Comparison of the characteristics of three kinds of HVDC systems with ABB, SIMENS, and Cigre Benchmark

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Abstract: This study presents the comparison among three control systems: Cigre Benchmark model, ABB model, and SIMENS model based on PSCAD. Firstly, the control systems which refer to Cigre Benchmark control model, ABB control model, and SIMENS control model are introduced, respectively. Analysis and comparison are done on these control systems about their design theories, control logic, and functional models, and the advantages and disadvantages of each control system are concluded. Secondly, simulations in both normal and fault conditions are done in order to verify the conclusions. On the one hand, the steady-state response characteristics of these three high-voltage direct current (HVDC) models are obtained and compared by setting different voltage of the receiving terminal AC bus. On the other hand, the transient response characteristics of these three HVDC models under different operating conditions are obtained, such as symmetrical and asymmetrical short-circuit fault, line switching on or off etc. The research results will provide experiences and references for the future optimisation of the HVDC control system.

1 Introduction

Until now, there are two kinds of high-voltage direct current (HVDC) systems mainly in practice: the SIMENS system and the ABB system. These two kinds of HVDC systems are widely used in southern power grid in China [1]. In order to find the advantages and disadvantages of the two systems and to find the improved direction, this paper will compare the two different models. In addition, the Cigre Benchmark model is mostly used in the simulation experiment to get various characteristics of the DC system. Therefore, this two control system should be compared with the Cigre Benchmark system to provide reference.

The load of the AC system at the receiving end is changing in real time. If the running power of the HVDC system can adapt to this change to some extent, it will be beneficial to the stability of the receiving end AC system. Therefore, in this paper, the response process of three systems is compared when the power set value is reduced by 0.1 p.u.

After short-circuit ground fault of the AC power grid of the inverter, it is very likely that communication failure occurs in the inverter [2, 3]. For the three-phase ground fault, due to the decrease in the voltage of AC bus in the inverter station, communication failure of the inverter will be caused [4]. For the single-phase fault, the reason why communication failure occurs is harmonic influence and phase angle change besides voltage drop [5, 6].

When the fault disappears, the rapid recovery of the HVDC system has a great influence on the stability of the weak receiving AC system. So, this article will compare the recovery speed of these three systems after the failure and hope to find some areas for improvement to clarify the future direction of work.

2 Description of three kinds of DC systems

2.1 Basic model of HVDC transmission

According to the steady-state mathematical model of the converter, the equivalent model of the two-terminal DC transmission system can be obtained, as shown in Fig. 1.

According to (1), it can be seen that both direct voltage and DC are controlled by the current controller on the rectifier side, and the direct voltage is controlled by the arc extinguishing angle controller on the inverter side. However, the HVDC system is controlled by these four variables. The different operating modes of the HVDC system need to be regulated by these variables. Usually, the control of the trigger and inverter, respectively, and their response speed is very fast, usually only need 1–5 ms. The valve side no-load voltage of the rectifier and inverter is represented by \( U_{dri} \) and \( U_{dqi} \) and their adjustment method is to change the tap of the converter transformer. However, their response speed is much slower than the trigger angle adjustment, usually need 5–10 s. In the DC system, the control of the trigger control angle is mainly used to deal with the fast change of the voltage or current in the DC system. The tap changer of the converter transformer is used to regulate the slow change of the AC system voltage.

2.2 ABB-NARI HVDC control system

In normal work, DC is controlled by the current controller on the rectifying side, and the direct voltage is controlled by the arc extinguishing angle controller on the inverter side. However, the control angle of both the rectifier and the inverter must be obtained through a variety of modules, including voltage-dependent current.
order limit (VDCOL), predictive arc extinguishing angle control (Amax), over-voltage limit, rectifier angle minimum limitation (RAML), voltage control (VCA), commutation failure prediction control (CFPRED), closed-loop current control (CCA), and closed-loop current limit value selector. These modules will be described in Fig. 2.

The relationship between the modules on the rectifying side is shown in Fig. 2a. By comparing the actual DC value and the DC reference value, the CCA module gets the control angle instruction (α_rec) through the PI module.

When the direct voltage is >0.7 p.u., the relationship between the modules on the inverter side is shown in Fig. 2b. In normal work, the output of CFPRED is zero. Owing to the existence of current margin, the output of CCA is always equal to the upper limit. In other words, under normal conditions, the inverter is controlled by Amax and VCA to maintain voltage stability and keep the arc angle to meet the requirements. If the direct voltage is <0.6 pu and exceeds a certain delay, the upper and lower limits of the CCA will be switched to the output value of the Amax to improve the recovery speed of the DC voltage.

2.3 Cigre Benchmark HVDC control system

The basic idea of the Cigre Benchmark control system is that current controller of the rectifier side controls the DC, and arc extinguishing angle controller of the inverter side indirectly regulates the direct voltage.

From Fig. 3, the control system of the Cigre Benchmark model consists of four parts: VDCOL, current deviation control, current control, and arc extinguishing angle control [8]. The reference value of the current is the minimum value between the output value of the VDCOL module and the set value of the transmission power, which is shared by the inverter side and the rectifying side. The control angle instruction of the rectifying side (α_rec) is the output value of the current controller with limited amplitude. The leading trigger angle (β_rec = π - α_rec) of the inverter side is the maximum value between the output value of the current controller and the arc extinguishing angle controller.

2.4 SIEMENS-XJ HVDC control system

The strategy of XJ-SIEMENS control system is that DC is regulated by rectifier station and direct voltage is governed by the inverter station [9]. In fact, the rectifier station also has a voltage control module. However, it is only used to limit the overvoltage of the rectifying side. At normal operation, the direct voltage of the rectifier is charged by direct voltage control module in the inverter plant and is equal to the sum of the voltage of the inverter and the voltage drop of the transmission line.

As shown in Figs. 4a and b, the switching between several control modes is implemented by the maximum value (minimum value) selection module. The error of the current, voltage, and arc extinguing angle (gamma) is the difference between the corresponding measured value and the reference value, respectively. Comparing these errors, the rectifier side selects the minimum error of the three as the current control mode, while the inverter station takes the maximum value of the three.

3 Methodology

The SIMENS and ABB HVDC model have been building in PSCAD. Also, PSCAD contains the Cigre Benchmark HVDC model. Therefore, these three models can be compared in PSCAD software.

4 Comparison of three kinds of systems

4.1 Steady-state response comparison of three systems

At 3 s, the power reference values of the three systems are all down 0.1 p.u., and then the response of these systems is observed.

According to Fig. 5a, it can be found that after the Cigre Benchmark system reaches the new steady-state operation point, the voltage of the rectifier side and inverter side is generally high, while the rectifier or inverter voltage of SIEMENS and ABB system can remain unchanged approximately after reaching the new steady state. As we can see from Figs. 5a and b, when the power set value changes, the ABB system responds fastest, the Cigre Benchmark system is the second, and the SIMENS system is the slowest.

From Figs. 5a and b and c, it can be concluded that after the change of the power setting value, the VCA module of the ABB inverter side control system keeps basically the same voltage at both ends, and the current controller of the rectifier side converts the current to a given value. During this period, the arc extinction angle (gamma) is not required to remain unchanged. When the current setting value changes, the strategy of Cigre Benchmark control system is that the arc extinction angle of the inverter side keeps arc extinguishing angle unchanged, and the current is adjusted to the given value by the current controller of the rectifier side. The result is the high DC voltage at both ends. As for the SIEMENS control system, after the change of the power given value, the inverter side keeps the same voltage and the extinction angle at both ends by the combination of the voltage control mode and the current control mode. The rectifier side controls the current to adjust the current to...
the new rated value. It is worth mentioning that the rated arc extinguishing angle of the SIEMENS system is so small that the commutation failure may occur in a slight disturbance.

4.2 Comparison of recovery process after three-phase failure of AC bus of inverter

The transient process of three systems is observed in three kinds of DC systems, which are set up from 3S for 0.05 s of metal three-phase grounding fault in AC bus of the inverter. The result is Fig. 7.

As can be obtained from Fig. 7a, commutation failure have occurred in all of these HVDC systems after the AC fault. As you can see from Figs. 7b and c, the three kinds of DC systems can all recover to the steady state after the failure. However, their recovery rate is different, the ABB system has the fastest recovery, the Cigre Benchmark system recovery speed is the second time, and the SIEMENS system has the slowest recovery speed.

In the control system of the ABB inverter station, the inverter station is controlled by the Amax controller after a certain delay, when the inverter side direct voltage is low (<0.6 p.u.) and continues for a period of time and by VCA module when direct voltage is high enough (>0.7 p.u.). As shown in Fig. 5c, even if the starting time of the voltage recovery of the ABB system is later than that of the Cigre Benchmark system, the direct voltage of the two systems reaches the maximum at almost the same time. When the direct voltage is maximum, the reactive power absorbed by the inverter at this time is greater than that of normal operation. After that, as the reactive power absorbed by the inverter is reduced to the stable state, all the indexes of the system return to the steady state. At normal operation, the output of VCA is always equal to the upper limit, that is, the output value of the Amax. In other words, the inverter is controlled by the Amax controller at normal operation and VCA only plays the role when reactive power fluctuation causes voltage deviation and in the later stage of recovery.

In the Cigre Benchmark HVDC system, the recovery speed of the DC current is very fast according to Fig. 7b. In the process of recovery, when the actual value of DC is equal to the reference value, the arc extinction compensation given by current deviation module will soon drop to zero, causing the extinction angle controller reference value dropped suddenly, causing the arc extinction angle suddenly dropped to a certain less than the rated value, which is easy to cause commutation failure if the parameters of the VDCOL and current deviation module are not suitable. After that, with the increase in DC voltage, the reference value of the DC given by VDCOL is gradually increased to the rated value. As the actual value of the DC is less than the reference value first and then is equal to the reference value, the arc extinction compensation given by the current deviation controller will first increase and then decrease, and the extinction angle of the inverter side will also increase first, then decrease. At the same time, the reactive power absorbed by the inverter in the beginning of recovery is larger than the rated value then gradually approaches the rated value. Under the above two factors, during the whole recover process, DC and direct voltage first increase firstly to the vicinity of the rated value, then decrease and finally gradually increase to the steady state. The extinction angle (gamma) is reduced firstly from a very large value to a certain value less than rated value, then increased to a certain value and finally reduced to the gamma steady state.

In SIEMENS DC-inverter side control system, the maximum error of DC current is greatest during the process recovery after fault, so the input of PI controller is current error value, and the corresponding time range is 3.07–3.15 s. Since then, the error value of the arc extinction angle is maximum and the inverter is the mode of arc extinction angle control (3.15–3.65 s). During this period, the error of direct voltage is very close to but smaller than the error of gamma. What is more, they have the same rule of change and when the error of gamma approaches and zero, the error of voltage is also approaching and zero. However, the response speed of the gamma module is so slow that it avoids the stage of reactive power change. The advantage is that the DC system does not have overvoltage (1.16 p.u.), and the disadvantage is that it is not conducive to the recovery of transmission power. As we can see from Fig. 5c, the response speed of VCA module of ABB is fast, whose advantage and disadvantage are just opposite of SIEMENS. In the process of recovery, the voltage of AC bus of the rectifier is less than normal voltage for a period of time (3.3–4.25 s), which causes DC decline. Then, as the error of the current becomes maximum, the inverter side becomes the current control mode and the system slowly restores the steady state (3.65–4.14 s). According to Fig. 5a, comparing the current control module of ABB and SIEMENS, it is found that the current control module of SIEMENS has a slow response, while the ABB current control module can maintain DC stability under the condition of reactive power fluctuation. So, the current control module of SIEMENS may need to improve the response speed.

4.3 Comparison of recovery process after single-phase failure of AC bus of inverter

The transient process of three systems is observed in three kinds of DC systems, which are set up from 3S for 0.05 s of metal single-phase grounding fault in AC bus of inverter.

From Fig. 6, it can be seen that the three systems have the failure of the commutation failure under the influence of the AC fault, but they all recovered to the steady state after the failure of the AC fault. However, the rate of recovery is not the same. The ABB system has the fastest recovery, the Cigre Benchmark system recovery speed is the second time, and the SIEMENS system has the slowest recovery speed.
When it comes to one-single phase fault, the dynamic recovery process of the ABB control system is similar to the dynamic process of the three-phase fault. The inverter is controlled by Amax when the DC voltage is low (<0.6 p.u., 3.06–3.17 s), regulated by the VCA controller when the direct voltage is high (>0.7 p.u.) but fluctuates (3.17–3.45 s) and charged by Amax controller in normal operation (3.45 s).

The recovery process of the Cigre Benchmark system after a single-phase fault is similar to the recovery process after a three-phase fault. Under the influence of the change of the arc angle and the reactive power absorbed by the inverter, the operating point is

Fig. 5 Waveform when current order changes
(a) Direct voltage, (b) DC, (c) Arc extinction angle (gamma), (d) αrec (AOR) and αinv (AOI)
first close to the steady state and then deviates from the steady state, and finally, it reached the steady state gradually. It is worth mentioning that Cigre Benchmark and ABB's control systems make the extinction angle less than the rated value at the beginning of the recovery process in order to accelerate the recovery speed according to Fig. 6a. If the parameters are not suitable or the influence of harmonics, commutation failure will occur.

As we can see from Figs. 6b and c, the difference between the recovery process after the single-phase failure and the three-phase failure is that direct current is fluctuating only during 3.5 ∼ 4.5 s and direct voltage has no obvious change. The reason is the control systems of the inverter do not transit to current control mode and the current's error is less than gamma's error continuously. In chronological order, the control system of the inverter goes through the current control mode and the gamma control mode. The DC is only regulated by the current controller of the rectifier whose response speed is still slow according to Fig. 6b.

5 Conclusion

By comparing the response of the three systems after the power setting change, the three-phase failure, and the single-phase fault, the following conclusions can be drawn.

The response speed of the SIMENS is slow, whether in the process of changing the running power or in the process of recovery after failures. When power set value drop, if there is no direct voltage control module in the inverter, there will be overvoltage in the HVDC system, which not only causes the power deviation but also threaten safe operation of the HVDC system. That is to say, it is not realistic to only indirectly regulate the direct voltage by the arc extinction angle (gamma) controller. In addition, in the recovery process after failures, if the voltage controller responds too quickly, it will cause a certain transient overvoltage, and if it is too slow, it will affect the recovery of transmission power. It is worth mentioning that the fluctuation of reactive power absorbed by the converter has a certain effect on the recovery process after the failure of the inverter. In the process of recovery after the failure, the current of the SIMENS HVDC system is generally slower, so there is some room for improvement in the current controller of the SIMENS HVDC system.

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Fig. 7 Waveform when three-phase failure occurs
(a) Gamma of the inverter (three-phase fault), (b) DC of the inverter (three-phase fault), (c) Direct voltage of the inverter (three-phase fault)

7 References

[1] Yan, X., Yang, G.: ‘Comparative study on response characteristic of low DC voltage measurements at inverter on Siemens and ABB technical route’, *High Volt. Appar.*, 2017, 53, (8), pp. 230–240

[2] Wang, J., Liang, Z., Jiang, M., et al.: ‘Case analysis and simulation calculation of simultaneous commutation failure with multiple infeed DC’, *Autom. Electr. Power Syst.*, 2015, 39, (4), pp. 141–146

[3] Liu, Y.: ‘Analysis of communication failure mechanism multi-infeed HVDC and research on its defending method’, PhD thesis, North China Electric Power University, 2015

[4] Yuan, Y., Wei, Z., Lei, X., et al.: ‘Survey of commutation failures in DC transmission systems’, *Electr. Power Autom. Equip.*, 2013, 33, (11), pp. 140–147

[5] Kai, J., Ren, Z., Jing, Y.: ‘Research on communication failure in HVDC transmission system part 1: communication failure factors analysis’, *Electr. Power Autom. Equip.*, 2003, 23, (5), pp. 5–8

[6] Wang, F., Liu, T., Zhou, S.: ‘Mechanism and quantitative analysis method for HVDC commutation failure resulting from harmonics’, *Proc. CSEE*, 2015, 35, (19), pp. 4888–4894

[7] Xv, Z.: ‘AC/DC power system dynamic behavior analysis’ (Mechanical Industry Press, Beijing, China, 2004, 1st edn. 2004)

[8] Li, R., Li, Y., Chen, X.: ‘A control method for suppressing the continuous commutation failure of HVDC transmission’, *Proc. CSEE*, 2017, 29, pp. 1–16

[9] Nie, X.: ‘Control system models for ultra high voltage direct current transmission’, PhD thesis, Beijing Jiaotong University, 2015