchronized. The distance of the power plant is shown in Figure 1. The time lag of the maximum G6 and G7 power plants far from the DC line reaches the maximum at 29.98 and 29.95 (minus 1 second timing error). Figure 2 is a comparison of the voltage fluctuation curves of G2 and G6. It can be seen from the figure that the voltage trends of the front end of the two power plants are the same, so the possible reason for reaching the maximum value after the G6 and G7 is that the voltage fluctuation of the near-end unit of the DC line is clear. Clear, and the remote unit has a small adjustment range. With the reactive power distribution and voltage change, the voltage regulation will reach the maximum value after the disturbance.

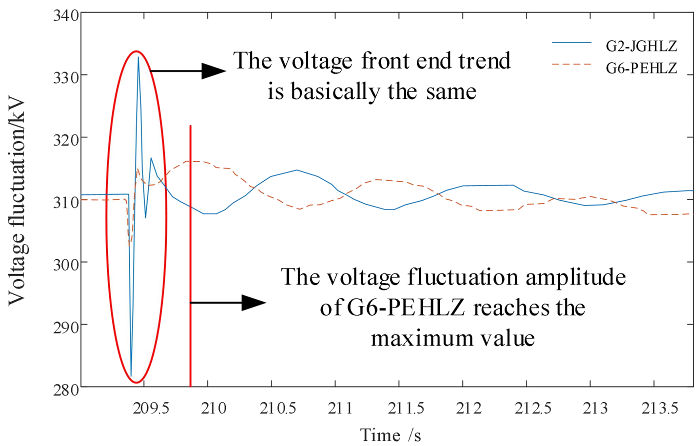

Figure 2. Comparative Analysis of Voltage Fluctuation Curves between G2 and G6.

(3) The voltage fluctuation of the DC near-end unit is the largest, and the voltage fluctuation of the unit farther from the DC line is smaller. The voltage fluctuations from large to small are: G2, G1, G3, G4, G5, G8, G6, G7.

3.2. Analysis of substation voltage fluctuation

Table 2. Substation voltage fluctuations.

Measuring point	Us(kV)	U_{min}	T_{min}(s)	U_{max}	T_{max}	ΔU
T1	308.007	252.0	29.38	344.8	29.44	92.8
T2	307.292	263.3	29.37	338.4	29.43	75.1
T3	288.68	278.8	29.37	288.7	29.4	9.9
T4	306.212	284.6	29.38	322.2	29.44	37.6
T5	310.145	294.7	29.37	318.7	29.43	24.0
T6	308.624	298.0	29.38	314.2	29.44	16.2
T7	310.149	302.5	29.37	315.4	29.44	12.9
T8	309.97	304.1	29.38	314.8	29.44	10.8
T9	309.894	305.9	29.39	315.6	29.45	9.7
T10	310.976	300.2	29.38	316.8	29.44	16.6
T11	311.316	303.1	29.38	315.1	29.8	12.0
T12	312.813	303.0	29.38	316.0	29.44	12.9
T13	313.156	300.5	29.38	318.6	29.44	18.1

Parameter meaning as described above and the voltage fluctuation start time of each substation is basically the same, between 209.35-209.37.

It can be seen from the above table: (1) The voltage reaches a minimum value after 0.02 seconds (corresponding to time 29.38), and reaches a maximum value after 0.06 seconds (corresponding to time 29.44), indicating that the voltage adjustment is basically synchronized. (2) The time lag of T11 which is far from the DC line reaches the maximum value, and reaches the maximum value at 29.8. Figure 3 is a comparison of the voltage fluctuation curves of T1 and T11. It can be seen from the figure that the voltage changes of the front end of the two substations are consistent. Therefore, the possible reason for reaching the maximum value after the T11 is that the voltage fluctuation of the near-end substation of the DC line is clear and clear. However, as the remote substation changes with the reactive power and voltage, the voltage regulation will reach the maximum value after the disturbance.

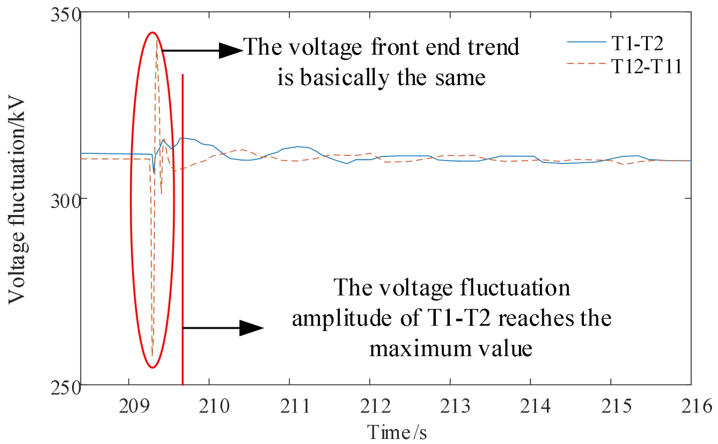

Figure 3. Comparative Analysis of Voltage Fluctuation Curves between T1 and T11.

(3) The voltage fluctuation of the near-end substation of the DC line is the largest, and the voltage fluctuation of the substation is farther away from the DC line. The voltage fluctuations from large to small are: T1, T2, T4, T5, T13, T10, T6, T7, T12, T11, T8, T3. It should be noted that the steady-state voltage of T3 itself is low, only 288.68kV. During the voltage fluctuation process, the voltage only has a falling process and there is no rising process. Therefore, it is not considered in the comparison of voltage fluctuations.

It can be seen from the table that the magnitude of the voltage fluctuation depends mainly on the distance of the plant. The closer to the DC line, the greater the voltage fluctuation of the plant station. It can be seen from the voltage fluctuation diagram that after about 4-7 cycles of fluctuation, the voltage fluctuation subsides and gradually disappears.

3.3. Effect of Commutation Failure on Reactive Power and Voltage of Rectifier Station

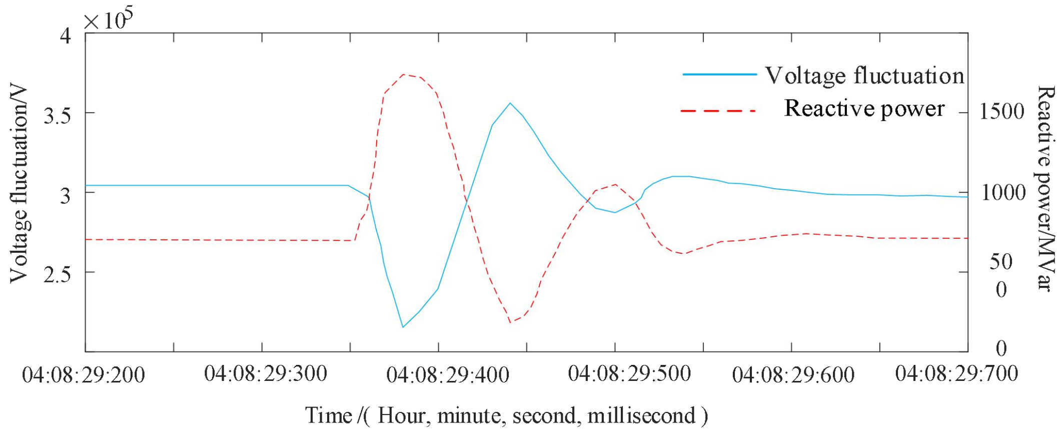

Figure 4. Switching voltage and reactive power of A Converter Station.

Figure 4 shows that when the commutation voltage is reduced, the reactive power is absorbed from the system, and when the commutation voltage is increased, the reactive power is delivered to the system.

From the view of the reactive power of the Xinping double line, it also shows that the DC commutation fails, resulting in a voltage drop on the rectifier side. The system fills the reactive power through the Xinping double line; after the DC power drops to 0, the commutation voltage rises. High, the reactive power is delivered to the system side; the commutation failure ends, the DC voltage is restored, and the system and the commutation voltage are restored. The power of each station is positive as it flows into the plant, and the flow station is negative.

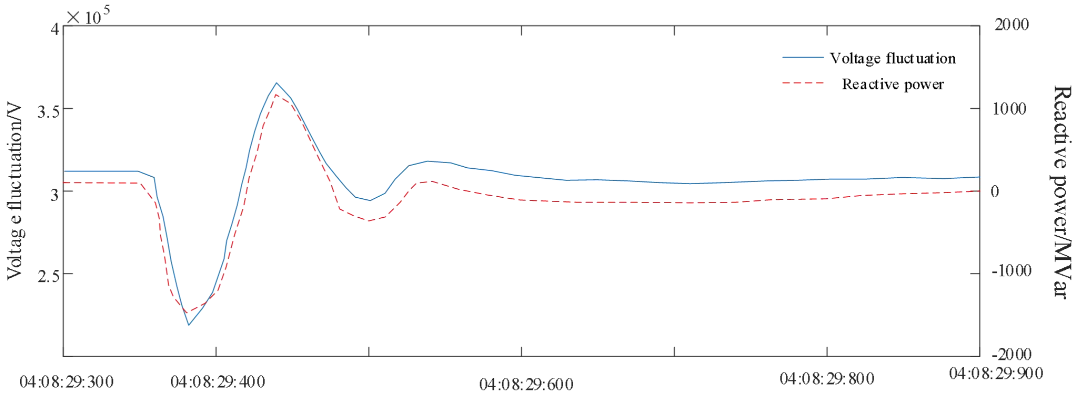

Figure 5. Xinping A line voltage and reactive power observed from A Converter Station.

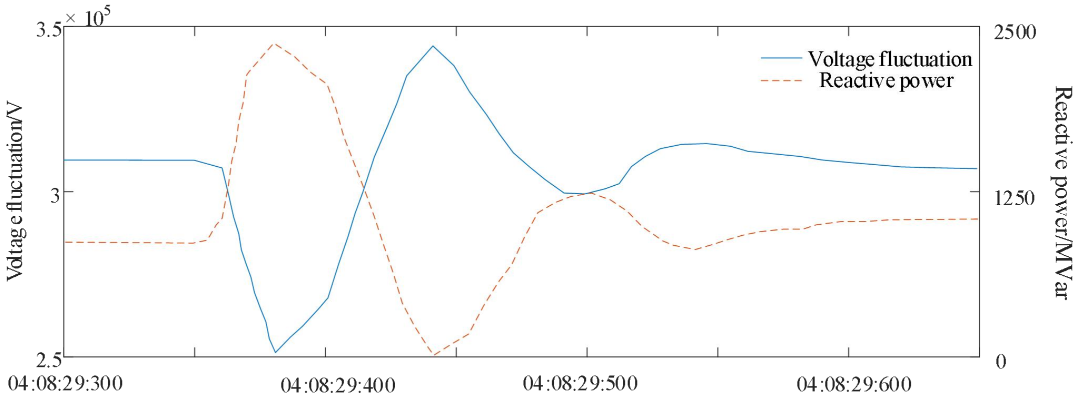

Figure 6. Xinping A line voltage and reactive power observed from T1.

It can be seen from Figures 5 and 6 that after the commutation failure, the DC voltage is reduced, the reactive power is changed from T1 to A, and the new Songs voltage rebounds in the later period, and the reactive power flows from A to T1.

Judging from the voltage fluctuations of other stations in the whole network, the basic and the failure of the commutation are basically the same, and the voltage fluctuation of the whole network is basically judged by the failure of the DC commutation. In addition, the voltage fluctuation caused by the commutation failure is generally unidirectional, and there is a positive or negative offset in the new loose voltage fluctuation.

4. RTDS and BPA simulation analysis

It can be seen from the table that the magnitude of the voltage fluctuation depends mainly on the distance of the plant. The closer to the DC line, the greater the voltage fluctuation of the plant station. As shown in the figure, the darker the color, the closer the voltage is to the DC terminal, and the greater the voltage fluctuation generated.

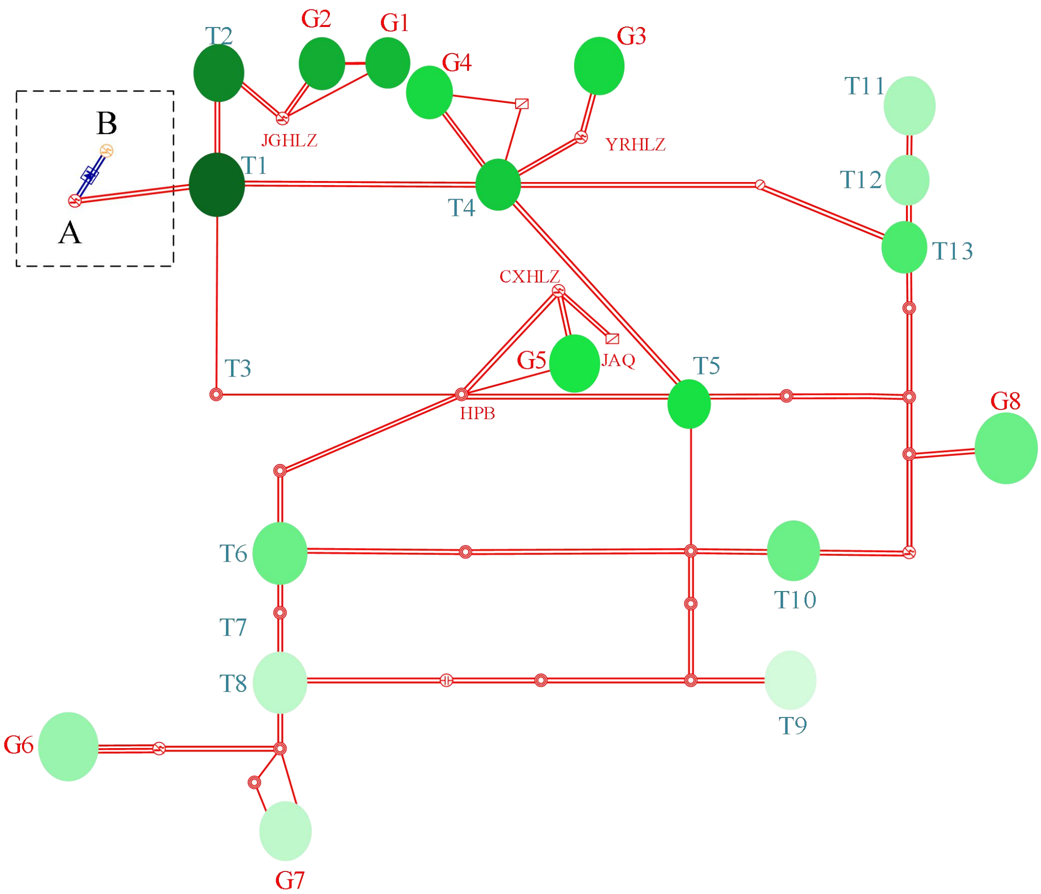

Figure 7. Voltage fluctuation intensity map.

(1) BPA-based system simulation

In the BPA, the actual operating conditions are established and simulated, and the waveform is shown in Figure 7.

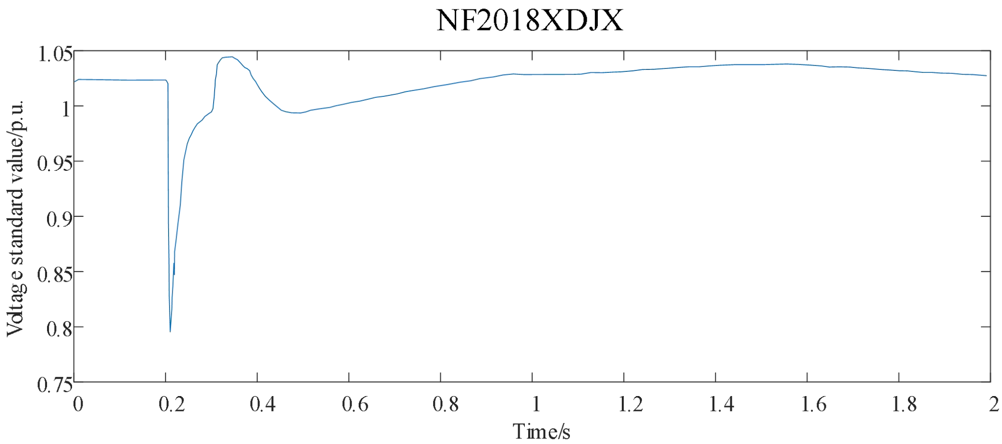

Figure 8. BPA-based DC commutation failure recurrence.

The simulation results show that the BPA-based electromechanical transient simulation can not reproduce the systematic voltage fluctuation, and can only characterize the voltage and current when the DC commutation fails. The lowest point voltage is 0.8pu, which is approximately 100kV, which cannot reflect the DC power. Electromagnetic transient voltage fluctuation process caused by electronic devices.

(2) Closed-loop simulation of DC control and protection based on RTDS

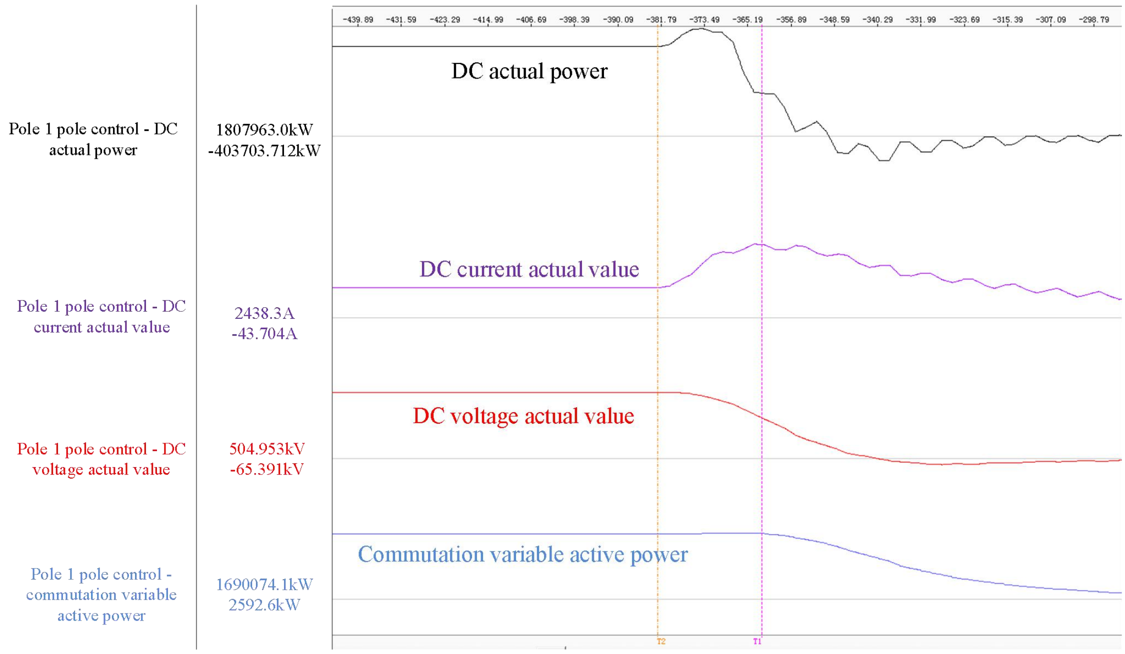

Figure 9. DCDS-based closed-loop simulation of RT control.

The closed-loop simulation result of DC control based on RTDS is shown in Fig. 8. At the time of T1, the DC system is reduced due to the failure of the AC system, and the DC commutation fails. However, the DC current rises first and then decreases, and the actual DC power is raised first. Decrease, at time T2, the DC current reaches a maximum value, and the time difference from T1 to T2 is approximately 20 ms.

The above simulation results show that there is a time difference between the attenuation of DC power and DC current and the attenuation of DC voltage. In the initial stage of commutation failure, the voltage drops, and the DC transmission power does not fall and rises due to the increase of DC current. It needs to absorb more from the system. The reactive power supports DC operation. At this time, the DC is characterized by absorbing more reactive power into the system. At the same time, the reactive power always flows from the point where the voltage is high to the point where the voltage is low, which intensifies the filling of the reactive power of the system. Due to the increase of reactive power between DC and system switching, the AC filter input command is issued, and the actual input is made after the delay. After T2, the DC current and DC current are rapidly attenuated to 0, the DC reactive power demand is reduced to 0, the AC filter is out of time, and a large amount of reactive power is output to the system. The AC filter with delayed input will increase the overflow of reactive power. After the commutation failure ends, the DC power is restored to the original value, the reactive power demand is restored to the original value, and the reactive power and voltage fluctuation processes are completed.

5. Conclusion

(1) The magnitude of the fluctuation of the voltage of the transmitting end grid caused by the failure of DC commutation depends mainly on the distance between the plant and the station. The closer to the DC line, the greater the voltage fluctuation of the plant station.

(2) The voltage fluctuation of the transmitting end grid caused by the failure of DC commutation is large, and the magnitude of the voltage fluctuation may cause the off-net new energy to be disconnected. It is necessary to take corresponding measures to avoid the high-low penetration of the near-end power electronic equipment which caused a bigger grid accident.

(3) The voltage fluctuation of the transmitting end grid caused by the DC commutation failure is millisecond, and the electromechanical simulation cannot trace back the fault process.

(4) The main reasons for voltage fluctuation: First, in the process of DC commutation failure, DC current and DC power rise first and then fall, and the timing lags behind the decrease of DC voltage,

causing the reactive power required for DC to rise first and then fall; Second, the reactive power exchange with the system increases, and the long-term commutation failure may cause the AC filter to operate, and the switching delay further aggravates the reactive power and voltage fluctuation.
This paper lists the actual operation cases, analyzes the system voltage fluctuations of the transmission network caused by DC commutation failure, and uses the high-fidelity simulation method to analyze the fault backtracking and the cause, which is the next phase failure. The induced power grid voltage fluctuation prevention and control and the high-low penetration setting of the DC near-end new energy plant station provide ideas to effectively ensure the safe and stable operation of the power grid.

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