Research on CIGRE benchmark model and improved DC control strategy

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Abstract. The safe and stable operation of the HVDC transmission system greatly depends on the control system. The DC control system realizes a series of control strategies such as constant-current, constant-voltage, and constant-extinction angle control by controlling the trigger phase. The CIGRE Benchmark model is often used as a standard test model for research, but it is usually necessary to improve in actual project. First of all, taking the CIGRE Benchmark model as the research object, the DC control mode and basic control functions are introduced systematically. On this basis, the improved control strategy is studied. At the same time, PSCAD / EMTDC simulation software is used to build an improved control system model. The transient response of CIGRE Benchmark and improved control system model. The transient response of CIGRE Benchmark and improved control system model is simulated and analyzed. Furthermore, the control mode conversion and control system response under different control strategies are studied.

1. Introduction
Due to the reverse distribution of energy and load in China, high voltage director current (HVDC) technology has become an inevitable choice for long-distance and large capacity transmission. Control and protection play an important role in HVDC system [1]. It is very important to study DC control strategy for safe and stable operation of HVDC system. The normal operation and system performance of the HVDC system based on thyristor are greatly dependent on the control system. The coordination between different controllers has an important impact on the transient performance of the HVDC system [2]. CIGRE benchmark model (hereinafter referred to as "benchmark model") has certain representativeness, but it is still difficult to meet the operation requirements of the actual DC project. Therefore, the improved DC control strategy should be adopted in the actual project. In order to study the influence of HVDC system control strategy on the safe and stable operation of AC / DC system, this paper firstly analyzes the control mode and basic control function configuration of the benchmark model based on CIGRE benchmark model. Then the improved control strategy is studied. At the same time, PSCAD / EMTDC electromagnetic transient simulation software is used to build an improved control system model based on the benchmark model. The fault simulation analysis of the benchmark model and the improved control system model is carried out. Besides, the transient response of DC control system under different control strategies is studied.
2. CIGRE benchmark model control strategy

2.1. Introduction of CIGRE benchmark

In 1991, the Benchmark model was put forward by the HVDC system control group 14.02 of the Conference International des grands reaux electriques (CIGRE) for HVDC control research. The main circuit, rectifier and inverter structure of the benchmark model are shown in Figure 1, Figure 2 and Figure 3 respectively.

Figure 1. Structure diagram of CIGRE Benchmark model main circuit.

Figure 2. Structure diagram of rectifier.

Figure 3. Structure diagram of inverter.

The benchmark model adopts two-terminal DC transmission system with single pole and single 12 pulse converter (two 6 pulse converters in series) of each pole. The rated voltage and transmission power is ± 500kV and 1000MW. The short-circuit ratio of the sending and receiving AC system is 2.5, which belongs to the weak system. The control system adopts the current margin control. The constant-current control was used in rectifier and constant-voltage control was used in inverter. In the benchmark model, the steady-state curve of DC system is shown in Figure 4. The control characteristics of rectifier and inverter are represented by thick line and thin line respectively.

Figure 4. Steady-state curve of CIGRE benchmark model.
The volt-ampere characteristic of rectifier is composed of constant-current control and minimum trigger angle \( \alpha_{\text{min}} \) limiter, as is shown in the thick wire. The inverter is equipped with constant-extinction angle, constant-current and current error control (CEC), as is shown in the thin line. The current settings of the converters on both sides are limited by the voltage dependent order limiter (VDCOL). The volt-ampere characteristic equation of VDCOL can be expressed as follows:

\[
I = \begin{cases} 
0.55 & U \leq 0.4 \\
0.9U + 0.19 & 0.4 < U \leq 0.9 \\
1 & U > 0.9 
\end{cases}
\]

(1)

In Formula (1), \( U \) is the starting voltage value of VDCOL regulator and \( I \) is the target value of constant-current control. The rectifier and the inverter adopt the same closed-loop current controller. The inverter current setting is the rectifier current setting minus 0.1pu, which is the current margin control. The volt-ampere characteristic equations of minimum triggering angle \( \alpha_{\text{min}} \) limiter and the constant-extinction angle control are as follows.

\[
U_{\text{dr}} = 1.35U_{\text{acr}} \cos \alpha_{\text{min}} - (3/\pi)X_rI_d
\]

(2)

\[
U_{\text{di}} = 1.35U_{\text{aci}} \cos \gamma - (3/\pi)X_iI_d
\]

(3)

In Formula (2) and Formula (3), \( U_{\text{dr}} \) and \( U_{\text{di}} \) are the DC voltage of the rectifier and inverter. \( U_{\text{acr}} \) and \( U_{\text{aci}} \) are the effective value of no-load voltage at the valve side of the converter transformer of rectifier and inverter. \( X_r \) and \( X_i \) are the equivalent commutation reactance of rectifier and inverter.

2.2. Rectifier control strategy

2.2.1. Rectifier basic control. The rectifier control mainly maintains the DC current constant by controlling the trigger angle \( \alpha \) in Figure 5. In the benchmark model, the constant-current control of rectifier compares the CMRS which is the current measurement value CMR filtered by the first-order linear filtering regulator \( G/(1+sT) \) with the current setting value transmitted from the VDCOL regulator. Then the current difference CERRR outputs the trigger angle \( \beta \) through the proportional integration (PI) regulator, and the trigger angle control instruction \( \alpha \) is obtained from \( \alpha = \pi - \beta \). The minimum trigger angle \( \alpha_{\text{min}} \) control is mainly used to prevent the thyristor conduction from getting worse at the same time [3]. The minimum trigger angle used in most DC transmission projects is 5 °. The maximum output of PI regulator set \( \beta \) is 3.054 in the benchmark model, that is, 175 ° to limit the minimum trigger angle \( \alpha \) to 5 °.

![Figure 5. Block diagram of rectifier constant-current control.](image)

![Figure 6. Block diagram of VDCOL regulator.](image)
VDCOL regulator. When the DC voltage drops to a certain value, the VDCOL regulator can limit the DC current [4]. The typical VDCOL regulator is shown in Figure 6, where $R_c$ is the compensation resistance, $I_{\text{max}}$ is the maximum allowable current value of VDCOL output and $I_{\text{des}}$ is the current value given by the operator. Besides, the minimum value of $I_{\text{max}}$ and $I_{\text{des}}$ is selected as the current setting value $I_{\text{ord}}$ of the converters on rectifier and inverter after MIN selector. The starting voltage of VDCOL regulator in the benchmark model is the line midpoint voltage, which is compensated by $R_c$. If voltage compensation is not used, the current value sent to VDCOL is the outlet voltage of the inverter side, which will be smaller than the actual VDCOL voltage starting value. And the system will enter the VDCOL regulator earlier, making the current unstable. In the benchmark model, rectifier and inverter are equipped with VDCOL regulator.

2.3. Inverter control strategy

As is shown in Figure 7, inverter control mainly maintains the DC voltage constant by controlling the trigger angle $\alpha$, but the inverter control system is more complicated than the rectifier because of the inverter's commutation failure problem [5]. The input of the inverter control in the Benchmark model is the measured value of the dual-bridge extinction angle $\gamma$, DC voltage $U_{d,\text{inv}}$ and DC current $I_{d,\text{inv}}$. The output is the trigger angle $\beta_{\text{inv}}$ and the setting value of the DC current $I_{d,\text{order}}$. The extinction angle $\gamma$ is often used as a characteristic quantity to describe the commutation failure. The task of constant-extinction angle control is to properly control $\gamma$. On the premise of ensuring safety, $\gamma$ is maintained as small as possible. In practice, the setting value of $\gamma$ is usually between $15^\circ$~$18^\circ$.

2.3.1. Constant-extinction angle control. In order to prevent the failure of commutation, constant-extinction angle control should take the minimum value of $12^\circ$ angles in a cycle to ensure that each $\gamma$ is greater than setting value $\gamma_N$. At the same time, after the minimum $\gamma$ is selected, the measured value of $\gamma$ is subtracted from the sum of the constant value $0.2618$ ($15^\circ$) and the output value of the CEC through an addition and subtraction process to ensure that the minimum value is greater than $15^\circ$. In order to prevent $\gamma$ from being too large, constant-extinction angle limiter is set limiting angle control. When the maximum value of $\gamma$ is selected, a constant value (-0.544) will be entered converting to an angle of approximately $31^\circ$. A minimum $\gamma$ ($15^\circ$) is plused, so the maximum $\gamma$ is not exceed $46^\circ$.

In the Benchmark model, the output of constant-extinction angle control and constant-current control are both the trigger angle $\alpha$. In order to prevent the inverter from failing in commutation, $\gamma$ should be large enough so the output of constant-extinction angle control and constant-current control needs to select the maximum value through the MAX selector [6]. Finally, the output of the MAX selector acts on the gate unit to establish a trigger pulse for the inverter.

![Figure 7. Block diagram of inverter control.](image-url)
2.3.2. Constant-current control. The inverter constant-current control is similar to the rectifier. During normal operation, the measured value of inverter current is always greater than the current setting value. The constant-current controller will show a tendency to reduce the DC current so that \( \alpha \) is adjusted to the maximum. Therefore, only when the measured current value of the inverter is less than the current setting value under the fault condition.

2.3.3. Current error control (CEC). Current error control is an auxiliary control regulator between inverter constant-current and constant-extinction angle control. When the difference between the current measured value and the current setting value on the inverter is too large. The function in the current error controller will output a larger value and add it to the addition and subtraction regulator of constant-extinction angle control, thereby \( \gamma \) will increase rapidly.

3. Improved DC control strategy

Benchmark model is widely used in the research of DC transmission because of its simple structure and reference. In actual projects, the control system needs to be improved and perfected. The biggest feature of the improved DC control system is that it is a limiting controller [7], which is mainly reflected in the limit of the output of the current controller CCA. The calculation of the upper and lower limits is controlled by a series of modules in the CFC. Improved DC control system mainly includes the \( \alpha_{\text{min}} \) control, AMAX control and constant-voltage control [8]. In addition, the commutation failure prediction function is introduced to improve the immunity performance of the inverter's commutation failure.

3.1. Inverter control strategy

Formula (3) shows that the volt-ampere characteristic of the inverter constant-extinction angle control is a negative slope curve and the inverter has a negative resistance characteristic. If the short-circuit capacity of inverter AC system is small, the slope of the constant-extinction angle control in the current margin characteristic will be greater than \( \alpha_{\text{min}} \) control. At this time, the volt-ampere characteristic curves of the rectifier and the inverter will have two intersections. The DC current will oscillate between the two setting values causing stability problems. In order to solve this problem, a correction item was introduced

\[
\beta = \arccos \left( \frac{\cos \gamma - 2d_x I_d}{I_0 \cdot U_{d0} \cdot \left( U_{d0} - k(I_0 - I_d) \right)} \right)
\]

In Formula (4), \( d_x \) is the inverter equivalent commutation reactance unit value. \( I_0, I_{d0} \) and \( I_d \) are the command value, rated value and actual value of DC current. \( U_{d0} \) and \( U_{d0} \) are the rated value and actual value ideal DC voltage of the inverter. \( k \) is the proportional coefficient.

\[
U_d = U_{d0} \cos \beta + d_x I_d = U_{d0} \cos \gamma - (2d_x + U_{d0}k)I_0 + (U_{d0}(k + d_x))I_d
\]

Figure 8. Block diagram of VDCOL regulator.
Formula (5) shows that the volt-ampere characteristic of the inverter after AMAX correction becomes a straight line with positive slope. AMAX limits the maximum value on the inverter side by predicting \( \beta \), thereby effectively preventing commutation failure and significantly improving the dynamic characteristics of current control. The AMAX control block diagram is shown in Figure 8.

\[ \Sigma \begin{bmatrix} U_a \\ U_b \\ U_c \end{bmatrix} \rightarrow [X] \rightarrow \begin{bmatrix} a \\ a>b \\ b \end{bmatrix} \rightarrow t \rightarrow \text{MAXH} \rightarrow \text{OLD} \rightarrow U_{\text{diff}} \rightarrow \begin{bmatrix} a \\ a>b \\ b \end{bmatrix} \rightarrow t \rightarrow \text{MAX} \rightarrow \text{OLD} \]

\[ \Sigma \rightarrow [X] \rightarrow \begin{bmatrix} a \\ a>b \\ b \end{bmatrix} \rightarrow t \rightarrow \text{MAXH} \rightarrow \text{OLD} \rightarrow U_{\text{diff}} \rightarrow \begin{bmatrix} a \\ a>b \\ b \end{bmatrix} \rightarrow t \rightarrow \text{MAX} \rightarrow \text{OLD} \]

**Figure 9.** Block diagram of CFPREV.

3.2. Constant-voltage control
Compared with constant-extinction angle control, constant-voltage control is more conducive to the voltage stability of the AC system on the inverter. When the receiving power grid is disturbed, the inverter AC bus voltage \( U_{\text{act}} \) drops. And it will cause the increase of commutation angle \( \mu_i \) and the decrease of \( U_{\text{di}} \). When constant-extinction angle control is adopted, the extinction angle regulator will increase \( \beta \) of the inverter because of the increase of the commutation angle \( \mu_i \). Therefore, the reactive power consumed by the inverter increases and the converter bus voltage is further reduced, which may cause the AC voltage to become unstable. When constant-voltage control is used, the AC voltage of the receiving power grid decreases and the voltage regulator will reduce \( \beta \), which makes the reactive power consumed by the inverter reduced. It is beneficial to the recovery of the converter bus voltage.

3.3. CFPREV control
In order to improve the immunity performance of commutation failure, commutation prediction CFPREV control is introduced in the actual project. CFPREV control judges whether commutation failure may occur according to the three-phase AC voltage level. If a condition is met, an angle margin that is not zero is output. The judging criteria are: 1) Calculate the symmetry of the three-phase voltage to judge the degree of asymmetric fault; 2) Calculate the voltage amplitude level to judge the severity of the three-phase fault. The CFPREV control block diagram is shown in Figure 9. In Figure 9, the upper half is for asymmetric fault detection. If the zero-sequence component of the AC voltage exceeds the threshold \( U_{\text{diff}} \) during the fault, a certain trigger offset angle will be output. The lower half is for three-phase fault detection. If the AC voltage drop exceeds the fault threshold \( U_{\text{act}} \) will also output a certain trigger offset angle. The maximum value of the two trigger offset angles will be taken as the output of CFPREV control. In addition to CFPREV control, the GAMMA0 function is also configured to improve the voltage stability of the AC system. When a DC voltage drop on the inverter side is detected, this function will make the inverter trigger angle command equal to the output of the extinction angle regulator.

4. Simulation analysis
Based on the PSCAD / EMTDC simulation platform, an is built based on Benchmark model. Then the comparative analysis of improved DC control strategy model and Benchmark model is completed. In view of the fact that single-phase faults in AC systems are more common than three-phase faults, the electrical quantity variation of the DC system during three-phase faults is similar to that of single-phase faults but the DC transmission power decreases more than three-phase faults. This paper takes the single-phase short-circuit fault on the inverter side as an example to analyze the transient response of the system under the control strategy of the benchmark model and the improved model.
When the system runs to 2s, the inverter AC bus single-phase short-circuit fault (phase A to ground) is set. The fault duration is 0.05s and the AC bus voltage drops about 30%. The DC voltage, DC current, extinction angle, VDCOL DC current order, trigger angle of rectifier and inverter waveforms under the Benchmark model control strategy and the improved control strategy can be obtained, as shown in Figure 10 and Figure 11.

![Waveforms](image-url)

**Figure 10.** Electrical quantities waveforms under the benchmark model control strategy.

It can be seen from Figure 10 that during the transient state there is a large change in each DC quantity, which will cause the corresponding actions of each regulator. At the same time, the actions of each regulator act on each DC quantity, thereby affecting the system recovery performance. At the beginning of the fault, the sudden drop in the AC voltage on the inverter side reduces the DC voltage. The DC current increases and the extinction angle decreases. If the commutation fails on the inverter side, the DC voltage will be 0 and the DC current will surge and the extinction angle will become 0. The extinction angle regulator will reduce the trigger angle to increase the extinction angle. The inverter is in the constant-extinction angle mode. After the commutation fails, the VDCOL action causes the DC current setting value to decrease rapidly. The DC current surge causes the rectifier current regulator to rapidly increase the trigger angle command and the DC current then decreases. When the commutation failure ends, the rectifier current regulator generates negative overshoot and its trigger angle command value is reduced. At the same time, the extinction angle overshoot and the smaller DC current make the inverter operating in constant-current mode. During the period from the failure of commutation to the removal of the fault, the DC current gradually stabilizes and the overshoot of the extinction angle gradually decreases. When the fault is removed, the AC and DC voltages are restored and the current command value of VDCOL increases accordingly. The DC...
current will be reduced to a certain extent at the moment of fault removal, so the inverter is still in constant-current control mode. And then the DC current gradually recovers with the current command. At this time, because the DC power is not restored completely, the AC system has extra reactive power injected and overvoltage will appear on the inverter. After that, the DC voltage and current gradually return to the steady state value.

![Figure 11. Electrical quantities waveforms under the improved control strategy.](image)

In Figure 11, it can be seen that the improved DC control model is as same as the benchmark model at the beginning of the fault. After the fault occurs, the CFPREV action reduces the trigger angle command on the inverter. The difference is that in the recovery phase after the commutation failure, in order to improve the voltage stability of the inverter side, the GAMMA0 function in the control strategy forces the trigger angle command equal to the output of the extinction angle controller. And the inverter is still running at the constant-extinction angle control mode. During the fault removal phase, the DC current decreases and the VDCOL output decreases due to the voltage recovery. The inverter becomes constant-current control mode. In the recovery phase after fault removal, the inverter mainly operates in the constant-current control mode. The inverter side is switched from constant-current to constant-voltage control due to overvoltage in the later period.

5. Conclusions
In this paper, based on the CIGRE Benchmark model, the benchmark model and the improved control strategy are analyzed in detail. Besides, the transient response of the DC system under 2 control strategies is studied. The conversion and response of the control modes under different control strategies are compared. The following conclusions were obtained:
(1) In the CIGRE Benchmark model and the improved control strategy, the cooperation modes of controllers are slightly different, but they are all constant DC current on the rectifier and constant DC voltage on the inverter.

(2) In order to improve the operation stability of the DC system, $\alpha_{\text{min}}$ limit, AMAX control, and constant-voltage control are introduced in the control system in the actual project. In addition, the CFPREV function is introduced to improve the inverter's immunity against commutation failure.

(3) After the AC system fails on the inverter, the rectifier is under constant-current control, but there are multiple control mode conversions on the inverter. The conversion process varies depending on the control strategy. In the recovery process after the failure, the improved control strategy has better fault recovery capability compared with the Benchmark system control strategy.

(4) The extinction angle control method on the inverter has a significant impact on the problem of system commutation failure. Benchmark model adopts the measured extinction angle control method, so the response speed of the trigger angle command is slower in the fault. The improved control strategy adopts the predictive extinction angle control method. The action of CFPREV during the fault can quickly reduce the trigger angle command so that the system has a better immune function against commutation failure.

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