Impact of Phase Locked Loop on Commutation Failure in LCC-HVDC

Peiyuan Tang¹,², Xiaoming Yuan¹, and Jun Lu¹

¹State Key Laboratory of Advanced Electromagnetic Engineering and Technology, Huazhong University of Science and Technology, 430074 Wuhan, China
²China-EU Institute for Clean and Renewable Energy, Huazhong University of Science and Technology, 430074 Wuhan, China

pytang@hust.edu.cn

Abstract. Besides the DC faults, AC faults and faults in converter, the dynamic process of control system has its influence on commutation failure. As an important element in LCC-HVDC control system, PLL provides the reference phase of receiving end power system for valve control system. When there is a difference between the real phase of receiving end power system and the output from PLL, control system cannot adjust extinction angle accurately. In this paper, the function of PLL in HVDC control system and the characteristic of PLL’s tracking process are analysed. Then the influence of the phase error caused by PLL’s tracking process on the extinction angle is discussed. At last, a detailed LCC-HVDC model is used to prove the impact of PLL’s dynamic process on commutation failure and test the influence of PLL with different parameters on commutation failure.

1. Introduction

Commutation failure is one of the most common faults in line commutated converter based high voltage direct current (LCC-HVDC) and there are different faults could cause commutation failure such as AC faults, DC faults and faults in converter[1]. In general, commutation failure would seriously damage LCC-HVDC’s economical operation and may bring about DC block if it cannot be cleared in time. Recent years, within the rapid development of HVDC transmission, commutation failure has been an important topic for grid’s steady operation. Research on commutation failure could help us to understand its mechanism and improve the reliability of grid.

At present, we have known the basic knowledge about the mechanism and causes of commutation failure. By analysing the physical characteristic of thyristor, the physical mechanism of commutation failure has been revealed. The extinction angle is smaller than the critical extinction angle corresponding to the complete dissipation of carriers in the thyristor[2]. Reference [1] analysed the influence of direct current, voltage of AC bus bar and firing angle of valves on commutation failure. However, the dynamic process of the control system was not taken into account in the above researches. With the increase of DC transmission capacity, receiving end power system has been weaker compared to the before[3]. As a result, the influence of controlling factors, such as phase locked loop (PLL), on commutation failure is getting more and more attention.

The PLL provides the reference phase of receiving end power system for the valve control system. Although the PLL is located in the last stage of LCC-HVDC control system, its dynamic process will
directly affect the commutation process of the thyristor valve. In view of the above research status, this paper focuses on the commutation failure related to the PLL’s dynamic characteristic and is organized as follows. In section 2, LCC-HVDC control system and the function of PLL in the control system are introduced. Then, the working principle of PLL and the cause of phase error during PLL’s tracking process are introduced. And the impact of PLL on commutation failure is analysed. In section 3, the LCC-HVDC detailed model built in PSCAD/EMTDC is used to test the influence of PLL on the commutation failure under different parameters.

2. Impact of PLL on commutation failure

The PLL provides the reference phase of the receiving end power system for valve control system. Reference phase is the basic information for valve control system to know the wave of commutation voltage and its zero-crossing point. If the phase of input signal changed, PLL needs time for tracking process. During this process, the PLL cannot always provides the real phase of receiving end power system for valve control system to generate the firing pulse. It brings the risk to commutation process.

2.1. Control system in LCC-HVDC

In LCC-HVDC, Graetz bridges with thyristors are used for commutation. Usually, 12-pulse converters which consist of two Graetz bridges in series are generally installed in inverter station and rectifier station\(^{[4-5]}\). Different from the converters used in voltage source converter based high voltage direct current (VSC-HVDC), the thyristor cannot be completely controlled because only when the current flowing through the thyristor is zero, thyristor could be shut off\(^{[6]}\). And thyristor needs time to complete dissipation of carriers under the negative voltage. These features of thyristor require higher accuracy for LCC-HVDC control system. Figure 1 shows the control system used in Cigre HVDC benchmark.

![Figure 1. Control system of LCC-HVDC.](image)

LCC-HVDC control system can be divided into the side of rectifier and inverter side. For rectifier station, the firing angle \(\alpha_r\) is usually smaller than 90° because the thyristor needs to work under rectifier mode. The thyristor valve which is going to exit the conduction usually has enough time to dissipate the energy within its carriers under the negative voltage. So, the extinction angle at rectifier station is usually larger than the critical extinction angle which would cause commutation failure. The research about commutation failure mainly focuses on the inverter station. The inverter station can be controlled by constant current control mode or constant extinction angle control mode. The leading angle order \(\beta_1\) will be transform to firing angle \(\alpha_i\), then deliver to valve control system (VCS).
As the direct control unit of thyristor in inverter, valve control system needs to keep the phase of the voltage from inverter equipment synchronized with the phase of the receiving end power system. The function of the PLL is to measure phase of receiving end power system and provide this information to the valve control system. Then the valve control system will obtain the position of the commutation voltage’s zero-crossing point, and generate the firing pulse for thyristor. The zero-crossing point of commutation voltage is reference system for valve control system to apply firing angle to generate pulse.

2.2. Mechanism of PLL
PLL is a control system that generates an output signal whose phase is related to the phase of the input signal. In LCC-HVDC, synchronous reference frame phase locked loop (SRF-PLL) is usually used to measure the phase of receiving end power system.

![Figure 2. Schematic diagram of SRF-PLL.](image)

As showed in Figure 2, SRF-PLL mainly includes phase detector (PD) which mainly composed of Park transformer, loop filter (LP) composed of PI controller and voltage controlled oscillator (VCO)[7]. The Park transformer can be used to establish the relation between the phase difference and the voltage on q axis.

\[ u_q = U_{abc} \sin(\theta - \theta_{PLL}) \]  

(1)

\( U_{abc} \) and \( \theta \) represents the voltage and phase of receiving end power system, \( \theta_{PLL} \) is the phase output from SRF-PLL, and \( u_q \) is the voltage on q axis.

After the phase detection completed, the PI controller in LF will output the adjusted angular velocity \( \Delta \omega \), which is added to the angular velocity \( \omega_0 \) corresponding to the standard frequency of power system to get the final angular velocity \( \omega \). Then the VCO outputs phase \( \theta_{PLL} \) through integral conversion, and the output phase signal will also be fed back to the PD.

The task of the PD is to detect the phase difference, so the Figure 3 can also be used to show the working principle of the SRF-PLL.

![Figure 3. Block diagram of SRF-PLL.](image)

\( \theta_e \) is the phase error between output signal and the real phase of receiving end power system. \( K_d \) represents the gain of PD. \( K_p \) and \( K_i \) respectively represent the proportional gain and integral gain of the PI controller.

PLL is a typical control system with feedback loop. When the phase of the input signal changes, it needs a tracking process to reach the locked status again. In this tracking process, PLL cannot always provides the accurate phase for valve control system. It will affect the accuracy of the firing pulse for thyristor.

For the PLL using the sine PD, such as SRF-PLL, it is impossible to ignore the non-linear characteristics when analysing the commutation failure related to PLL. The regular linearization method cannot be used because the phase difference \( \theta_e \) is not close to zero. So, it is hard to precisely
describe the variety in PLL’s tracking process and impossible to completely eliminates PLL’s error during its tracking process.

2.3. Impact of PLL on extinction angle
The valve control system can only determine the zero-crossing point of the commutation voltage according to the reference phase provided by the PLL. In the tracking process of the PLL, the valve control system of the inverter station cannot always get the accurate phase of the receiving end power system. The phase error will affect the extinction angle in commutation process.

Though it is hard to precisely describe the variety in tracking process. For each moment, the relation between phase output from PLL \( \theta_{PLL} \) and the phase of receiving end power system \( \theta \) can be classified as one of these three conditions.

1. The phase from PLL \( \theta_{PLL} \) equal to the phase of receiving end power system \( \theta \).
2. The phase from PLL \( \theta_{PLL} \) is smaller than the phase of receiving end power system \( \theta \).
3. The phase from PLL \( \theta_{PLL} \) is larger than the phase of receiving end power system \( \theta \).

When the phase from PLL to valve control system equal the real phase. There is no influence of PLL on the commutation process.

When the phase from PLL is different from the one of receiving end power system, there will be influence on firing pulse and commutation process. Figure 4 and 5 shows the relation between real angle and the ones in control system.

**Figure 4.** The relation between angle in real and ones in control system when phase from PLL is smaller than phase of receiving end power system.

In Figure 4, if the phase from PLL \( \theta_{PLL} \) is smaller than the phase of receiving end power system \( \theta \), the reference commutation voltage will lag behind the real commutation voltage because PLL provide the phase for reference commutation voltage. For the same firing pulse, the real extinction angle \( \gamma \) is small than the reference extinction angle \( \gamma_c \) in value control system. The relation is as following.

\[
\gamma = \gamma_c - (\theta - \theta_{PLL})
\]  

(2)

Although the control system generates the firing angle which can ensure the reference extinction angle \( \gamma_c \) is safe, the real extinction angle \( \gamma \) still has risk occurring commutation failure. For this situation, dynamic process of PLL is harmful for commutation process and increase the possibility of commutation failure.

**Figure 5.** The relation between angle in real and ones in control system when phase from PLL is larger than phase of receiving end power system.

Figure 5 shows a opposite condition. When the reference commutation voltage leads the real commutation voltage, the real extinction angle \( \gamma \) will be large than reference extinction angle \( \gamma_c \) which means good to commutation process. The relation is like following.

\[
\gamma = \gamma_c + (\theta_{PLL} - \theta)
\]  

(3)

It can be seen that when the PLL is in the tracking process, the control system cannot ensure that the phase of reference commutation voltage is same as the phase of receiving end power system. When the reference commutation voltage lag behind the real commutation voltage, the real extinction
angle $\gamma$ is smaller than the reference extinction angle $\gamma_r$ in the control system, which will increase the possibility of commutation failure. When the reference commutation voltage leads the real commutation voltage, the tracking process of the PLL brings a larger real extinction angle $\gamma$, which reduces the possibility of commutation failure.

3. Simulation analysis
Based on the simulation model built in PSCAD/EMTDC, a single-phase inductive ground fault was set with the AC bus bar of the inverter station. The initial moment of the fault is 1.4s, the duration of the fault is 0.1s, and the fault inductance value is 2.1H.

| No. | P   | I    |
|-----|-----|------|
| 1   | 9   | 770  |
| 2   | 30  | 5000 |

Table 1. Parameters of PI controller in SRF-PLL.

The PI controller of SRF-PLL was set with two different parameters to compare the effects of different tracking process’s characteristics on commutation failure.

Figure 6. Phase of the receiving end power system.
Figure 6 shows that single-phase inductive ground fault causes the change of receiving end power system’s phase. Phase changes more rapidly during the period of fault compared with the period of recovery.

Figure 7. Output signal from PD.
Figure 7 illustrates the output signal from PD. The phase difference could be quickly detected because the output phase from SRF-PLL doesn’t change at the beginning of the fault period. Meanwhile, non-zero signal from PD proves that SRF-PLL gives a wrong phase for valve control system. Between 1.41s to 1.45s, the phase difference changes rapidly. Then in the second 0.05s of
fault, the phase difference is still large but showing a decreasing trend. After the fault is removed in 1.5 seconds, it goes into recovery period. The phase difference is already very small and gradually approaching zero.

![Adjusted frequency output by LF in PLL](image)

**Figure 8.** Adjusted frequency output by LF in PLL.

The curves in Figure 7 and 8 have similar trends because the adjusted frequency from PI controller is dependent on the phase difference detected by PD. For Figure 8, at the beginning, tracking time is short, and the difference caused by different controller parameters is limited. So, the curve doesn’t show too much difference between two SRF_PLL. Then the time between 1.41s to 1.5s, the difference of dynamic characteristic is showed dramatically. When the PI control is set as $P = 30$ and $I = 5000$, it shows more obvious changes.

![Measured extinction angle at inverter station](image)

**Figure 9.** Measured extinction angle at inverter station.

Figure 9 describes the change of the extinction angle. When the parameters are set as $P = 30$ and $I = 5000$, the extinction angle has dropped twice, and the recovery time is longer.

By setting different parameters for the PI controller of the PLL, phase locked loops with different tracking process’s characteristics can be obtained. The difference of the extinction angle curve proves that the different tracking characteristics of the PLL have different impact on commutation failure.

4. Conclusion

Starting from the function of PLL in LCC-HVDC transmission and the characteristics of tracking process of PLL, the influence of PLL’s dynamic process on commutation failure is analysed. The main conclusions are as follows.

1. As a control system with feedback loop, PLL will go through tracking process after the phase of input signal is changed. During this process, the PLL cannot always output the accurate phase of the input signal.

2. Valve control system get phase from PLL to determine the zero-crossing point of commutation voltage. Wrong information will influence the possibility of commutation failure in LCC-HVDC.
3. If the phase from PLL is smaller than the real phase of receiving end power system, the real extinction angle is smaller than the reference extinction angle in control system. It will increase the possibility of commutation failure. If the phase from PLL is equal to or greater than the real phase, PLL’s dynamic process will not be harmful to commutation process.

5. References
[1] C. V. Thio, J. B. Davies and K. L. Kent, Commutation failures in HVDC transmission systems, IEEE Transactions on Power Delivery, vol. 11, no. 2, pp. 946-957, April 1996, doi: 10.1109/61.489356
[2] W. Yao, C. Liu, J. Fang, X. Ai, J. Wen and S. Cheng, Probabilistic Analysis of Commutation Failure in LCC-HVDC System Considering the CFPREV and the Initial Fault Voltage Angle, IEEE Transactions on Power Delivery, vol. 35, no. 2, pp. 715-724, April 2020, doi: 10.1109/TPWRD.2019.2925399
[3] Khazaei, J., Idowu, P., Asrari, A., Shafaye, A. B., & Piyasinghe, L. (2018), Review of HVDC control in weak AC grids, Electric Power Systems Research, 162, 194-206
[4] Oni, O. E., Davidson, I. E., & Mbangula, K. N. (2016, June), A review of LCC-HVDC and VSC-HVDC technologies and applications, 2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC) (pp. 1-7). IEEE
[5] M. Daryabak et al., Modeling of LCC-HVDC Systems Using Dynamic Phasors, in IEEE Transactions on Power Delivery, vol. 29, no. 4, pp. 1989-1998, Aug. 2014, doi: 10.1109/TPWRD.2014.2308431
[6] Aboushady, A. A., Ahmed, K. H., & Abdelsalam, I. (2020), Modified dual active bridge DC/DC converter with improved efficiency and interoperability in hybrid LCC/VSC HVDC transmission grids, IEEE Journal of Emerging and Selected Topics in Power Electronics, 2020
[7] A. K. Verma, R. K. Jarial and U. M. Rao, An Improved Pre-Filtered Three-Phase SRF-PLL for Rapid Detection of Grid Voltage Attributes, 2019 National Power Electronics Conference (NPEC), Tiruchirappalli, India, 2019, pp. 1-4, doi: 10.1109/NPEC47332.2019.903470