Modeling and Simulation of ±10 kV DC Transmission System based on Mechanical DC Circuit Breaker

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Abstract. In order to simulate the interruption process of mechanical DC circuit breaker in actual DC power grid and obtain various stress characteristics of DC circuit breaker in actual interruption process, it is necessary to establish a stable and effective flexible DC system model with good dynamic performance. In this paper, the controller models of system level, converter station level and converter valve level are established for the 10kV flexible DC system, and then the steady-state characteristics and dynamic characteristics of power step of the system are simulated. After analyzing the variation of voltage, current and power and dynamic response speed of converter station, the simulation results show that DC voltage and active power of the system operate stably according to the reference value and the fluctuation error of DC voltage is less than 1%. The internal and external loop controllers all track the dynamic changes of their respective command values rapidly within 0.5s. The control performance of the flexible DC system model can meet the requirement of the interruption simulation of DC circuit breakers.

1. Introduction

Researchers at home and abroad have established different simulation models to study the operation characteristics of flexible DC systems. Jianzhong Xu[1-2] proposed a fast simulation model based on controlled sources, which is suitable for systems that need to study the internal fault characteristics of modules. However, it is too simplified to study the interaction between ac and dc systems, which will affect the accuracy of simulation results. Ming CHEN[3], U. N. Gnanarathna[4] and Yingbiao LI[5] proposed a simulation model based on davenan's theorem, which can accurately simulate the charging and discharging process of the internal capacitor, but cannot fully reflect the external dynamic characteristics of MMC. J Peralta[6] and Min HE[7] proposed a fast simulation model of MMC based on the mean value, which can better reflect the external dynamic characteristics of the converter station. However, compared with the detailed simulation model of MMC, there will be insufficient simulation accuracy with the change of the number of sub-modules.

The simulation of interruption characteristics of mechanical DC circuit breakers need to consider the interaction between AC and DC systems and put forward more requirements on external operation characteristics of DC systems. In this paper, the performance of the coordinated control strategy is studied, and the detailed mathematical modeling of 10kV flexible DC system is established. The fast dynamic characteristics in a small time scale and steady state operation characteristics are simulated in PSCAD. The simulation results have verified the effectiveness of the controller and parameters established in this paper, which not only provides a preliminary simulation platform and a certain
theoretical basis for the project planning and operation, but also lays a foundation for the research on the over-voltage and DC switching of the system.

2. Simulation model of ±10kV flexible DC system at both ends

In this paper, the MMC-HVDC system as shown in Fig. 1 is built in the environment of electromagnetic transient simulation software PSCAD/EMTDC. In modeling, the AC side of the DC system is connected to the 10kV AC system, which is connected to the converter through a 10kV/10kV transformer. The terminal 1 is the energy conveying terminal, and the power is transmitted to the receiving terminal via two DC cables with a length of 15km and a voltage of 10kV.

![Figure 1. The simulation model of 10kV MMC at both ends](image1.png)

The number of submodules mainly affects the harmonic content, but not the other operating characteristics of the dc system. Therefore, in this paper, the number of sub-modules of single bridge arm is set as 20 for simulation, and the sub-modules are connected in series with each other. In modeling, the interconnected submodules in the converter station are equivalent to a whole. The converter station model is shown in Fig. 2. The converter 1 adopts constant DC voltage and constant AC voltage control for stabilizing DC voltage and regulating power output; the converter 2 is set as the constant active power and constant reactive power control, and the output of converter power is adjusted by changing the reference value of power. The DC cable model built in this paper adopts the distributed parameter cable model built by PSCAD, and the main circuit parameters at both ends of the MMC-HVDC system model are consistent, which is shown in Tab. 1.

![Figure 2. The model diagram of converter station](image2.png)

| Project                      | Parameter  |
|------------------------------|------------|
| Ac system voltage(Uₐ)        | 10kV       |
| Transformer ratio(Uₐ₁/ Uₐ₂)  | 10/10kV    |
| DC voltage(Uₐₑ)              | 10kV/-10kV |
| Transformer capacity(Sₜ)     | 24MVA      |
| Converter station capacity(Sₙ) | 20MVA     |
| Number of submodules(Nₘₜₐₘ)  | 20         |
| Submodule capacitance(C₀)    | 8000uF     |
| Bridge arm inductor(L₀)      | 3.0mF      |
| DC cable length(l)           | 15km       |
3. Simulation results

3.1. Steady state simulation analysis

In order to verify the rationality of parameter design in the system, the effectiveness of the selected controller, and whether the output characteristics of each variable of the system are good, the steady-state characteristics of the above mentioned 10kV system are firstly simulated and analyzed. The corresponding active power control strategy and its reference value of each converter station are listed in detail in Tab. 2, and the simulation results are shown in Fig. 3 to Fig. 5.

Table 2. The control strategy of each terminal converter station.

| Converter station | Control strategy                              | Reference value |
|-------------------|-----------------------------------------------|-----------------|
| converter station 1 | constant DC voltage/constant reactive power | 20kV/0MVar      |
| converter station 2 | constant active power/constant reactive power | 2MW/3MVar       |

Figure 3. The comparison diagram of Vdc1-Vdcref1

Figure 4. The positive and negative voltage on the DC side
The DC side voltage waveform figure of the converter 1 is shown in Fig. 3 and Fig. 4. The converter 1 plays the role of regulating the DC voltage, making the voltage between the dc side electrodes of the system constant to 20kV. Due to the small number of submodules, the DC voltage fluctuates to different degrees, but the fluctuation error is less than 1%, which meets the dynamic performance index. The active power waveform of the converter station at both ends is shown in Fig. 5. The actual active power of the converter 2 is stable at the corresponding reference value. Due to the voltage drop and loss on the DC line and other components, the active power of the converter 1 is higher than that of the converter 2. The simulation results show that the DC voltage and active power of the converter station operate stably according to its reference value and the fluctuation error meets the requirements. What’s more, the positive and negative electrical quantities are mutually symmetrical, which verifies the reasonability of the converter control method and parameters.

3.2. Dynamic simulation analysis

The dynamic simulation analysis of the system is to verify the dynamic response of the converter to disturbance. The simulation analysis is carried out by changing the active power and reactive power of the converter 2. On the basis of the steady-state results above, the power step test was conducted. When t=1.5s, the reactive power of converter 2 was changed from 0MW to -3MW; when t=2.0s, the active power was changed from -2MW to -3MW and the reactive power was changed from -3MW to -1MW. When t=3.0s, the active power transmitted by the system is reversed again, and the active power of converter 2 is changed from -3MW to 2MW. The parameters of the dynamic simulation process are set in accordance with the steady-state operation parameters, and the simulation results are shown in Fig.6 to Fig.9.
Figure 8. The comparison diagram of id-idref

According to Fig. 6 and Fig. 7, when $t=1.5s$ and $t=2.0s$, the reactive power changes, and the reactive power controller takes effect rapidly, so that the new stable reference value of reactive power can be tracked at around 50ms. When $t=2.0s$ and $t=3.0s$, the active power decreases and the power flow reverses respectively, and then the active power controller takes effect to enable the active power to quickly track the new stable reference values at around 150ms and 500ms respectively. In addition, obtained from Fig. 8 and Fig. 9, the inner loop current controller achieves fast decoupling control of the current components of the d-axis and q-axis, so that they can quickly track the dynamic changes of their respective reference values. Through the simulation of power step, the effectiveness and dynamic response characteristics of the converter station level and valve level controllers are verified. The controller parameters of active d reactive power classes are decoupled from each other and can be controlled independently without affecting each other.

4. Conclusion

In this paper, the topological structure and principle of MMC are firstly studied, and the detailed mathematical model is established. Then, the control strategy of MMC-HVDC is studied in detail. Based on the AC-DC decoupling model of MMC and the direct current control strategy, the internal current loop controller, external power loop controller and corresponding PI controller parameters are designed. Finally, the ±10kV MMC-HVDC system was built in PSCAD/EMTDC, and the simulation analysis was carried out under the three conditions of steady state operation of the system, power step change and power flow reversal in small time scale. The simulation results show that the voltage of the DC system is symmetrical and stable, and the fluctuation error meets the requirements of the interruption simulation of DC circuit breakers, which lays a theoretical foundation for the subsequent work.

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