Research on Commutation Failure of DC Transmission System Based on Harmonics

Chu Chenyang\(^1\)* and Sun Lixia\(^1\)

\(^1\)College of Energy and Electrical Engineering, Hohai University, Nanjing, China

*ccy1996@hhu.edu.cn

**Abstract.** The paper summarizes the micro mechanism and key influencing factors of consequential commutation failure in the HVDC transmission system, which mainly includes the harmonic impacts on the secondary commutation failure. And it quantitatively analyses the adverse effects of harmonics on commutation through the time area of commutation voltage, hence the main factors affecting the time area of harmonic voltage can be obtained. And the harmonic influence coefficient \(F_n\) is introduced to reflect harmonic voltage’s influence level in the worst case of commutation. Then, a method based on harmonic voltage area is proposed to reduce the risk of secondary commutation failure, that is, through introducing the negative harmonic current feedback by harmonic voltage feedback gain index \(K_n\) to reduce the direct current at fault. The validity and practicability of the method were proved by simulation analysis.

1. Introduction

In recent years, China's high voltage direct current (HVDC) power grid has undergone rapid expansion, and several multi-infeed direct current systems (MIDC) have been built in the east China and middle China power grid. With the increase in the proportion of heavily stressed transmission network in the power grid, HVDC transmission systems have become increasingly widely used, at the same time, the stability of AC systems is becoming weaker and weaker [1]. Because HVDC appears as reactive load characteristics in the AC/DC transmission system, that is, while the transmission line is transmitting active power, due to the commutation of the converter station requiring a great quantity of reactive power, it is not conducive to the AC system connected by HVDC. If the voltage stability of the AC/DC system cannot be guaranteed, the commutation failure is likely to happen [2].

The basic theory and characteristics of conventional HVDC transmission systems are introduced in detail in reference [3], and it discussed the important problems, solutions, analysis, and simulation techniques related to operation and control about HVDC in depth. However, the multi-feed DC transmission technology in China is developing rapidly at present, the technology used in conventional single high-voltage direct current transmission line has been less suitable for MIDC system. Reference [4] comprehensively analyzed the domestic and foreign research status of the voltage stability problem of the AC/DC transmission system, especially for the voltage stability problem of MIDC system. Reference [5] proposed to use the harmonic voltage compensation component to support the reactive power to the power system during recovery.

Reference [6] adopted a set of damped interregional power oscillation fuzzy controller in the DC power control system and generator excitation system of the multi-infeed AC-DC transmission system and optimized parameters through a genetic algorithm. Reference [7] pointed out that the study of the coupling law of multiple influencing factors of commutation failure is the emphases of future study on suppression of commutation failure. Reference [8] introduced a thyristor-based controllable capacitor (TBCC) based on power electronics for the problem of commutation in high-power/current HVDC transmission systems. It introduces its topology and working principle in detail, and the CCC-HVDC constructed on this basis can effectively reduce the number of times the commutation failure occurs.
Although researches on the conversion failure of conventional DC power transmission have been relatively perfect, due to the reciprocal effect in AC/DC systems, the dynamic characteristics, steady state analysis and control coordination of MIDC system are becoming more complex, and there is no precise indicator for the measurement of AC system strength in MIDC system. When MIDC is connected to a weak AC system, problems such as harmonic resonance, transient dynamic overvoltage, and prone commutation failure may occur during operation. Among the many factors that influence the failure of commutation, many scholars have not paid enough attention to the harmonic impacts on commutation failures.

To reduce the commutation failure due to harmonics in MIDC system, we proposed an effective method to relieve the problem of commutation failure from the control level. The main sections of this paper are:
1) This paper briefly describes the process of commutation failure, and studies harmonic impacts on the secondary failure of commutation in MIDC system when the first commutation failed.
2) This paper proposes a method based on harmonic voltage area to reduce the secondary commutation failure risks associated with harmonics.

2. MIDC commutation failure analysis

2.1. Microcosmic mechanism of commutation failure

The inverter station usually uses two 6-pulse converter bridges to make up a 12-pulse converter bridge in general HVDC transmission systems. Figure 1 takes the commutation from converter valve VT1 to VT3 in the 6-pulse commutation bridge as an example to illustrate the micro principle of commutation failure.

![Equivalent circuit diagram of converter valve](image)

Figure 1. Equivalent circuit diagram of converter valve

The converter valve VT1-VT6 represents the six bridge arms of the converter, and they conduct in sequence of 1-6. The voltage equation can be written when VT1 commutates to VT3:

$$L \frac{di}{dt} - L_c \frac{di}{dt} = U_b - U_a$$

(1)

where $L_c$ is the commutation reactance, $i_1$ and $i_2$ represent the current flowing through VT1 and VT3 respectively, $U_a$ and $U_b$ are phase voltage.

In HVDC transmission systems, it is generally believed that once the extinction angle $\gamma$ of the converter valve is less than the minimum extinction angle $\gamma_{an}$, the commutation will fail. And the $\gamma_{an}$ is calculated by the duration the thyristor carrier needed to recover the positive blocking ability, it is supposed to be about 7’ in this paper. Considering the shift of the zero-crossing phase angle when asymmetric faults occur, the extinction angle calculation equation can be described as:
\[ \gamma = \arccos\left(\sqrt{\frac{2n I_d X_c}{U_d}} + \cos \beta\right) - \varphi \]  

where \( n \) is the ratio of converter transformer, \( I_d \) is the DC current, \( X_c \) is the commutator’s commutation reactance, \( U_d \) is the converter bridge line voltage, \( \varphi \) is the zero-crossing phase angle.

Derivation of equation (2) can be obtained:

\[
\begin{align*}
\frac{\partial \gamma}{\partial I_d} &= -\frac{1}{\sqrt{1-\cos^2 \gamma}} \cdot \frac{\sqrt{2n X_c}}{U} \\
\frac{\partial \gamma}{\partial X_c} &= -\frac{1}{\sqrt{1-\cos^2 \gamma}} \cdot \frac{\sqrt{2n I_d X_c}}{U} \\
\frac{\partial \gamma}{\partial U} &= \frac{1}{\sqrt{1-\cos^2 \gamma}} \cdot \frac{\sqrt{2n I_d X_c}}{U^2} \\
\frac{\partial \gamma}{\partial \beta} &= \frac{\sin \beta}{\sqrt{1-\cos^2 \beta}}
\end{align*}
\]  

Therefore, it can be preliminarily determined from Equation (3) that the main factors affecting the commutation failure include equivalent reactance, direct current, converter bus voltage and advance trigger angle. In MIDC system, factors such as fault extent in AC systems [9], coupling intensity between stations [10], multi-infeed short-circuit ratio, DC controller parameters and high harmonics should also be considered [11].

2.2. Influence of harmonics on MIDC commutation failure

Commutation failure may result from voltage waveform distortion. Two factors are generally considered: voltage drop of commutation bus and zero-crossing phase shift of waveform. Since there is no specific law for harmonic impacts on the voltage of commutation, it is necessary to consider the influence of harmonics on commutation failure by combining two influencing factors. As the voltage of AC bus drops sharply when the inverter station fails, the harmonic impacts on primary commutation failure can be ignored compared with the influence of fundamental frequency voltage drop, so the study mainly focuses on the adverse effects that the harmonic scattered on the secondary failure of commutation. The voltage-time area during normal commutation time can be deduced by combining figure 2 and figure 3.

**Figure 2.** The voltage waveform of the phase change process  
**Figure 3.** The harmonic effect on voltage-time area
If commutation continues from \( t_1 \) to \( t_2 \), we can obtain \( t_i = \alpha_i / \omega \), \( t_f = (\pi - \gamma) / \omega \) in figure 2. When we substitute \( i_i + i_r = I_d \) into equation (1) and integrate over time, the critical area \( A_{cr} \) of commutation required can be obtained from (4)

\[
2L_c I_d = \int_{t_1}^{t_2} u_{ho}(t) dt = A_{cr}
\]

Figure 3 shows when considering the harmonic impacts on commutation, the critical commutation area \( A_{cr} \) increases, and the probability of commutation failure also greatly increases. The commutation area is proportional to direct current in Equation (4). So, the influence of harmonic on commutation failure can be relieved by reducing the direct current appropriately.

3. The influence of harmonics on DC current during commutation

3.1. Calculation of harmonic voltage time area
When the DC transmission system fails, the constant current control in inverter side can quickly limit the transient fault current to protect the thyristor. In the normal inverter-side control system, constant current control does not take the effects of harmonics into consideration. As the commutation area obtained above is mainly proportional to the DC current, we can reduce the DC current in the process of commutation to ameliorate the occurrence of fault.

The equation (5) to convert the harmonic voltage time area into DC current can be simplified by equation (4):

\[
I_d = \int_{t_1}^{t_2} u_{ho}(t) dt \frac{2}{2L_c}
\]

The line voltage can be written as equation (6) and by substituting (6) into (5), (5) can be written as (7) when considering the \( n \) th harmonic voltage,

\[
U_{ho} = E_n \sin(\omega t) + \sum_{n=2}^{N} E_n \sin(n \omega t + \varphi_n)
\]

\[
I_d(t_f) = \int_{t_1}^{t_2} E_n \sin(\omega t) dt + \int_{t_1}^{t_2} \sum_{n=2}^{N} E_n \sin(n \omega t + \varphi_n) dt
\]

where \( \sum_{n=2}^{N} \left( E_n \sin(\omega t + \varphi_n)/2L_c \right) dt \) is all harmonic orders’ total quantity. And \( \omega t_f \leq \pi - \gamma_{min} \) must be satisfied in order to prevent commutation failure. The harmonic voltage time area in equation (7) is denoted as

\[
H_{n} = \int_{t_1}^{t_2} \sum_{n=2}^{N} E_n \sin(n \omega t + \varphi_n) dt = \frac{E_n \cos(n \alpha + \varphi_n) - E_n \cos(n \pi - \gamma + \varphi_n)}{n \omega L_c}
\]

Equation (8) shows that the harmonic voltage time area mainly relates to the harmonic amplitude, phase, harmonic order and delayed triggering angle. When considering the worst scenario, we take \( \gamma = \gamma_{min} = 7^\circ \), and (8) can be simplified as

\[
H_{n} = 2A_n E_n \sin(\delta_n + \varphi_n)
\]

where \( A_n = \left| \sin\left(\left(\left((n \alpha + n \gamma - n \pi)/2\right)\right)/\left(n \omega L_c\right)\right)\right|, \delta_n = (n \pi + n \alpha - n \gamma)/2 \).

To simplify the calculation, we substitute \( \sin(\delta_n + \varphi_n) = 1 \) into (9) and introduce the harmonic influence coefficient \( F_n \) which reflects the influence degree of harmonic voltage in the worst case.
\[ F_n = \frac{H_n}{H_1} = \frac{A_n}{A_1} \frac{E_n}{E_1} = G_n \cdot \frac{E_n}{E_1} \] (10)

3.2. Improving methods of commutation failure based on harmonic voltage area

In the normal commutation process, considering the fluctuation of the connected AC system, there is a margin for the extinction angle, usually 15-20 degrees, the commutation voltage time area \( S \) is:

\[ S = \int_{\alpha}^{\alpha_{max}} \frac{E_1 \sin(\omega t)}{2L_c} \] (11)

When the extinction angle comes to the extreme case that \( \gamma_{min} = \gamma \), the voltage time area based on the reference voltage could provide could be:

\[ S_M = \int_{\alpha}^{\alpha_{max}} E_1 \sin(\omega t) \] (12)

Then subtract the equation (14) and (13) to obtain the commutation voltage time area margin as:

\[ S_{margin} = S_M - S \] (13)

When the superposition of the harmonic voltage time area is greater than \( S_{margin} \), the probability of commutation failure will increase greatly. From this, the basis for judging the failure of commutation can be obtained as \( \sum F_n \geq S_{margin} \).

According to the previous analysis, the negative feedback current about harmonic voltage time area can be added to the inverter current control output to reduce the direct current at fault, and reduce the probability of commutation failure in further. In the system, it is more convenient to monitor harmonic voltage, and the judgment basis of harmonic voltage can be obtained from equation (10):

\[ \frac{E_n}{E_1} \geq \frac{A_n S_{margin}}{\sum A_n} \] (14)

where the left part denoted as \( P_n \) is the proportion of harmonic voltage amplitude, the right part denoted as \( S_\gamma \) is the critical value to judge whether harmonics will cause commutation failure. When adding negative feedback on the time area of the harmonic voltage, the harmonic voltage feedback gain index \( K_\gamma \) is introduced, and negative current feedback based on harmonics can be obtained:

\[ \Delta I_d = K_\gamma P_n \geq F_n - S_{margin} \Rightarrow K_\gamma \geq G_n \] (15)

The gain index \( K_\gamma \) needs to have an appropriate margin for guaranteeing the harmful impacts caused by harmonics being managed. When the value of \( K_\gamma \) is too large, too high sensitivity will overcompensate and reduce the transmission power, which is not conducive to economic benefits; when the value of \( K_\gamma \) is too small, the sensitivity is too low and the harmonic effects cannot be perfectly controlled. So, the general margin is 15-25%. The improvement plan that can be obtained from the above analysis is shown in figure 4.

**Figure 4. The flow chart of harmonic management strategy**

---

**Note:** The angles in the figure refer to the following: \( \gamma_{min} = \gamma \), and \( \alpha_{max} \) refers to the maximum angle. The feedback terms \( K_\gamma \) and \( G_n \) are used to denote the sensitivity and gain values, respectively. The flowchart illustrates the process of adding harmonic feedback to improve the system's commutation failure rate.
4. Simulation and analysis

It has been discussed above that due to the too small extinction angle, the time area of commutation voltage influenced by harmonics will leads to the commutation failure. In this paper, a double-feed DC transmission benchmark model is built in PSCAD/EMTDC. In addition, in the inverter side control circuit, the negative current feedback as shown in figure 4 is added to the constant current control part. The treatment scheme is as follows: firstly, the harmonic in AC voltage on the inverter side is separated and measured by FFT module in PSCAD, then the ratio of harmonic voltage amplitude $P_n$ is calculated. Then, $P_n$ and $S_{ac}$ is compared by judgment module, if the judgment output is positive, the current negative feedback calculated by (15) is added, the equation is

$$\sum \Delta I_d = \sum K_n P_n$$  \hspace{1cm} (16)

The paper introduces the harmonic distortion influence index (HDII) to better describe the effectiveness of the method under different faults, it can be described as:

$$HDII_n = \left( \frac{E_n}{E_1} \times 100 \right)^2 Z_{\text{fault}} S_{ac}$$  \hspace{1cm} (17)

where $Z_{\text{fault}}$ is short circuit ground admittance, $S_{ac}$ is system short-circuit capacity.

From figure 5, we can see the amplitude of each harmonic component when the second commutation failure occurred as we set a short circuit on the inverter of line 1.

![Harmonic amplitude histogram of MIDC](image)

**Figure 5.** Harmonic amplitude histogram of MIDC

Taking the harmonic influence index when $n=2$ to represent the influence of harmonics on the second commutation, table 1 can be calculated from (17), where HDII and ground impedance are inversely distributed.

| Ground impedance/Ω | 0.0100 | 0.1000 | 1.000  | 10.00 |
|--------------------|--------|--------|--------|-------|
| HVDC1              | 10.45  | 0.0409 | 0.0246 | 3.260×10^{-1} |
| HVDC2              | 0.1347 | 0.0127 | 0.0000 | 5.060×10^{-5} |

It can be seen from figure 5 that the first four harmonics have a large proportion when the second commutation failure occurred, when the negative feedback of direct current based on harmonics is added, we only consider the influence of the second, third and fourth harmonics. Suppose
HDII=10.45, and calculate the relevant parameters for harmonic control, the data shown in table 2 can be obtained.

| Harmonic Order | $A_n$ | $G_n$ | $E_n$ | $K_n$ | $S_{cr}$ |
|----------------|-------|-------|-------|-------|---------|
| 1              | 0.267 | ——   | 135   | ——   | ——      |
| 2              | 0.257 | 0.963 | 21.6  | 1.15  | 0.039   |
| 3              | 0.242 | 0.942 | 13.0  | 1.13  | 0.036   |
| 4              | 0.221 | 0.913 | 3.93  | 1.09  | 0.033   |

By substituting the above data into the control circuit of benchmark model in PSCAD and setting a short circuit on the inverter of line 1, the waveform comparison diagrams are shown blow. The dotted black and solid red lines respectively represent the data before and after adding the negative feedback of direct current based on harmonics to VDCOL.

Figure 6. The extinction angle waveform before and after improvement of HVDC1

Figure 7. The extinction angle waveform before and after improvement of HVDC2

Figure 8. The AC voltage waveform before and after improvement of HVDC1

Figure 9. The AC voltage waveform before and after improvement of HVDC2

Figure 10. The direct current waveform before and after improvement of HVDC1

Figure 11. The direct current waveform before and after improvement of HVDC2

In figure 6-7, when the negative harmonic current feedback is not added, once the DC transmission system fails, the two lines fail to commutate twice consecutively. When adding the negative harmonic current feedback to the constant current control of the inverter’s control circuit, although the failure of primary commutation hardly relieved, the second commutation has disappeared. It can be seen that the harmonic control has achieved remarkable results.
From figure 8-11, we can see that after adding negative harmonic current feedback, the DC current and voltage on the inverter side recovered quickly to a stable value when the first failure of commutation happened, and the transmission efficiency of DC power did not decrease, ensuring the economic benefits of the method.

5. Conclusion
This article briefly describes the micro-mechanism of commutation failure, which mainly analyses the harmonic effect on the process of secondary commutation failure. The detailed theoretical formula is used to explain the adverse influence of each harmonic voltage area on the failure of commutation. And based on the fact that harmonic commutation time voltage area is proportional to the direct current at fault, a method to relieve the secondary commutation failure from the control level by negative harmonic current feedback is introduced. The simulation results proved that the occurrence of secondary commutation failure can be effectively reduced or avoided when a short-circuit fault occurs in MIDC system, so the improving method put forward has practical value.

References
[1] Xu Z. Dynamic performance analysis for AC/DC systems[M]. Beijing: China Machine Press, 2004.
[2] Wang Y X, Zhang X, Mu Q, et al. Parameter Optimization of Commutation Failure Prevention and Control of UHVDC Hierarchical Connection to AC Grid System[J]. High Voltage Engineering, 2018, 44(1): 329-336.
[3] Guo J. Research on Additional Reactive Power Control of Hybrid Multi-infeed HVDC System[D]. Zheng Zhou, Zhengzhou University, 2019.
[4] Lin W F, Tang Y, Bu G Q. Study on voltage stability of multi-infeed HVDC power transmission system[J]. Power System Technology, 2008, 32(11): 7-12.
[5] He X F, Li C X, Xia C J, et al. Control strategy to suppress hybrid HVDC continuous commutation failure by harmonic voltage compensation[J]. Jiangsu Electrical Engineering, 2019, 38(4):112-117.
[6] Zhu H J, Cai Z X, Liu H M, et al. Coordinate optimization algorithm of fuzzy controller in multi-infeed AC/DC power systems[J]. Proceedings of the CSEE, 2006, 26(13): 7-13.
[7] Lin S, Liu J, Liu L, et al. A Review of Commutation Failure Suppression Methods for HVDC Systems Based on Control Protection Measures[J]. Proceedings of the CSEE, 2020:1-16.
[8] Xue Y, Zhang X P, Yang C H. Commutation Failure Elimination of LCC HVDC Systems Using Thyristor-Based Controllable Capacitors[J]. IEEE Transactions on Power Delivery, 2017, 33(3): 1448-1458.
[9] Li Y M, Li X Y, Xiao J, et al. Simulation analysis of commutation failure risk in multi-infeed systems[J]. Proceedings of the CSU-EPSA, 2014, 26(8): 1-5.
[10] Wang F, Liu T Q, Li X Y. Decreasing the frequency of HVDC commutation failures caused by harmonics[J]. IET Power Electronics, 2017, 10(2): 215-221.
[11] Wang L, Wen J, Li Y N, et al. The harmonic effects on commutation failure of multi-infeed direct current transmission systems[J]. Transactions of China Electrotechnical Society, 2017, 32(3): 27-34.