Analysis and calculation method of critical voltage of DC commutation process considering AC system single-phase fault moments

Jingqiu Zhang1, Yongli Li1, Xiaolong Chen1

1Key Laboratory of Smart Grid of Ministry of Education, Tianjin University, Tianjin, People’s Republic of China

Abstract: This paper takes a close research on the impact of voltage reduction in a single phase as well as its occurring moments on commutation failures (CFs). When there is a sudden voltage reduction in a single phase, the change rule of post-fault magnitudes and phases of commutation voltages is researched theoretically. On the basis of the change characteristic, valves that are most probable to suffer from CFs are carefully elaborated. Moreover, a method for calculating critical voltage of a single phase considering different fault moments is developed. As long as the phase voltage is lower than the critical voltage, it may result in a CF. In addition, the change regularity of critical voltage along with different fault moments and phases is given. All the analysis and theoretical calculation results are validated by simulation in PSCAD/EMTDC.

1 Introduction

Commutation Failure (CF) is the phenomenon that a valve which is supposed to turn off continues to conduct without transferring its current to the next valve in the firing sequence [1, 2]. Main factors affecting the onset of a CF include reduction of AC voltage amplitude, rise of DC current, ratio, and leak reactance of the transformer, fault occurring moments, zero-crossing phase shift, and distortions on the voltage wave form etc [1–5]. CFs arisen from AC system fault moments have been common in AC/DC hybrid systems. According to the statistics, AC system single-phase fault accounts for 93% of the total faults [6]. In China, an AC system single-phase fault triggering multi-infeed HVDC transmission systems blocked has been frequent during the past years, resulting in threat to the stability to power grids and great economical loss [7–9]. Nevertheless, in the practical power system engineering application in China, it takes the method of judging whether AC bus voltage drops to a critical value to determine if or not a CF occurs [10]. Therefore, authentic research to reveal the complex relationship between critical voltage of the AC bus and a single-phase fault occurring at different moments is high on the agenda.

In [1], an AC system single-phase fault is carefully studied by a reduction in the magnitude of the fault phase voltage. Moreover, research in paper [2, 11] shows that methods proposed in [1] may produce inaccurate results because of neglecting dynamics of AC voltage and DC current. In [11], a new CF criterion considering DC current dynamics to reveal the impact of fault occurring moments has been proposed. Fast calculation methods for CF in multi-infeed HVDC system are studied in paper [12, 13]. All of the research in paper [11–13] focus on AC system balanced three-phase fault. The influence of an AC system single-phase fault as well as its occurring moments on the commutation voltage at valve side and commutation process still lacks authentic research.

Here, when there is a sudden voltage reduction in a single phase, the change rule of post-fault magnitudes and phases of commutation voltages at valve side is researched theoretically. On the basis of the change characteristic, valves that are most probable to suffer from CFs are carefully elaborated. After that, a method for calculating critical voltage of a single phase considering different fault moments is developed. In addition, the change regularity of critical voltage along with different fault moments and phases is discussed in detail.

2 Calculation of commutation voltages

Valves on the inverter side are connected to the transformer in a 12-pulse pair in HVDC system, shown in Fig. 1. \( e_a \), \( e_b \), \( e_c \) stands for equivalent potential. \( U_{dc} \), \( I_{dc} \), \( L_c \) is the DC voltage, DC current, commutation inductance, respectively.

At the normal operating point, commutation voltage of valves in the delta group lags 30° behind that of valves in the wye group. When a single-phase fault occurs at the converter bus, AC voltages at the bus would become unbalanced. The commutation voltages of valves in a 12-pulse pair change along with the voltage reduction magnitude of the fault phase. For example, if \( A \)-phase voltage magnitude is reduced to some per unit value, designated as \( k \) \((0 < k < 1)\), then the post-fault values of voltages at the converter bus can be given by:

\[
\begin{align*}
\varepsilon_{ha} &= \frac{\sqrt{3}}{2} k E \sin(\omega t + 150°); \\
\varepsilon_{hb} &= \varepsilon_{hc} = \frac{\sqrt{3}}{2} k E \sin(\omega t + 30°); \\
\varepsilon_{ha}' &= \varepsilon_{hc}' = \frac{\sqrt{3}}{2} E \sin(\omega t - 90°) 
\end{align*}
\]  

(1)

where \( E \) is the pre-fault line-to-line rms voltage of the converter bus. \( \omega \) is system angular frequency. Then, the post-fault phase voltage of a 12-pulse pair can be calculated as:
where \( \theta = \gamma, \phi, d, \delta = 0, \pi/6; a = e^{j2\pi/3}, a_2 = e^{j4\pi/3} \), \( k_T \) is the ratio of the transformer. Therefore, commutation voltages of valves in the wye group and the delta group can be solved separately as:

\[
\begin{align*}
\varepsilon_{L_y}(a) &= \frac{1}{3k_T} \left[ e^{j\theta} + e^{j\omega t} - e^{j\omega t + j\theta} \right] \\
\varepsilon_{L_y}(b) &= \frac{1}{3k_T} \left[ e^{j(\theta + \delta)} + e^{j(\omega t + \delta)} - e^{j(\omega t + \delta + \theta)} \right] \\
\varepsilon_{L_d}(a) &= \frac{1}{3k_T} \left[ e^{j\theta} - e^{j\omega t} - e^{j\omega t + j\theta} \right] \\
\varepsilon_{L_d}(b) &= \frac{1}{3k_T} \left[ e^{j(\theta + \delta)} - e^{j(\omega t + \delta)} - e^{j(\omega t + \delta + \theta)} \right] \\
\varepsilon_{L_y}(a) &= \frac{1}{3k_T} \left[ e^{j\theta} + e^{j\omega t} + e^{j\omega t + j\theta} \right] \\
\varepsilon_{L_y}(b) &= \frac{1}{3k_T} \left[ e^{j(\theta + \delta)} + e^{j(\omega t + \delta)} + e^{j(\omega t + \delta + \theta)} \right] \\
\end{align*}
\]

(2)

where \( \theta = 0 \), \( \phi = 0, \delta = 0, \pi/6 \).

According to (3)–(6), when there is a sudden reduction in A-phase voltage, commutation voltages at the side of the wye transformer and the delta transformer differ greatly and the change regularity is illustrated in Fig. 2.

As can be seen from Fig. 2, the magnitudes and phases of voltages in the wye group and delta group change along with A-phase voltage reduction magnitude at the converter bus, namely the value of \( k \). The rules with \( k \) can be concluded as follows:

(a) For valves connected to the wye transformer, when there is a sudden reduction in A-phase voltage, the post-fault magnitudes of \( e_{L_y}(a) \), \( e_{L_y}(b) \), \( e_{L_y}(c) \), \( e_{L_d}(a) \), \( e_{L_d}(b) \), \( e_{L_d}(c) \) drop a little. The relationship of post-fault magnitude values can be written as:

\[
\varepsilon_{L_d} < \varepsilon_{L_y} < \varepsilon_{L_y} \quad \text{for } k \leq 1
\]

(b) For valves connected to the delta transformer, when A-phase voltage at the converter bus suffers from a sudden reduction, the post-fault phase of \( e_{L_d}(a) \) lags while that of valves in the delta group can only be up to 15° (when \( k = 1 \)). The magnitudes of \( e_{L_y}(a) \), \( e_{L_y}(b) \), \( e_{L_y}(c) \), \( e_{L_d}(a) \), \( e_{L_d}(b) \), \( e_{L_d}(c) \) decrease.

(c) Special attention should be paid to the values of phase shift that the phase shift of valves in the wye group can be up to 30° while that of valves in the delta group can only be up to 19° (when \( k = 0 \)).

Thus, the magnitude values can be written as:

\[
2k + 1 \leq \frac{k^2 + 3}{3} \quad \text{for } k \leq 1
\]

(7)

Hence, it can be predicted that valves that take \( \varepsilon_{L_y}, \varepsilon_{L_d} \) as their commutation voltages are most likely to suffer from CFs. Hence, this will be verified by later simulations here.

3 Calculating critical voltage considering different fault moments

The sudden reduction in A-phase voltage (the value of \( k \)) may have a great influence on the magnitudes and phases of commutation voltages, and then the commutation process. Moreover, different fault moments can also have impact on the post-fault DC current, which directly influences the commutation process. Accordingly, quantified calculation method can be proposed considering fault moments based on the analysis on magnitudes and phases of commutation voltages.

At the normal operating point, valves in a 12-pulse pair are triggered every 30° in the sequence of \( V_{11} \cdots V_{12} \cdots V_{16} \cdots V_{60} \). Valves are under the normal working modes '4-5'. At working mode '4', four valves are at work (two in the wye group and another two in the delta group, illustrated in Fig. 3a). At working mode '5', five valves are at work (three in the group which is experiencing a commutation process and two in the other, illustrated in Fig. 3b). For the normal working condition, DC current can be calculated as [1]:

\[
I_d = \frac{\sqrt{2}E}{20Lk_T}(\cos \gamma - \cos \beta)
\]

(8)
where γ and β are the extinction angle and leading angle at the normal working point.

### 3.1 Single-phase fault occurring at working mode ‘4’

Take the commutation process from V1_1 to V1_3 as an example. When there is a sudden reduction in A-phase voltage during time period of V1_1, V1_2, V1_3, V1_Δ, V1_Δ being at work (working mode ‘4’, as shown in Fig. 2a), the commutation process from V1_1 to V1_3 would then carry on under the influence of ε<sub>cube</sub>. The basic circuit relationship during the commutation process from V1_1 to V1_3 can be described as:

\[
L_s \frac{d i_{y_1}(t)}{dt} - L_c \frac{d i_{y_3}(t)}{dt} = \sqrt{2} E \frac{k_f}{k_r} \sqrt{\frac{k^2 + k + 1}{3}} \sin(\alpha t + \phi_i) \tag{9}
\]

Substituting (10) into (9), then the circuit relationship can be written as:

\[
\sqrt{2} E \frac{k_f}{k_r} \sqrt{\frac{k^2 + k + 1}{3}} \sin(\alpha t + \phi_i) = \left( I_d + I_y \right)
\]

From (14) and (8), 'the critical k value' can be calculated as:

\[
\sqrt{k^2 + k + 1} = \left( I_d + I_y \right)
\]

It is worth mentioning that the phase shift φ<sub>1</sub> is also related to k (as stated in (4)). According to (4) and (13), the critical value of k can be calculated. The per unit DC current reflects the influence of different fault moments. At working mode ‘4’, once per unit sudden voltage reduction in A-phase is lower than ‘the critical k value’, it will cause a CF.

### 3.2 Single-phase fault occurring at working mode ‘5’

Likewise, when there is a sudden reduction in A-phase voltage during time period of V1_1, V1_2, V1_3, V1_Δ, V1_Δ being at work (working mode ‘5’, as shown in Fig. 2b), the commutation process from V1_1 to V1_3 will then be divided into two parts in order to calculate ‘the critical k value’. One part is the time period from (π-β)/ω to (π + β + θ)/ω, during which the commutation process will carry on under normal commutation voltage ε<sub>cube</sub>. The other is the period from (π-β + θ)/ω to (π-γ<sub>imin</sub>-φ<sub>1</sub>)ω, during which the commutation process will carry on under post-fault commutation voltage ε<sub>cube</sub>. (θ represents for the single phase fault moment.) Detailed calculations are elaborated as follows.

From (π-β)/ω to (π-β + θ)/ω, the basic relationship between valve currents and commutation voltage can be depicted as:

\[
L_s \int_{\frac{\pi - \beta}{\omega}}^{\frac{\pi - \beta + \theta}{\omega}} \frac{d i_{y_1}(t)}{dt} \frac{d t}{\omega} - L_c \int_{\frac{\pi - \beta}{\omega}}^{\frac{\pi - \beta + \theta}{\omega}} \frac{d i_{y_3}(t)}{dt} \frac{d t}{\omega} = \int_{\frac{\pi - \beta}{\omega}}^{\frac{\pi - \beta + \theta}{\omega}} \frac{\sqrt{2} E}{k_r} \sin(\alpha t + \phi_i) \frac{d t}{\omega}
\]

Solving for the current flowing through valve V1_3 at the fault moment (π-β + θ)/ω,

\[
i_{y_1} \frac{\pi - \beta + \theta}{\omega} = \frac{\sqrt{2} E}{2 \omega k_r} (\cos(\beta - \theta) - \cos \beta) \tag{14}
\]

From (π-β + θ)/ω to (π-γ<sub>imin</sub>-φ<sub>1</sub>)ω, similar results can be gotten:

\[
L_s \int_{\frac{\pi - \beta + \theta}{\omega}}^{\frac{\pi - \gamma_{\text{imin}} - \phi_1}{\omega}} \frac{d i_{y_1}(t)}{dt} \frac{d t}{\omega} - L_c \int_{\frac{\pi - \beta + \theta}{\omega}}^{\frac{\pi - \gamma_{\text{imin}} - \phi_1}{\omega}} \frac{d i_{y_3}(t)}{dt} \frac{d t}{\omega} = \int_{\frac{\pi - \beta + \theta}{\omega}}^{\frac{\pi - \gamma_{\text{imin}} - \phi_1}{\omega}} \frac{\sqrt{2} E}{k_r} \sqrt{\frac{k^2 + k + 1}{3}} \sin(\alpha t + \phi_i) \frac{d t}{\omega}
\]

Substituting (14) and (8) into (15), ‘the critical k value’ can be calculated as: (see (16)) In (16), the value of θ and the per unit DC current reflect the impact of different fault moments.

The critical voltage reduction of valves in the wye group (value of k) can be calculated considering different moments based on (13) and (16). However, valves in the delta group will also influence the occurrence of a CF. The controls may respond for the leading angle β. It may not keep constant during the commutation process afterwards. The leading angle β’ can be calculated by (14):

\[
\beta' = \beta + k_p (\gamma_{\text{ref}} - \gamma') \tag{17}
\]

where k<sub>p</sub> is a constant of the PI controller. γ<sub>ref</sub>, γ’ are the reference extinction angle and extinction angle of the former commutation process, respectively.

Replacing β with β’ and substituting the magnitude, phase of the post-fault commutation voltage for valves in the delta group into (13), then ‘the critical k value’ for valves in the delta group can also be calculated.

Hence, the critical voltage of a HVDC system is decided by the largest one, with all valves connected in the wye group and the delta group taken into consideration.
The wiring diagram of ±500 kV, rated power of 3000 MW, rated results are listed below by comparison. (Table 1).

| Fault moments, s | Calculation results of $k$, pu | Simulation results of $k$, pu | Error, % |
|-----------------|-------------------------------|-------------------------------|----------|
| 1.0757          | 0.891                         | 0.926                         | 3.5      |
| 1.0797          | 0.887                         | 0.914                         | 2.7      |
| 1.0809          | 0.808                         | 0.833                         | 2.5      |
| 1.0824          | 0.903                         | 0.932                         | 2.9      |
| 1.0840          | 0.897                         | 0.925                         | 2.8      |
| 1.0932          | 0.899                         | 0.928                         | 2.9      |

4 Simulation and results

The wiring diagram of ±500 kV, rated power of 3000 MW, rated DC current of 3 kA HVDC system is shown in Fig. 4. The simulation model is built in PSCAD/EMTDC. For the rectifier station, the rated voltage is ±525 kV. The transformer ratio is 525 kV/209.7 kV. For the inverter station, the transformer ratio is 525 kV/198.9 kV. The length of DC line is 891.5 km. At the normal working point, the extinction angle and leading angle of the inverter valve are 15° and 37°, respectively. The minimum extinction time for inverter valves is 444 μs (corresponding to 8° in a 50 Hz system). Simulations are carried out by reduction in one-phase voltage at the inverter commutating bus.

4.1 Verification of post-fault commutation voltages

The simulation results of post-fault magnitudes and phases of commutation voltages changing along with different $k$ values are shown in Fig. 5. Simulation results of commutation voltages in Fig. 5 are generally consistent with theoretical analysis in Fig. 2. Therefore, the detailed analysis on commutation voltages can act as a basis of calculation method considering single-phase fault moments.

4.2 Verification of proposed method for calculating critical voltage considering fault moments

Numerous simulations are carried out to verify the correctness of the analysis and the validation of the proposed method. Several results are listed below by comparison. (Table 1).

Other large quantities of simulations show that error between calculation and simulation results is relatively small. Three different scenarios are specially shown as follows to verify the analysis of valves that are prone to CFs.

**Scenario 1:** When A-phase voltage reduction occurs at 1.0797 s (during time period of $V_{1Y}$, $V_{2Y}$, $V_{1A}$, $V_{2A}$ being at work), the voltage reduction will cause a CF during the commutation process from $V_{1Y}$ to $V_{2Y}$. (Fig. 6)

**Scenario 2:** The sudden voltage reduction occurring at 1.0809 s ($V_{1Y}$, $V_{2Y}$, $V_{1A}$, $V_{2A}$ being at work) will cause a CF during the process from $V_{1A}$ to $V_{2A}$, shown in Fig. 7.

The sudden voltage reduction will result in a dramatic decrease in the magnitude of $e_{lyba}$ which is the commutation voltage of $V_{1Y}$ to $V_{2Y}$. Therefore, the commutation process from $V_{1Y}$ to $V_{2Y}$ is prone to fail.

**Scenario 3:** When A-phase voltage reduction occurs at 1.0840 s ($V_{1Y}$, $V_{2Y}$, $V_{1A}$, $V_{2A}$ being at work), it will cause a CF during the process from $V_{1A}$ to $V_{2A}$, shown in Fig. 8.

\[
\sqrt{k^2 + k + 1} = \frac{3(I_d(\gamma_{\text{max}} - \gamma_{\text{min}})/\omega)I_d + 1)\cos \gamma}{2(\cos \gamma_{\text{max}} - \cos(\beta - \phi_{\text{d}}))}
+ \frac{\sqrt{3}\cos(\alpha + \theta)}{(\cos \gamma_{\text{max}} - \cos(\beta - \phi_{\text{d}})) + \sqrt{3}(I_d(\gamma_{\text{max}} - \gamma_{\text{min}})/\omega)I_d + 1)\cos \alpha}{2(\cos \gamma_{\text{max}} - \cos(\beta - \phi_{\text{d}}))}
\]

(16)

Fig. 4 Wiring diagram of ±500 kV HVDC system

Table 1 Comparison between results by proposed method and by simulation

Fig. 5 Simulation results of commutation voltages of inverter valves

(a) Commutation voltages of valves in the wye group, (b) commutation voltages of valves in the delta group

Fig. 6 Extinction angle of inverter valves: fault occurring at 1.0797 s

According to the analysis above, A-phase voltage reduction will cause an advance in the zero-crossing point of $e_{lyba}$ which is the commutation voltage of $V_{1Y}$ to $V_{2Y}$. Therefore, the commutation process from $V_{1Y}$ to $V_{2Y}$ is prone to fail.

**Scenario 2:** The sudden voltage reduction occurring at 1.0809 s ($V_{1Y}$, $V_{2Y}$, $V_{1A}$, $V_{2A}$ being at work) will cause a CF during the process from $V_{1A}$ to $V_{2A}$, shown in Fig. 7.

The sudden voltage reduction will result in a dramatic decrease in the magnitude of $e_{lyba}$ which is the commutation voltage of $V_{1A}$ to $V_{2A}$. The process from $V_{1A}$ to $V_{2A}$ is prone to a CF.

**Scenario 3:** When A-phase voltage reduction occurs at 1.0840 s ($V_{1Y}$, $V_{2Y}$, $V_{1A}$, $V_{2A}$ being at work), it will cause a CF during the process from $V_{1A}$ to $V_{2A}$, shown in Fig. 8.
From Fig. 9, concerning a single phase, critical voltages are periodically changing in 180° in one cycle. In terms of three phases, critical voltage curve of A-phase fault is 120° ahead of B-phase and 240° of C-phase.

5 Conclusion

Here, when there is a sudden voltage reduction in a single phase, the change rule of post-fault magnitudes and phases of commutation voltages at valve side is researched theoretically. Results show that voltage reduction in A-phase will bring about an unfavourable phase-shift of \( e_{L\Delta b} \) and \( e_{L\Delta c} \) and a significant decrease in the magnitude of \( e_{L\Delta ac} \). Therefore, valves that take \( e_{L\Delta ac}, e_{L\Delta b}, e_{L\Delta c} \) as their commutation voltages are most probable to suffer from CFs. After that, a method for calculating critical voltage of a single phase considering different fault moments is developed. In addition, the change regularity of critical voltage along with different fault moments and phases is given. Critical voltage curves are periodically changing in 180° in one cycle. The phase difference of A, B, C is 120°. All the analysis and theoretical calculation results may help to come up with measures to avoid continuous CFs. The conclusions may work as a foundation for the judgement of the onset of a CF in practical engineering application.

6 Acknowledgments

This work is supported by Key project of smart grid technology and equipment of national key research and development plan of China (2016YFB0900603) and Technology Projects of State Grid Corporation of China (52094017000W).

7 References

[1] Thio, C.V., Davies, J.B., Kent, K.L.: ‘Commutation failures in HVDC transmission systems’, IEEE Trans. Power Deliv., 1996, 11, (2), pp. 946–957
[2] Rahimi, E., Gole, A.M., Davies, J.B.: ‘Commutation failures in single and multi-infeed HVDC systems’, IEEE Trans. Power Deliv., 2011, 26, (1), pp. 378–384
[3] Zhang, L.D., Bollen, M.H.J.: ‘Characteristics of voltage dips (sags) in power systems’, IEEE Trans. Power Deliv., 2000, 15, (2), pp. 827–832
[4] Wang, G., Huang, M., Li, H.: ‘Influence of initial fault voltage angle on commutation failure identification in a HVDC system’, Auto Electr. Power Syst., 2010, 34, (4), pp. 49–54
[5] Wang, F., Liu, T., Zhou, S., et al.: ‘Mechanism and quantitative analysis method for HVDC commutation failure resulting from harmonics’, Proc. CSEE, 2015, 35, (19), pp. 4888–4894
[6] Vaahedi, E., Li, W., Chia, T., et al.: ‘Large-scale probabilistic transient stability assessment using BC hydro's online tool’, IEEE Trans. Power Syst., 2010, 15, (2), pp. 661–667
[7] Shao, Y., Tang, Y.: ‘A commutation failure detection method for HVDC systems based on multi-infeed interaction factors’, Proc. CSEE, 2012, 32, (4), pp. 108–114
[8] Jian, H., Jian, Z., Jun, Y.: ‘Mechanism of power oscillation on AC tie-line for two-area interconnected power systems caused by HVDC commutation failure’, Chinese Society for Electrical Engineering Annual Meeting, Heifei, China, November 2016, pp. 264–268
[9] Ping, W., Weifang, L., Huadong, S.: ‘Research and electromechanical transient simulation on mechanism of commutation failure in multi-infeed HVDC power transmission system’, Power Syst. Technol., 2012, 36, (5), pp. 269–274
[10] Hui, L.: ‘The analysis of commutation failure prediction in UHVDC system’. Master thesis, Shanghai Jiaotong University, 2015
[11] Hu, Y., Liu, J., Zhou, H.: ‘Commutation failure analysis considering direct current systems in LCC-HVDC systems’. 12th IET Int. Conf. on AC and DC Power Transmission, Beijing, China, May 2016, pp. 1–5
[12] Shao, Y., Tang, Y.: ‘Fast evaluation of commutation failure risk in multi-infeed HVDC systems’, Proc. CSEE, 2017, 37, (112), pp. 3429–3436
[13] Chen, X., Gole, A.M., Guo, C.: ‘A fast calculation method for the local commutation failure immunity indices in single- and multi-infeed HVDC systems’. 11th IET Int. Conf. on AC and DC Power Transmission, Birmingham, UK, February 2015, pp. 1–6
[14] Jingyou, X., Haiyan, T., Haishun, S.: ‘Research on method to analyze commutation failure in HVDC power transmission system considering the impact of DC current variation and occurrence moment of AC fault’. Power Syst. Technol., 2015, 39, (5), pp. 1261–1267