A Control Strategy for Recovery from Commutation Failures in LCC-based HVDC Systems Based on Trajectory Prediction

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Abstract. Commutation failures are very common in LCC-based HVDC systems, and many control strategies have been developed to enhance the immunity against commutation failures. Among these strategies, one key idea is to enlarge the commutation margin by firing the gate with a specific time advance. However, the controllers based on PI-scheme may induce unexpected overshoot, leading to the failure of recovery. A recovery strategy to eliminate the overshoot is proposed for improving the performance of recovery from commutation failures, where the fast-changing trend of system states including commutating voltage and dc current are considered. Case studies show the effectiveness of the proposed method.

Introduction

Commutation failures (CFs) are very common in line commutated converter (LCC)-based HVDC systems, most of which are caused by voltage reductions following AC-side faults [1]. The occurrence of CFs will inevitably cause many transients, such as temporary interruption of power transmission, voltage fluctuation, etc. If the CF continues to happen for a specific while, it will lead to the blocking of the HVDC system [2], threatening the safety of system operation. It becomes increasingly important to take further countermeasures to improve the immunity against CFs, and many papers have been dedicated to this topic, e.g., installing dynamic var sources [3-5], new converter structures [6,7], etc.

The main reason of CFs induced by voltage sags is that, the commutation margin will be reduced with the reduction of commutating voltage and the rise of dc current. Typically, enlarging the commutation margin is one of the most effective approaches to avoid CFs, where firing the gate with a specific time advance is widely applied [8]. Authors in [9] proposed a dc current predictive control strategy, where the current order was lowered to enlarge the commutation margin. In [10], a fuzzy controller was developed to decrease the commutation failure frequency, where a self-adjusting control scheme is applied.

However, the results in [11] showed that many control strategies neglected the response time of controllers, although the dynamics of controllers is very fast. To overcome this problem, the authors proposed a pseudo extinction angle calculation method to improve the performance of controllers. In [12], a compound phase-shifting control is proposed to shorten the response speed of PI-controllers. Moreover, if the response characteristic of PI controllers is considered, the overshoot of the firing angle order may induce unexpected CFs. To overcome this problem, we propose a novel control strategy for the recovery from commutation failures based on the trajectory prediction of extinguish angle. A dynamic hard limiter is added to ensure a safety commutating margin.

The rest of the paper is organized as follows: Section 2 presents the procedure of recovery trajectory prediction based on first-order derivatives. Then the dynamic hard limiter to ensure commutation margin safety is introduced in section 3. In section 4, case studies are performed to demonstrate the effectiveness of the approach, followed by the conclusion in the last section.
Recovery Trajectory Prediction

From [1], it is known that the extinguish angle can be evaluated by

\[
\cos \alpha - \cos \gamma = \frac{\omega L_c I_d}{\sqrt{2K_I U_c}}
\]  

(1)

where \( \alpha \) is the firing angle, \( \gamma \) is the extinguish angle, \( \omega \) is the system angular velocity, \( L_c \) is the commutating inductance, \( I_d \) is the dc current, \( K_I \) is the transformer ratio, \( U_c \) is the commutating voltage.

Here, the firing angle is controlled following the command of controllers to maintain the system operation, based on the states of voltages and currents of both ac side and dc side. To ensure a safety commutation, \( \alpha \) should be controlled to make \( \gamma > \gamma_{\text{lim}} \) hold, which is the minimum extinguish angle. The difference between \( \gamma \) and \( \gamma_{\text{lim}} \) can be used to denote the safety of commutation. Typically, the difference is over 7-8 degrees in the normal operation of practical systems.

Assume that, the commutating voltage is \( U_c(t) \), then

\[
U_c(t + \Delta t) = U_c(t) + U_c'(t) \cdot \Delta t
\]  

where \( \Delta t \) is the prediction time step, \( U_c'(t) \) is the derivative of commutating voltage at time \( t \). For the dc current, we have

\[
I_d(t + \Delta t) = I_d(t) + I_d'(t) \cdot \Delta t
\]  

(3)

where \( I_d'(t) \) is the derivative of dc current at time \( t \).

Thus, to ensure a successful commutation, the maximum firing angle at time \( t \) should be

\[
\alpha_{\text{max},1}(t) = \arccos \left[ I_d(t) \frac{\omega L_c}{\sqrt{2K_I U_c(t)}} + \cos \gamma_{\text{lim}} \right]
\]  

(4)

and at time \( t+\Delta t \)

\[
\alpha_{\text{max},2}(t) = \arccos \left[ I_d(t + \Delta t) \frac{\omega L_c}{\sqrt{2K_I U_c(t + \Delta t)}} + \cos \gamma_{\text{lim}} \right]
\]  

(5)

By applying the first-order derivative, the values of commutating voltage and dc current at the next time step are estimated. To make sure the commutation at the next time step success, the maximum firing angle order can be calculated based on the estimated trajectory of commutating voltage and dc current.

Dynamic Hard Limiter of Firing Angle Order

Although the order of firing angle is generated by the controller based on some specific strategies to ensure the commutation safety, the dynamic response of PI-controller can never be instantaneous and the overshoot may lead to unexpected commutation margin reduction. In this paper, a dynamic hard limiter is implemented to ensure that, the order of firing angle can lead to a successful commutation. If the firing angle order sent to firing pulse generator exceeds the limiter, the order will be forced to be under the safety value.

Firstly, the maximum firing angles at time \( t \) and \( t+\Delta t \) are compared to find the smaller one, which will be used as the hard limit of firing order.

\[
\alpha_{\text{max}}(t) = \min \left\{ \alpha_{\text{max},1}(t), \alpha_{\text{max},2}(t) \right\}
\]  

(6)
Then, the firing angle order is compared with this hard limit, producing the final firing angle order:

\[
\alpha_{ord}(t) = \min\{\alpha_{ctr}(t), \alpha_{\text{max}}(t)\}
\]

where \(\alpha_{ctr}(t)\) is the \(\alpha\) order generated by the controllers.

It should be noted that, this hard limit is dynamically calculated and updated. Figure. 1 shows the whole structure of the proposed method.

![control_structure_diagram]

**Figure 1.** The control structure of the proposed method.

**Case Studies**

To show the effectiveness of the proposed method, the CIGRE benchmark model for LCC-based HVDC system in PSCAD/EMTDC is applied, and the short circuit ratio of the inverter side is set to 2.0. Here, a three-phase fault is applied at the inverter side at \(t=0.2s\), and cleared at \(t=0.3s\). Figure. 2 shows the response of commutating voltage and dc current. It can be seen that, after the fault is cleared, the system begins to recover from CF. However, the system becomes unstable from \(t=0.5s\), and the voltage and current start to oscillate. At the moment of about \(t=0.78s\), a continuous CF take place. The dc current rise to a very high value at a very short time.

![system_response_diagram]

**Figure 2.** System response without hard limiter.
Figure 3. Comparison between firing angle order from controller and hard limiter.

Figure 3 shows the comparison between firing angle order and the limit of firing angle order calculated by the proposed method. At about $t=0.78s$, the firing angle order is greater than the safety limit, and commutation failure takes place due to insufficient commutation margin.

Figure 4. System response by the proposed method.

Figure 5. Firing angle comparison between the proposed method and the one without hard limiter.
Figure. 4 shows the recovery response by the proposed method. It can be seen that the system can recover to normal operation in about 300ms, and no continuous CF happens. In Figure. 5, the firing angle orders sent to firing pulse generator are compared. It can be seen that, the proposed method can limit the firing angle order, with consideration of the trend of system trajectory. During the period between t=0.31s and t=0.33s, the commutating voltage and dc current change very fast. The dynamic performance of PI-controllers may provide an inaccurate firing angle order, but the dynamic hard limit of firing angle can ensure the commutation carry out successfully.

Conclusion
This paper proposes a novel control strategy to improve the dynamic performance of recovery from CFs, where the trend of system trajectory and commutation safety limit are considered. With the help of dynamic hard limiter, the firing angle order is ensured to induce successful commutations. Case studies show the effectiveness of the proposed method.

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References
[1] C. V. Thio, J. B. Davies, K. L. Kent, Commutation failures in HVDC transmission systems, IEEE Transactions on Power Delivery 11 (2) (1996) 946–957.
[2] Y. Zhou, H. Wu, Y. Song, W. Ling, B. Lou, H. Deng, Analyses of static and dynamic reactive power allocation between synchronous compensators and shunt capacitors to counter commutation failures, International Transactions on Electrical Energy Systems 28 (10) (2018) e2605. doi:10.1002/etep.2605.
[3] Q. Zheng, X. Wang, Y. Fu, H. Yan, Z. Ou, G. Wang, Y. Wang, A STATCOM compensation scheme for suppressing commutation failure in HVDC, in: IECON 2016—42nd Annual Conference of the IEEE Industrial Electronics Society, Florence, Italy, 2016, pp. 1081–1086.
[4] A. U. Rehman, C. Zhao, C. Guo, Coordinated control strategy for transient performance improvement of LCC based HVDC transmission system with STATCOM under weak AC grid, in: 2018 2nd IEEE Conference on Energy Internet and Energy System Integration (EI2), Beijing, China, (2018) 1–6.
[5] Y. Zhou, H. Wu, W. Wei, Y. Song and H. Deng, Optimal Allocation of Dynamic Var Sources for Reducing the Probability of Commutation Failure Occurrence in the Receiving-End Systems, IEEE Transactions on Power Delivery, 34 (1) (2019) 324-333.
[6] T. Tanaka, M. Nakazato and S. Funabiki, A new approach to the capacitor-commutated converter for HVDC-a combined commutation-capacitor of active and passive capacitors, 2001 IEEE Power Engineering Society Winter Meeting. Conference Proceedings (Cat. No.01CH37194), Columbus, OH, USA, 2 (2001) 968-973.
[7] H. H. Zeineldin, E. F. El-Saadany and M. Kazerani, "Capacitor commutated converter using an adaptive active capacitor for HVDC system," CCECE 2003 - Canadian Conference on Electrical and Computer Engineering. Toward a Caring and Humane Technology (Cat. No.03CH37436), Montreal, Quebec, Canada, 1 (2003) 529–534.
[8] G. Zhang, L. Jing, M. Liu, B. Wang, X. Dong, An improved continuous commutation failure mitigation method in high voltage direct current transmission system, in: 2018 China International Conference on Electricity Distribution (CICED), (2018) 1132–1136. doi:10.1109/CICED.2018.8592449.

[9] Z. Wei, Y. Yuan, X. Lei, H. Wang, G. Sun and Y. Sun, Direct-Current Predictive Control Strategy for Inhibiting Commutation Failure in HVDC Converter, IEEE Transactions on Power Systems, 29 (5) (2014) 2409-2417.

[10] Y. Z. Sun, L. Peng, F. Ma, G. J. Li and P. F. Lv, Design a Fuzzy Controller to Minimize the Effect of HVDC Commutation Failure on Power System, IEEE Transactions on Power Systems, 23 (1) (2008) 100-107.

[11] L. Liu, S. Lin, P. Sun, K. Liao, X. Li, Y. Deng, Z. He, A calculation method of pseudo extinction angle for commutation failure mitigation in HVDC, IEEE Transactions on Power Delivery 34 (2) (2019) 777–779.

[12] S. Wang, S. Lu, Y. Hou, F. Liu, Z. Xu, Improvement of HVDC commutation failure response based on compound phase-shifting control, The Journal of Engineering 2017 (13) (2017) 1473–1477.