Consecutive Commutation Failure Mitigation Caused by AC Filters Switching

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Abstract. AC filter bank switching in the HVDC inverter station may cause harmonics which leads to commutation failure. This paper analyses the characteristics of AC filter switching and build the transient progress circuit and mathematics model. And the time-response solution of AC filter overvoltage is acquired, the AC voltage magnitude decrease and distortion can be calculated. Commutation caused by these reasons was analyzed. And a consecutive commutation failure mitigation method is proposed. The algorithm was verified in the PSCAD/EMTDC.

1. Introduction

Traditional HVDC transmission has developed rapidly in China in recent years due to its large transmission capacity, strong economy and controllability of long-distance transmission, and its advantages of asynchronous interconnection [1]. When adjusting HVDC operating state, switching filters are needed to eliminate harmonics and ensure the supply of reactive power. Therefore, switching of AC filters is usually very frequent. When the switching time of the filter is inappropriate, the voltage distortion of AC bus in the transient process is large. Although AC filters are generally equipped with selectable phase closing devices to control the switching time of the filters, it is difficult to suppress the voltage distortion due to uncertain factors such as environment, temperature and so on. While voltage distortion may lead to commutation failure [2-5]. Commutation failure are investigated in Guangzhou converter station of Tian-Guang HVDC project in [6], which prove that commutation failure in inverter station can be caused by AC filter switching-on when AC filter switching-on at a wrong timing, especially if the AC system strength of inverter side of HVDC system is weak. Based on Shanghai Fengjing converter station, inverter converter commutation failure caused by AC filter switching-on in engineering application are analyzed, and improvement measures are proposed [7]. In [8] the correlation between operation performance and harmonic characteristic of UHVDC system is analyzed, then a detailed hybrid simulation model for UHVDC/UHVAC system of CSG in the year of 2010 is built and by use of this model the commutation failure caused by the switching of filters is researched. The above literature reported the HVDC commutation failure caused by filter switching, but did not analyze the reason of commutation failure from the mechanism, so it is impossible to give a mitigation method to prevent the consecutive commutation failure caused by AC filters switching.
In this paper, the circuit model of AC filter switching process is established and its analytical solution is given. The mathematical expression of commutation voltage time-area method is further derived. On this basis, the mechanism of commutation failure of AC filter switching is analyzed, and the countermeasures to prevent commutation failure caused by filter switching are given.

2. Analysis of commutation failure caused by AC filter switching

2.1. Analysis of AC filter switching process

The commutation process of HVDC depends on AC system voltage. To analyze the commutation process, it is necessary to model the transient voltage process of AC filter switching. Each group of filters usually adopts double or triple-tuned filters, which can be equivalent to the parallel connection of single-tuned filters. Therefore, the circuit model of the switching process of filters is the parallel connection of multiple series single-tuned filters. Transient voltage also needs to consider the system operation mode, converter transformer impedance and load state[5].

The frequency domain circuit model of filter switching transient process is shown in Fig. 1. $u(s)$ is the voltage source with constant internal potential in receiving end power grid. $R_i$ and $L_i$ is equivalent internal impedance which represent the receiving end power grid. $L_1I(0)$ is the zero-state potential of equivalent reactance. There are $i$ ($i=1, 2, 3, \ldots, m$) filter branches in the model, while $I_i(s)$ is the current of each branch. Each branch is a single-tuned filter branch connected in series with resistor $R_i$, capacitor $C_i$ and inductor $L_i$. $U_{ci}(0)/s$ is the zero-state potential of capacitor $C_i$. $L_1I_i(0)$ is the zero-state potential of inductance $L_i$. $K(i)$ is the state of the filter branch, including switching, steady state or non-switching state. $I(s)$ is the current flowing out of the system. The current source $I_i(s)$ represents the system load. Each filter branch is in the switched or switched steady state. The general circuit equation is listed as shown in equation (1) - (3).

$$ u(s)+L_1I(0)-(R_i+L_1)sI(s)=(1/C_s+L_1s+R_i)I_i(0)s+u_{ci}(0)/s-L_1I_i(0) $$

$$ (1/C_s+L_1s+R_i)I_i(s)+u_{ci}(0)/s-L_1I_i(0)=(1/C_s+L_1s+R_i)I_i(s)+u_{ci}(0)/s-L_1I_i(0) $$

$$ I_i(s)=\frac{s}{j=1}I_i(s) $$

Where $j=1, 2, 3, \ldots, m, i\neq j$. Simplified by formula (1) - (3).

$$ \left\{ \frac{1}{C_s} \left[ L_s + \sum_{j=1}^{m} C_j \right] s + \left[ R_s + \sum_{j=1}^{m} C_j \right] \right\} I_i(s)=u(s)+L_1I_0(s)+L_1I_i(0)-u_{ci}(0)/s $$

$$ -(sL_s+R_s) \sum_{j=1}^{m} \frac{u_{ci}(0)}{s} - \frac{u_{ci}(0)}{s} - L_1I_i(0) + L_1I_i(0) $$

$$ \left( \frac{1}{C_s} + L_s + R_s \right) \sum_{j=1}^{m} \frac{u_{ci}(0)}{s} - \frac{u_{ci}(0)}{s} - L_1I_i(0) + L_1I_i(0) $$

$$ \left( \frac{1}{C_s} + L_s + R_s \right) \sum_{j=1}^{m} \frac{u_{ci}(0)}{s} - \frac{u_{ci}(0)}{s} - L_1I_i(0) + L_1I_i(0) $$

$$ \left( \frac{1}{C_s} + L_s + R_s \right) \sum_{j=1}^{m} \frac{u_{ci}(0)}{s} - \frac{u_{ci}(0)}{s} - L_1I_i(0) + L_1I_i(0) $$
$i_i(t)$ can be achieved for (4) after simplification. The transient voltage of capacitors, reactors and resistors can be further obtained.

$$
 u_i(t) = a x_i \sin(\alpha t + \theta) - \frac{a x_i^2}{a_i} \cos \theta + \frac{a x_i}{a_i} \sin \omega t e^{-\alpha t} \cos \theta + \frac{a x_i}{a_i} \sin \omega t e^{-\alpha t} \cos \theta
$$

$$
 u_i(t) = -a x_i \sin(\alpha t + \theta) + ax_i \cos \theta + \frac{a x_i}{a_i} \sin \omega t e^{-\alpha t} \cos \theta + \frac{a x_i}{a_i} \sin \omega t e^{-\alpha t} \cos \theta
$$

$$
 u_i(t) = a R \cos(\alpha t + \theta) + a R \frac{a x_i}{a_i} \cos \omega t e^{-\omega t} \cos \theta + \frac{a x_i}{a_i} \sin \omega t e^{-\alpha t} \cos \theta + \frac{a x_i}{a_i} \sin \omega t e^{-\alpha t} \cos \theta
$$

Where

$$
 u(t) = u_i \sin(\alpha t + \theta)
$$

$$
 x_i = x_i + x_i a_i [1 - \frac{x_i}{x_i}]
$$

$$
 R = R_i + R_i \frac{a_i}{a_i} [1 - \frac{x_i}{x_i}]
$$

$a$, $b$ and $c$ are constant respectively.

$$
 a = \frac{u_i}{x_i - x_i}
$$

$$
 b = \frac{x_i f(0) + x_i f(0)}{x_i}
$$

$$
 c = \frac{u_i(0)}{x_i}
$$

$\theta$ is the initial phase angle of filter closing or opening. The initial values of current and voltage of each branch are approximated by formulas (14), (15).

$$
 I_i(0) = \frac{u_i}{x_i - x_i - x_i} \cos \theta
$$

$$
 u_i(0) = \frac{x_i u_i}{x_i - x_i - x_i} \sin \theta
$$

The transient voltage of AC bus can be obtained.

$$
 u_s(t) = u_i(t) + u_i(t) + u_h(t)
$$

2.2. Commutation failure mechanism caused by switching of AC filter

After commutation, the thyristor passes from the forward to the reverse to withstand a certain time of reverse voltage. Otherwise, the thyristor may be re-turned on under the action of forward voltage, leading to commutation failure. The turn-off angle $\gamma$ represents the electrical angle between the turn-off time of the commutator valve and the zero-crossing point of the line voltage. When $\gamma < \gamma_{\text{min}}$, commutation failure occurs in converters. $\gamma_{\text{min}}$ is the inherent critical turn-off angle of thyristor which reflects the shortest time required for thyristor to withstand reverse voltage to recover its blocking ability.

$$
 |S_r| < |S_r|
$$

Where $|S_r|$ is the commutation voltage time area provided by AC system. $|S_{cr}| = 2L_c |I_d|$, where $L_c$ is the commutation reactance, $I_d$ is the DC side current during commutation, $|S_{cr}|$ is the voltage time area required during commutation.

When the value of $\Delta S = |S_{cr}| - |S_r|$ is positive, the bigger the value is, the greater the commutation margin. When the filter is switched on and off, the voltage waveform is distorted, and
the transient waveform can be obtained according to formula (16). The time area of commutation voltage that the AC system can provide has changed. When the value of 
\[ \Delta S = |S_{cr} - |S_a| \] 
is negative, a commutation failure occurs.

3. Method of consecutive commutation failure mitigation caused by AC filters switching

When HVDC inverter side converter commutates from valve 6 to valve 2, the commutation process can be expressed as follows:

\[ L \frac{di_6}{dt} - L \frac{di_2}{dt} = \sqrt{2}U \sin(\alpha t) \]  

(18)

Where \( i_6, i_2 \) are the current flowing through thyristor 2 and thyristor 6 respectively. \( L \) is the system equivalent commutation reactance. \( U \) is the valid value of valve commutation line voltage \( U_{BC} \). \( \alpha \) is the angular frequency of AC system. Considering harmonics and zero-crossing offset of commutation voltage, by integrating the two sides of the equation (2), the relationship between thyristor commutation area \( S \) and turn-off angle \( \gamma \) can be obtained.

\[ S = \frac{L}{2} I_i \frac{\gamma - \varphi - \Upsilon}{\cos \beta} \sqrt{2}U \sin(\alpha t) d(\alpha t) \]  

(19)

Formula (18) is simplified to obtain:

\[ \gamma = \arccos \left( \frac{\sqrt{2}L}{U} \frac{I_i}{I_2} + \cos \beta \right) + \varphi + \Upsilon \]  

(20)

Where \( \varphi \) is the zero-crossing offset of commutation voltage. \( \Upsilon \) is the harmonic content factor. When asymmetric faults occur, the zero-crossing offset of commutation voltage can be calculated using the following formula:

\[ \Delta \varphi = \arctan \left( \frac{\Delta U}{\sqrt{2}U} \right) \]  

(21)

The harmonic component can be derived from the following equation.

\[ D = \frac{\Delta L Z}{E_i} \times 100\% \]  

(22)

Where \( I_i, Z_i \) are the current and impedance of \( n \)th harmonic respectively. Harmonic influence factor can be given by the following formula.

\[ \Upsilon = \Upsilon_{low} = \left\{ \begin{array}{ll} \frac{D \times K_{low}}{U_{low, min} > k} \hfill \\
0 & \text{if } U_{low, min} < k \end{array} \right. \]  

(23)
increase the turn-off angle of the follow-up valves to avoid the failure of consecutive commutation. The proposed algorithm can be applied to commutation failure control module, and its topology is shown in Figure 2. The zero sequence component is used to detect asymmetric faults, the modulus transformed by $\alpha\beta$ is used to detect three-phase faults, and the harmonic module is used to detect the harmonic content. When the fault of AC system is detected, the commutation failure control module is started and the arc extinguishing angle is increased [10].

4. Simulation analysis
In order to validate the effectiveness of the proposed algorithm, a standard test model based on CIGRE benchmark is used to verify the validity of the proposed algorithm. The rectifier side of CIGRE model is equipped with a constant current controller, and the inverter side is equipped with a constant extinguishing angle controller. When the system fails, the control system contains a low voltage dependent current order limit (VDCOL) to restore the system. The AC bus on the inverting side contains three groups of filters, which filter out 11 harmonics, 13 harmonics and provide reactive power compensation, respectively, as shown in Figure 3.

In the simulation, the 11th harmonic filter is removed at 1.0s, and the voltage waveform of AC bus on the inverting side is shown in Figure 4. When the filter is removed, obvious voltage waveform distortion occurs.
commutation failure occurred around 200 ms. The corresponding waveforms of DC current and arc extinguishing angle are shown in Figure 5.

![Waveforms of DC current and arc extinguishing angle](image)

**Figure 5.** HVDC system response: (a) DC current; (b) extinction angle.

Fourier decomposition of converter buses is carried out to obtain the magnitude of each harmonic, as shown in Figure 6. As can be seen from the figure, the switching of the filter causes a large number of harmonics, the amplitude of fundamental voltage decreases, and the amplitude of harmonic voltage rises, which leads to commutation failure.

![Fundamental voltage and harmonic voltage magnitude](image)

**Figure 6.** Fundamental voltage and harmonic voltage magnitude.

Total harmonics distortion (THD) of commutation voltage is shown in Figure 7. It can be seen that when two commutation failures occur, the harmonic distortion rate increases, which can be judged as the first commutation failure caused by harmonics.

![Commutation voltage total harmonics distortion](image)

**Figure 7.** Commutation voltage total harmonics distortion.

The second, eleventh and thirteenth harmonic amplitudes are extracted. It can be seen that after the first commutation failure, the second harmonic amplitude rises rapidly. It can be judged that the rise of DC current leads to the saturation of the converter transformer, and then a large number of harmonics lead to the second commutation failure, as shown in Figure 8.

![2nd and 11th, 13th harmonic voltage magnitude](image)

**Figure 8.** 2nd and 11th, 13th harmonic voltage magnitude.

In order to suppress the consecutive commutation failure caused by harmonics, the proposed algorithm is modeled in PSCAD/EMTDC [11], and the dynamic calculation of the turn-off angle...
controller setting value is carried out when the filter banks are switched on and off. The simulation results are shown in Figure 9. It can be seen that when the filter banks are removed, the setting value of the turn-off angle increases rapidly, which improves the turn-off margin of the follow-up valves. Then, due to the effect of harmonic term, the turn-off angle setting value continues to increase, and finally tends to be stable [10].

The response of the DC system is shown in Figure 10. After applying the proposed algorithm, the DC current overshoot is smaller and the recovery is more stable. The arc-extinguishing angle decreases to zero when the AC filter is removed, and the first commutation failure occurs. Then the arc-extinguishing angle increases rapidly and keeps to a larger value, which ensures the commutation margin and effectively avoids the second commutation failure.

5. Conclusion
In this paper, the circuit model of AC filter switching process is established and its analytical solution is given. The mathematical expression of commutation voltage time-area method is further deduced. On this basis, the mechanism of commutation failure of AC filter switching is analyzed, and the countermeasures to prevent consecutive commutation failure caused by filter switching are given. The proposed strategy is simulated in PSCAD/EMTDC, and the simulation results prove its effectiveness.

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