Variable Extinction Angle Control Strategy Based on Virtual Resistance to Mitigate Commutation Failures in HVDC System

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ABSTRACT To mitigate commutation failures (CFs) and minimize the instability of HVDC systems due to AC faults or control mode ambiguity, a constant extinction voltage-time area based control strategy with virtual resistance is proposed. In this strategy, using sine-cosine components detector and considering zero-crossing phase shift of commutation voltage, the extinction angle setting value can be adjusted dynamically. Meanwhile, to reflect the characteristics of DC current during the fault and recovery process, a virtual resistance is introduced into the control system and DC voltage considering the voltage drop of the virtual resistance is taken as the input of voltage-dependent current order limiter (VDCOL). Through theoretical analysis, the proposed strategy not only reduces the firing angle dynamically, but also reduces DC current by lowering the current order on the rectifier side immediately when the AC voltage disturbance is detected, thereby further reducing the occurrence of CFs. Therefore, the control strategy can effectively suppress successive and intermittent CFs. The effectiveness of the proposed control strategy is verified by simulation of the single HVDC and multi-infeed HVDC model based on the CIGRE HVDC benchmark system, in which AC-DC current criterion of identifying CF and suppression ratio index are adopted. The simulation results show that the proposed control strategy can effectively mitigate CFs under single-phase and three-phase faults to a certain extent. Comparing with the existing control strategies based on controller modification, i.e. commutation failure prevention, DC current predictive control, smooth logic switching control and DC current limitation control strategy based on virtual resistance, the proposed control strategy is superior in mitigation effects. The average suppression rates of these strategies are 1.66%, 3.21%, 6.11%, 3.35%, and 8.33% under single-phase fault, respectively; with the rates of 1.4%, 2.72%, 4.97%, 0%, and 6.8% under three-phase fault, respectively.

INDEX TERMS Commutation failure, commutation failure criterion, constant extinction voltage-time area, control mode switching, HVDC, virtual resistance.

I. INTRODUCTION Commutation failures (CFs) caused by AC faults are the most common and unfavorable dynamic events, which have been recorded in several practical systems [1]. With the rapid development of HVDC technology, HVDC transmission projects have become important technical means to optimize the allocation of power system resources and coordinate regional economic development [2]. In practical multi-infeed HVDC systems, a number of HVDC inverter stations are located electrically close to each other, such as the East China Power Grid and China Southern Power Grid [2].

The interactions among inverter stations as well as that between DC and AC systems increase the possibility of complex CFs. Concurrent CFs may even lead to the interruptions of multiple HVDC transmissions, threatening the stability of the whole power system [3]–[6]. The authors in [7] reported some cases of CFs of HVDC systems occurred in China. Therefore, the research on the CF mitigation strategies has important theoretical and practical significance.

To handle these problems, efforts have been made to reduce the risk of CFs. And the existing approaches can be broadly divided into three categories: 1) reactive power compensation-based strategies [8]–[13], 2) power electronics technology-based strategies [14]–[20] and 3) controller modification-based strategies [21]–[36]. This paper is...
dedicated to mitigating CFs using controller modification-based strategy.

Most of the controller modification-based strategies are designed to mitigate successive CFs rather than CFs caused by control mode switching. They rely on fast and predictive detection of inverter side faults and are designed to provide greater commutation margin by advancing the inverter firing angle or/and controlling DC current during faults and system recovery. The main differences among these strategies are: 1) the way of CF detection, 2) the way of calculating the firing angle advancement, and 3) the way of changing the DC current order.

For CF detection method, a sine-cosine components detector was proposed to measure the single-phase voltage [21], in which the commutation voltage can be detected quickly. The authors in [22] presented the commutation failure prevention (CFPREV) method, in which zero-sequence voltage detection and abc-αβ transformation are used for predicting CFs during single- and three-phase faults. Considering the transient voltage and current characteristics under single- and three-phase faults, the authors in [23] proposed a power component fault detection strategy to improve fault detection. Based on the CFPREV, the authors in [24] developed a sliding-window iterative algorithm of discrete Fourier transformation (DFT) to detect voltage harmonics. A harmonic voltage-time area criterion was proposed to detect CFs caused by harmonics [25]. The above strategies can improve the response sensitivity to faults, and provide a basis for further adopting strategies such as advancing the firing angle and reducing DC current order.

For the method of calculating firing angle advancement, the authors in [26]–[28] used fuzzy logic based controllers to determine the extent of firing angle advancement, which can reduce the risk of CFs caused by the nonlinearity of thyristor valve models and the uncertainty of external disturbances. The authors in [21], [29]–[36] directly used the inverter AC voltage to calculate the required firing angle; While the authors in [24] used the harmonic characteristics of commutation voltage to calculate. These improved strategies can mitigate successive CFs to some extent, but it should be noted that by decreasing the inverter firing angle, the inverter reactive power consumption will increase, which will lead to further AC voltage drops. Such behavior is unfavorable as higher AC voltages are needed for better recovery [23]. Therefore, it is necessary to appropriately increase the extinction angle.

For the method of changing DC current order, a DC current predictive control (DCPC) was presented in [30], in which the DC current order from the voltage-dependent current order limiter (VDCOL) [31] is reduced if a potential CF is detected by the CFPREV. The authors in [23] presented an improved current order limiter control that can quickly limit the DC order. Considering the influence of inverter commutation harmonics, the authors in [24] proposed a voltage distortion-dependent CF prevention strategy to limit the DC current order when harmonics are detected. The authors in [32] conducted an in-depth research of the VDCOL parameters setting method, considering the reactive power characteristics of the HVDC system. The author in [33] reviewed the VDCOL control strategies for improving the DC system recovery characteristics. A variable slope VDCOL controller based on fuzzy control was proposed in [34]. And a nonlinear dynamic VDCOL control strategy was proposed in [35], which considered the fault severity of the system and dynamically adjusts control curve of the VDCOL controller according to the voltage level. These control strategies can be combined well with 1) and 2).

In addition, in order to mitigate the CFs caused by the control mode ambiguity shortly after the fault of the HVDC system is cleared, the authors in [36] proposed a control strategy that can mitigate intermittent CFs in a transient state, which makes up for the shortcomings of the aforementioned strategies to some extent.

Although various controller modification-based strategies have been proposed to mitigate the CFs to some extent, most of the above-mentioned control strategies are complex and is not conducive to engineering practice. Also, potential misjudgments may occur in electromagnetic transient (EMT) simulations, using the conservative critical voltage reduction or critical extinction angle criteria [37]. At the same time, comparisons between the controller modification-based strategies are lacking in the literature. Moreover, the widely adopted VDCOL is based on the DC voltage information, and DC current changes have not been reflected in its performance for further improvement.

Based on the above concerns, in order to dynamically adjust the setting value of extinction angle and take advantage of the DC current characteristics during the fault and recovery process, a constant extinction voltage-time area (CEVTA) control strategy with virtual resistance is proposed. The main contributions of the paper are as follows. 1) The setting value of the extinction angle is adjusted using a sine-cosine components detector and considering the zero-crossing phase shift of the commutation voltage. 2) A virtual resistance is introduced into the control system to reflect the characteristics of the DC voltage and current, and the DC voltage considering the voltage drop of the virtual resistance is taken as the input of VDCOL. Through theoretical analysis, the proposed strategy not only reduces firing angle dynamically, but also reduces the DC current by lowering the current order. Therefore, successive CFs and intermittent CFs caused by control mode switching can be effectively suppressed. 3) The effectiveness of the proposed control strategy is verified by EMT simulations on the CIGRE HVDC model, in which AC-DC current criterion (ADCC) [37] and suppression ratio index are adopted to objectively evaluate the suppression effect. Compared with the existing controller modification-based strategies, the proposed control strategy is superior in CF mitigation effect.

The rest of this paper is organized as follows. In Section II, the mechanism of commutation failure is further explored. In Section III, a constant extinction voltage-time area control strategy with virtual resistance is proposed. In Section IV,
the proposed strategy is verified by simulations performed on the CIGRE HVDC model. Conclusions are given in Section V.

II. COMMUTATION FAILURE MECHANISM

In thyristor valves, the internal stored charges generated during a forward conduction interval must be removed before the valve can establish forward voltage blocking capability [1]. Therefore, the inverter valve requires a certain minimum negative commutation voltage-time area; otherwise, a CF will occur. The CF phenomenon is that a valve will continue to conduct when the commutation current from the outgoing valve to the incoming valve has not been completed before the commutating voltage across the outgoing valve reverses, i.e., reverse commutation [38]. To find a theoretical basis of the CF suppression strategy, this section analyzes the impact of DC current on the commutation process.

A. NORMAL COMMUTATION PROCESS

The equivalent circuit of a 6-pulse Graetz bridge inverter connected to the Y-Y transformer is shown in Fig. 1. Under normal operation, the valves VT1-6 turn on and off sequentially, the conduction interval of adjacent valve arm is \( \pi/3 \), and the range of the firing angle \( \alpha \) is \((\pi - \mu)/2 \leq \alpha \leq \pi \). The steady-state operation is as follows: two phases are short-circuited during commutation, and one phase is disconnected during non-commutation [39].

Taking the commutation process from VT1 to VT3 as an example, valves 1, 2, and 3 are in a conducting state, as shown in Fig. 2. For the loop containing VT1 and VT3, according to the boundary conditions, taking a definite integral of the commutation voltage with respect to time \( t \), with the lower limit corresponding to the start of commutation \( \alpha/\omega \) and an upper limit \((\pi - \gamma)/\omega \), we have

\[
\begin{align*}
\int_{\alpha/\omega}^{(\pi - \gamma)/\omega} u_{ba} \, dt &= \int_0^{i_d(\pi - \gamma)} 2L_c \, di_3 - \int_{i_d(\alpha)}^{i_d(\pi - \gamma)} L_c \, di_3 \\
&= \int_{i_d(\alpha)}^{i_d(\pi - \gamma)} L_c \, di_3 + \int_0^{i_d(\pi - \gamma)} 2L_c \, di_3 - \int_{i_d(\alpha)}^{i_d(\pi - \gamma)} L_c \, di_3
\end{align*}
\]

where \( u_{ba} \) is the commutation voltage, \( L_c \) is the commutation inductance of each phase, \( i_3 \) is the current flowing through VT3, \( i_d \) denotes the instantaneous DC current, \( \gamma \) is the extinction angle.

At present, in the derivation process of commutation voltage-time area, the DC current is assumed to be constant, i.e., \( i_d(t) = I_d \). \( I_d \) is the DC steady-state current. Equation (1) can be rewritten as

\[
\int_{\alpha/\omega}^{(\pi - \gamma)/\omega} u_{ba} \, dt = \int_0^{i_d(\pi - \gamma)} 2L_c \, di_3 = 2L_c I_d (2)
\]

Equation (2) reveals the main factors affecting the commutation of the inverter, which are characterized by \( \gamma, \alpha, L_c, I_d \), and the amplitude of commutation voltage.

B. COMMUTATION PROCESS WITH AC SYSTEM DISTURBANCES

Some results have demonstrated that the main reason for the CFs is the commutation voltage reduction and the shrinkage of the voltage-time area required for the commutation process [1]. However, in (2), when the system operates under the fault condition that may not cause CFs, the DC current will also change significantly, which is ignored in the steady-state analysis. In fact, the DC current will be change to a certain range, thus the term \( \int_{i_d(\alpha)}^{i_d(\pi - \gamma)} L_c \, di_3 \) should not be neglected, and it is not accurate enough to study the CF mechanism only by (2). In view of the above analysis, it is necessary to adjust the assumption of constant DC current, thus the error caused by DC current fluctuations can be theoretically avoided. So (1) is rewritten as

\[
\int_{\alpha/\omega}^{(\pi - \gamma)/\omega} u_{ba} \, dt = L_c [i_d(\pi - \gamma) + i_d(\alpha)] (3)
\]

It can be seen from (3) that the success or failure of commutation is also relevant to \( i_d \) at the start/end moment of inverter commutation. The AC faults may cause AC voltage to drop dramatically and DC current to increase remarkably. The reduction of \( \alpha \) can only advance the firing instant, however, the DC current control can be applied to the entire commutation process. Therefore, by adjusting the DC current order and controlling the DC current to satisfy (3), the commutation process can be more effectively controlled, especially in terms of preventing or reducing the risk of CFs.

III. CONSTANT EXTINCTION VOLTAGE TIME AREA CONTROL STRATEGY WITH AN IMPROVED VDCOL

In order to avoid control mode ambiguity, current error control (CEC) is added to the control system for mode stabilization in the CIGRE HVDC Benchmark [40]. This function provides a characteristic with positive slope (constant firing advance angle control) at the transition between constant...
extinction angle (CEA) control and constant current (CC) control. Although the existing controller modification-based strategies for mitigating CFs can effectively suppress successive CFs to a certain extent, these strategies have their inherent limitations and cannot suppress the CFs caused by the transient switching of the control mode. Therefore, a strategy is required to mitigate CFs and minimize the control mode instability of the HVDC system due to AC faults or control mode ambiguity. In response to this problem, a CEVTA control strategy with virtual resistance is proposed in this paper, considering the main factors affecting CFs and the control characteristics of VDCOL. The proposed control strategy plays a role in realizing a smooth switching between the CEA control and the CC control, in which the output of the CEA control is able to track the output of the CC control.

A. THE CONTROL PRINCIPLE OF VIRTUAL RESISTANCE

VDCOL has been widely used in HVDC systems to reduce the risk of CFs and improve fault recovery performance according to DC voltage [39]. However, the change in DC current is not reflected in its performance.

In order to solve this problem, inspired by the compensation resistance in the CIGRE HVDC Benchmark [40], this paper considers the limiting effect of resistance on DC current, the concept of virtual resistance is introduced to reflect the characteristics of the DC current during the fault and recovery process. The control principle of virtual resistance is presented as follows.

A virtual resistance is introduced into the control system to form a new equivalent voltage measurement point. The voltage drop caused by the DC current change on the virtual resistance is subtracted from the original DC voltage input to the VDCOL to obtain a new DC voltage, which is calculated as

\[ u'_d = u_d - R_V(i_d - i_{DN}) \]  

where \( u_d \) and \( u'_d \) denote the original and modified DC voltages respectively, \( i_{DN} \) is the nominal DC current, \( R_V \) denotes the virtual resistance. Reasonable choice of \( R_V \) is particularly important for the fault response characteristics of the control system. For a specific system, the value of \( R_V \) is determined by the allowable range of DC voltage and current. During the fault, the maximum allowable changes of \( i_d \) and \( u_d \) are \( \Delta i_{d_{\text{max}}} = i_{d_{\text{max}}} - i_{DN} \) and \( \Delta u_{d_{\text{max}}} = U_{DN} - u_{d_{\text{min}}} \), respectively. Therefore, \( R_V \) can be calculated as

\[ R_V = \frac{\Delta u_{d_{\text{max}}}}{\Delta i_{d_{\text{max}}}} \]  

The control method of the virtual resistance is shown in Fig. 5, then the relationship between \( u'_d, i_d \) and DC current order \( i_{ord} \) is given as

\[ i_{ord} = \begin{cases} i_{\text{min}} & u'_d \leq u_{\text{min}} \\ i_{\text{min}} - i_{\text{min}}(u'_d - u_{\text{min}}) + i_{\text{min}} & u_{\text{min}} < u'_d \leq u_{\text{max}} \\ u'_d + 0.1 & u'_d > u_{\text{max}} \end{cases} \]  

The \( u'_d \) is used as the input for VDCOL control and the \( i_{ord} \) is derived from the characteristics of VDCOL control. Under normal operating conditions, due to the smoothing reactors, \( i_d \) only has a slight fluctuation. From (4), \( u'_d \approx u_d \), therefore, the \( i_{ord} \) of VDCOL output is the same as the output without \( R_V \).

When an AC fault occurs, there will be \( u'_d < u_d \). Since the DC voltage input to VDCOL reflects the increase in DC current, when \( u'_d < u_{\text{max}} \), \( i_{ord} \) will decrease from the initial \( i_{\text{max}} \). Therefore, \( R_V \) makes the VDCOL more sensitive to the fault response and reduces \( i_{ord} \) in advance, which will help to reduce the occurrence of CFs and the current stress of inverter valve during fault. When \( i_d \) slowly decreases under the control system, such that \( i_d < i_{DN} \), we will have \( u'_d > u_d \), then VDCOL controls \( i_{ord} \) to increase, so that the significant reduction of transmitted power can be mitigated.

Therefore, the virtual resistance can reflect the dynamic characteristics of DC current change during the fault and system recovery process. Considering the control efficiency of VDCOL, it can quickly limit the DC current during the fault and help to restore the system.

B. CONSTANT EXTINCTION VOLTAGE-TIME AREA CONTROL STRATEGY

In order to improve the ability to suppress CFs, based on the above analysis, we present a CEVTA control strategy, in which the setting value of \( \gamma \) is adjusted dynamically using a sine-cosine component detector and considering the zero-crossing phase shift of the commutation voltage.

The objective of this control strategy is to calculate the \( \alpha \) required to maintain the rated extinction voltage-time area at the current moment. From (3), the commutation voltage-time area \( A \) is

\[ \int_{\alpha/\omega}^{(\pi-\gamma)/\omega} \sqrt{2} U_L \sin \omega t \, dt = \sqrt{2} U_L [\cos \alpha + \cos \gamma] = A \]  

where \( U_L \) is the line voltage of the inverter bus.

In order to reduce the control variables, a single relationship between \( U_L \) and \( \gamma \) is established. Based on the analysis of commutation mechanism, the extinction voltage-time area \( G \) is obtained as

\[ \int_{(\pi-\gamma)/\omega}^{\pi} \sqrt{2} U_L \sin \omega t \, dt = \sqrt{2} U_L (1 - \cos \gamma) = G \]  

The commutation voltage-time area \( A \) and the extinction voltage-time area \( G \) are shown in Fig. 3.

From (3), when the DC current is constant, \( A \) will be a constant. If the commutation voltage of inverter decreases, \( A \) will extend to the right, leading to the reduction of \( G \) and \( \gamma \). When \( \gamma < \gamma_0 \), where \( \gamma_0 \) is the critical extinction angle, a CF will occur. Therefore, from the CF mechanism, when \( G < G_0 \), a CF will occur, which can be referred to as the minimum extinction voltage-time area criterion. Under this criterion, the influence of the AC voltage, DC current and phase shift of the commutation voltage can be considered on the basis of \( \gamma_0 \) so as to better characterize the CFs. Compared
with the traditional CEA control method, the CEVTA control method is able to consider the influence of the commutation voltage change on the commutation process, and is more accurate to control $\gamma$.

From (8), we have

$$G_N = \sqrt{2} U_{LN}(1 - \cos \gamma_{refN})$$  \hfill (9)

The purpose of the rated extinction voltage-time area control strategy is to control the extinction area equal to the rated extinction area, namely

$$\sqrt{2} U_L(1 - \cos \gamma_{ref}) = \sqrt{2} U_{LN}(1 - \cos \gamma_{refN})$$  \hfill (10)

From (10), it can be deduced that

$$\gamma_{ref} = \arccos\left(1 - \frac{1 - \cos \gamma_{refN}}{U_L/U_{LN}}\right)$$  \hfill (11)

Considering zero-crossing phase shift of commutation voltage $\Phi$, (11) can be rewritten as

$$\gamma_{ref} = \arccos\left(1 - \frac{1 - \cos \gamma_{refN}}{U_L/U_{LN}}\right) + \Phi$$  \hfill (12)

It can be seen from (12) that if $U_L = U_{LN}$, then $\gamma_{ref} = \gamma_{refN}$; if $U_L < U_{LN}$, then $\gamma_{ref} > \gamma_{refN}$, the commutation margin will increase; if $U_L > U_{LN}$, then $\gamma_{ref} < \gamma_{refN}$. However, AC voltage recovery needs to absorb a certain amount of reactive power, which means that the $\gamma$ cannot be too small. Therefore, $\gamma_{ref}$ is used as the reference value of the CEA control to determine the required $\alpha$ at the current moment. The control block diagram of dynamic adjustment of $\gamma_{ref}$ is shown in Fig. 4.

The sine-cosine component detector is used to measure the single-phase voltage, in which the commutation voltage can be quickly detected [21]. It can be seen from Fig. 4 that the control system calculates the amplitude of each phase according to the instantaneous value of the three-phase AC voltage, and selects a smaller value between the minimum amplitude of AC voltage and the root mean square (rms) value of line voltage. Meanwhile, the difference between the maximum and the minimum value of three-phase voltage, and the maximum phase shift angle are calculated according to the sine theorem, so $\gamma_{ref}$ can be obtained. Compared with the CEA control, the improved variable CEA control takes into consideration the influence of the commutation voltage amplitude and the zero-crossing phase shift on the commutation process, and dynamically adjusts the $\gamma_{ref}$.

As discussed in Section III A and B, the improved control structure on the CIGRE HVDC benchmark is shown in Fig. 5.

### IV. CASE STUDY

Since the occurrence of a CF relates highly to the fault severity and the time of the fault [42], [43], thus in this paper, single- and three-phase inductive faults are applied to the inverter bus in the CIGRE HVDC benchmark system to verify the effectiveness of the proposed control strategy. The AC fault severity is represented by a inductance $L_f$. For each $L_f$, ten fault moments are set equidistantly within the range of 6.000s to 6.020s (an AC cycle of 20ms) respectively, and each fault lasting 50 ms. Four kinds of state-of-the-art control strategies are chosen for comparison, namely, CFPREV [22], DCPC [30], smooth logic switching control [36], and DC current limitation control based on virtual resistance. And the dynamic characteristics of AC voltage, DC current and extinction angle under different control strategies are analyzed, so as to test the performance of CF mitigation.

The CIGRE HVDC model and multi-infeed HVDC model are established using PSCAD/EMTDC. The CF control module of the pole control layer is constructed according to the structure diagram shown in Fig. 5. The data used in the model can be found in [42], and $\gamma_0$ is chosen as 7.2° [6]. The AC-DC current criterion (ADCC) of identifying CFs is adopted to
verify the effectiveness of control strategy in this paper, as it gives the most accurate assessment [37].

Based on the original control system, CFPREV needs to optimize four control parameters: the starting value of single- and three-phase fault voltage, and the corresponding \( \alpha \) advancement of the unit voltage drop; DCPC needs to optimize five control parameters, including the above four parameters and the DC current prediction setting value; The smooth logic switching control needs to optimize three control parameters: the starting value of the single-phase fault voltage and two PI control parameters. However, these traditional control strategies involve more parameters, which are not universal and not easy to apply in engineering practice. If the parameters are not adjusted correctly, they may cause a CF. Therefore, the parameters need to be comprehensively considered in the controller design. In addition, the starting value of voltage in these strategies is determined by multiple runs of EMT simulation. As analyzed in Section III, we can see that the proposed strategy involves only one parameter, namely the virtual resistance, and this parameter is much easier to determine.

A. SIMULATION IN CIGRE HVDC BENCHMARK
1) SINGLE-PHASE FAULT SIMULATION

For the single-phase case study on the CIGRE HVDC Benchmark system, the improvement of control strategies is studied under different fault severities of \( L_f \) and fault occurrence instants of \( t_f \). \( L_f \) varies from 0.0 to 1.0 H with a step of 0.01H. For convenience of observation, 3D graphs of the correlation between the CF occurrence and the fault level and fault instance has been converted into 2D graphs. The simulation results for different control strategies are shown in Fig. 6, where the green and yellow rectangles indicate non-CFs and CFs at one particular point respectively. Typically, CFs will occur approximately 3-6ms after the faults. From Fig. 6, whether a CF occurs or not is highly related to \( L_f \) and \( t_f \); and for a given \( L_f \), whether a CF occur or not depends highly on \( t_f \). All of the 8 kinds of control strategies can suppress CFs to some extent. However, the mitigation effects of control strategies (b), (c), (d), (e), (f), and (g) are not obvious, because the fault occurs during the commutation process or near the commutation moments, so the valve firing control system does not have enough time to adjust the firing angle. The control strategies (c), (e), (f), and (g) even deteriorate the operating characteristics of the original system and reduce the system’s ability to suppress CFs at certain instants.

In order to quantify the effectiveness of these control strategies in suppressing CFs at the same instant, the suppression ratio index \( \eta \) is defined as

\[
\eta = \frac{L_{\text{fm}} - L_{\text{in}}} {L_{\text{fm}}} \quad (13)
\]

where \( L_{\text{fm}} \) is the minimum fault inductance that the original CIGRE HVDC benchmark system can withstand without CFs at a certain instant; \( L_{\text{in}} \) is the minimum fault inductance that the improved control system can withstand. Then the suppression rate of CFs under different control strategies is shown in Table 1.

From Table 1, we can see that at 6.006s, 6.008s, 6.016s, and 6.018s, the control strategy (e) is superior to other control methods in suppressing CFs, whereas at 6.002, 6.004, 6.012 and 6.014s, CFs are more likely to occur than the original control (a). At 6.006, 6.012 and 6.016s, the control strategy (d) has better suppression effect, while the control strategies (c), (e), (f) and (g) may reduce the system’s ability to resist CFs at certain instants. Average suppression rates of the control strategies (b), (c), (d), (e), (f), and (g) are 1.66%, 3.21%, 3.35%, 6.11%, 0.95%, and 1.44%, respectively. Overall, the suppression effects of the proposed control strategies (h) and (i) are 8.12%, and 8.33%, and the occurrence of CFs can be more effectively suppressed.

Since Fig. 6 does not distinguish whether a CF occurred during the fault or the recovery process, and also without the information of successive CFs or one single CF. It only reflects whether CF occurs. Thus, it cannot be seen the real suppression effects of the control strategies (h) and (i), from Fig. 6 and Table 1. Therefore, in order to reflect the role of the virtual resistance, Fig. 7 shows the dynamic response of the system under \( L_f = 0.6 \)H and \( t_f = 6.0 \)s. In Fig. 7, ADCC_Y and ADCC_D denote the occurrence flag of CFs at the Y- and D-bridge using the proposed ADCC criterion, respectively; CEAC denotes the occurrence flag of CFs using the critical extinction angle criterion; where 1 and 0 indicate CFs and non-CFs, respectively.

As can be seen from Fig. 7 (a), without virtual resistance as a fault current limiter, the AC voltage \( U_{\text{inv}} \), DC current \( i_d \) and DC power \( p_d \) fluctuated significantly three times, shortly after the fault and subsequent recovery process; \( \gamma \) also decreased to zero three times, which indicates three consecutive CFs. And the maximum value of \( i_d \) is 2.402 p.u..

On the contrary, with the virtual fault current limiter, the system response is shown in Fig. 7 (b), and \( U_{\text{inv}} \), \( i_d \) and \( p_d \) show just one significant fluctuation. The first CF is somewhat difficult to avoid because the fault occurs when the commutation process is about to start immediately or while it is in progress, and the DC current on the inverter side cannot change fast enough and the valve firing control system does not have enough time to adjust the firing angle. However, after introducing the proposed control strategy, the DC voltage input to VDCOL is more sensitive to faults, which makes the DC current order of VDCOL decline faster. Compared with no virtual fault current limiter, it means that the commutation voltage is increased equivalently. Therefore, with virtual fault current limiter, the current stress of inverter valve can be reduced, and the maximum value of \( i_d \) decreases from 2.402 to 2.262 p.u.. Moreover, during the recovery process of the DC system, the virtual resistance reflects the dynamic fluctuation of the DC current and avoids the subsequent two CFs, thus the impact of AC faults on the inverter valves is further reduced.

As can be seen from Fig. 6, in the case of \( L_f = 0.77 \)H and \( t_f = 6.002 \)s, CFs do not occur under the proposed...
FIGURE 6. Improvement of CF mitigation during inverter single-phase faults for single HVDC.
TABLE 1. Suppression rate of CFs under different control strategies (%).

| Control Methods | Fault occurrence instants t_f /ms | \( \eta \) |
|-----------------|-----------------------------------|----------|
| a               | 0                                 | 2.2      |
| b               | 2                                 | 0.0      |
| c               | 4                                 | 2.4      |
| d               | 6                                 | 3.2      |
| e               | 8                                 | 3.2      |
| f               | 10                                | 4.8      |
| g               | 12                                | -1.6     |
| h               | 14                                | 0.0      |
| i               | 16                                | 9.4      |
| j               | 18                                | 0.0      |

FIGURE 7. System responses under single phase fault (\( L_f = 0.6H \), \( t_f = 6.00s \)).

FIGURE 8. System responses under single phase fault (\( L_f = 0.77H \), \( t_f = 6.002s \)).

It can be seen from Fig. 8, \( 2i_{do} \) and \( 2i_{dp} \) denote 2 times DC current under the original and proposed strategies, respectively; \( i_{so} \) and \( i_{sp} \) denote the absolute sum of Y- and D-bridge valve side AC currents under the original and proposed strategies, respectively. The indicators of ADCC_o and ADCC_p denote the occurrence flag of CFs under the original and proposed strategies using ADCC respectively.

It can be seen from Fig. 8 that, the proposed control strategy can timely suppress the DC current during the fault and improve the DC current recovery characteristics after the fault. In practical engineering, if \( \gamma \leq 7.2^\circ \), a CF is considered to occur [6]. However, CFs would not occur under the proposed control strategy, when \( \gamma = 6.586^\circ \). The simulation results also show that accuracy of ADCC is higher than the critical extinction angle criterion. Thus, ADCC is used to identify CFs in our simulation. Meanwhile, it is found that CF phenomenon is affected by the speed of the voltage drop, not by the magnitude of the voltage drop.

2) THREE-PHASE FAULT SIMULATION

For the three-phase fault on the CIGRE HVDC Benchmark system, the improvement of control strategies is studied under different \( L_f \) and \( t_f \) parameters, and \( L_f \) varies from 0.0 to 1.3H with a step of 0.01H. Due to limited space, detailed CF simulation results similar to Fig. 6 are not shown here. The summarized suppression rates of CFs under different control strategies, using the suppression ratio index \( \eta \), are shown in Table 2.

From Table 2, we can see that the control strategies (b), (c), (e), (f), (g), (h), and (i) can suppress CFs to some extent; however, the mitigation effects of these control strategies will be inconspicuous if the fault occurs when the commutation process is about to start immediately or while it is in progress; The control strategy (d) has no effect on the control strategy, while CFs will occur under other control strategies. The simulation waveforms of \( U_{inv} \), \( i_d \), ADCC and
first CF; the control strategies (f) and (h) even deteriorate the dynamic performances of the original system and reduce the system’s ability to suppress CFs at certain instants; At 6.006s, 6.008s, 6.010s, and 6.018s, the control strategy (e) is better than other control strategies in suppressing CFs. The average suppression rates of strategies (b) to (i) are 1.4%, 2.72%, 0%, 4.97%, 1.25%, 1.81%, 3.59% and 6.8%, respectively. Overall, the proposed control strategy (i) is more effective in mitigating CFs under three-phase faults, and followed by control strategies (e), (c), and (g).

Similarly, in order to reflect the role of the virtual resistance, Fig. 9 shows the dynamic response of the system under \( L_f = 0.6 \)H and \( t_f = 6.0 \)s. The analysis of Fig. 9 is similar to Fig. 7, during the fault and recovery process, the virtual resistance reflects the dynamic fluctuation of the DC current and suppresses the subsequent CFs, thus the impact of AC fault on the inverter valves is further reduced, and the maximum value of \( i_d \) decreases from 2.611 to 2.55 p.u.

From the analysis of Fig. 9 and Table 2, it can be seen that the proposed control strategy (i) and the smooth logic switching control (e) are better at suppressing CFs.

The simulation waveforms of \( U_{inv} \), \( I_d \), ADCC and \( \gamma \) in the case of \( L_f = 1.19 \)H, \( t_f = 6.004 \)s are shown in Fig. 10 without CFs under the control strategies of (i) and (e). It can be seen that compared with other control strategies, the proposed control strategy (i) and control strategy (e) can timely suppress the DC current during the fault and improve the DC current recovery characteristics after the fault, which improves the automatic recovery ability of the system under AC faults. The simulation results also show that the accuracy of the ADCC is higher than the critical extinction angle criterion. Similarly, it is also found that CF phenomenon is affected by the speed of the voltage drop, not by the magnitude of the voltage drop.
B. SIMULATION IN MULTI-INFEED HVDC SYSTEM BASED ON THE CIGRE HVDC BENCHMARK MODEL

As analyzed in section IV A, the proposed control strategy can more effectively suppress the occurrence of CFs, than the other comparative control strategies. Therefore, this section will only compare the CF suppression effect between the original control system and the proposed control strategy, in multi-infeed HVDC systems.

![Schematic representation of multi-infeed HVDC systems.](image)

1) DUAL-INFEED HVDC SYSTEM MODEL

The schematic representation of a typical dual-infeed HVDC system is shown in Fig. 11 [41], in which the data in the model is from [42]. The AC fault severity is also represented by fault inductance $L_f$, applied to the local inverter bus. In multi-infeed HVDC systems, CFs that only occur at the local inverter is called “local CFs”, CFs that occur at both the local and remote inverters are called “concurrent CFs”.

Due to the interaction between the multiple inverters at the receiving-end AC system, multi-infeed HVDC system has more complex CF behaviors than the single-infeed HVDC system, namely the anomalous CF phenomenon [42]. That is, concurrent CFs not only occur under more severe faults expected based on the existing results, but also occur under unexpected minor faults. There may be a risk of concurrent CFs in multi-infeed HVDC systems if the anomalous CF phenomenon is unconsciously neglected by the power system engineers.

In this paper, the anomalous CF caused by the voltage distortion under low fault severity is determined using the EMT multiple runs method. It is found that if $Z_{12} < 2.0p.u.$, there will be no anomalous CF in the system, and the multi-infeed HVDC system can be regarded as a single-infeed HVDC system. In this case, the result of the CF suppression effect is the same as that of a single-infeed HVDC system. For the case of $2.0 \leq Z_{12} < 2.5p.u.$, the anomalous CF in concurrent CF will occur. And when $Z_{12} \geq 2.5p.u.$, anomalous CF will disappear again. Therefore, the case of $Z_{12} = 2.0$ p.u. is selected to verify the CF suppression effect of the proposed control strategy in the multi-infeed HVDC system. The phenomenon of anomalous CF at the remote inverter, with the parameters of $\text{SCR}_1 = \text{SCR}_2 = 2.5$, $Z_{12} = 2.0$ p.u., is shown in Fig. 12. Fig. 12 (a) shows that whether a remote CF occurs or not at one particular point, also represented by the yellow and green dots, respectively. Fig. 12 (b) shows the probability of remote and local CFs with the fault severity through the red and blue curve respectively. The probability of CFs can be calculated by counting up the CF number at different fault moments under each fault severity. For each $L_f$, 100 fault-instants are set equidistantly within an AC cycle of 20ms.

In order to verify the effectiveness of control strategy to inhibit concurrent CFs in multi-infeed HVDC systems, the anomalous CF phenomenon must be sufficiently considered so as not to exaggerate the effect of suppressing CFs. Typically, CFs occur approximately 3-6ms and 5-18ms after the fault for local and remote inverter respectively.

2) SINGLE-PHASE FAULT SIMULATION

The improvement of the proposed control strategy for both local and remote CF suppression is studied under different single-phase fault parameters of $L_f$ and $t_f$. $L_f$ varies from 0.0 to 1.0H with a step of 0.01H. It can be seen from the simulation results in Fig. 13 that, the proposed control strategy is more effective in mitigating CFs. Since that under the original control strategy, the anomalous CF phenomenon in the remote inverter of the system, as shown in Fig. 13 (a); while under the proposed control strategy, the anomalous CF phenomenon disappears, as shown in Fig. 13 (b).

Similarly, to quantify the effectiveness of the control strategy in suppressing CFs, the suppression ratio index $\eta$ is used.
TABLE 3. CF Suppression Rate under original and Proposed control strategies (%).

| Control Methods | Fault occurrence instants t_f /ms |
|-----------------|-----------------------------------|
|                 | 0 | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 | 18 |
| Original        | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| Proposed        | 6.6 | 4.5 | 9.3 | 6.7 | 5.3 | 5.3 | 4.6 | 0 | 8.1 | 7.9 |

The suppression rates of CFs under different control strategies are shown in Table 3.

From Table 3, we can see that the proposed control strategy can effectively mitigate the occurrence of CFs. It should be noted that under the original control strategy, the anomalous CF phenomenon often occurs in the remote inverter, whereas the anomalous CF phenomenon basically disappears under the proposed control strategy, so the suppression rate of the proposed control strategy is relatively satisfactory.

3) THREE-PHASE FAULT SIMULATION

For the three-phase fault on the multi-infeed HVDC system, the improvement of the proposed control strategy is studied for both local and remote CFs under different three-phase fault parameters of L_f and t_f. L_f varies from 0.0 to 1.2H with a step of 0.01H. The simulation results are shown in Fig. 14,
indicating that the proposed control strategy is also effective in mitigating CFs under three-phase faults.

Similarly, the suppression ratio index \( \eta \) is used to quantify the effectiveness of the proposed control strategy. The suppression rates of CFs under different control strategies are shown in Table 4.

| Control Methods | Fault occurrence times \( t_i / s \) |
|-----------------|-----------------------------|
| Original        | 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 |
| Proposed        | 6.5 6.7 3.9 4.9 5.7 2.9 6.7 8.3 3.7 1.0 |

From Table 4, we can see that the proposed control strategy can mitigate CFs more effectively. It should be noted that the proposed control strategy can still better suppress the anomalous CF phenomenon in the remote inverter, so the overall suppression rate of the proposed control strategy is relatively high. However, for some instances, i.e., 6.006s, 6.008s, 6.010s, 6.018s, the mitigation effect of the proposed control strategy is inconspicuous, because the fault occurs during the commutation process or near the commutation instant, so the DC current cannot change fast enough and the valve firing control system does not have enough time to adjust the firing angle.

V. CONCLUSION

In order to address the control mode ambiguity issues of existing controller modification-based strategies for the inverters in HVDC systems, this paper proposed a constant extinction voltage-time area control strategy with virtual resistance to mitigate successive and intermittent CFs. The improved variable extinction angle control considers the influence of the commutation voltage amplitude and the zero-crossing phase shift on the commutation process, so the extinction angle setting value can be adjusted dynamically. Meanwhile, the virtual resistance is able to reflect the dynamic characteristics of DC current during the fault and system recovery process, which has good response sensitivity. Combining the control efficiency of VDCOL, the proposed control strategy can improve the DC current recovery characteristics after the fault and make the system easy to recover. Based on the ADCC criterion and the suppression ratio index, a standard for objectively evaluating the suppression effect is given.

Using the EMT multiple runs method on PSCAD/EMTDC, the effectiveness of the proposed control strategy is verified by simulation of the CIGRE HVDC benchmark system. Comparing with the existing controller modification-based strategies, the proposed control strategy has considerably better average suppression rates of 8.33% under single-phase faults and 6.8% under three-phase faults. Further simulations on the multi-infeed HVDC systems also verify the effectiveness of control strategy to suppress concurrent CFs, at multiple inverters. Therefore, the proposed strategy would provide a new orientation for the future studies on prevention and control measures of CFs in HVDC systems.

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