Coordination of synchronous compensators and converters to improve the commutation failure recovery performance in HVDC systems

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Abstract. A novel control strategy of synchronous compensators and converters is proposed to increase the ability of line commutated converter (LCC) based HVDC systems to successfully recover from commutation failures (CFs). The dynamic var support is one of the most important factors, which impact the commutation process. Many synchronous compensators have been implemented to enhance the transient voltage stability for improving the CF recovery performance. However, the traditional automatic voltage regulator (AVR) of synchronous compensator may not be suitable for the commutation voltage support, because the transient var demand of converters during the CF recovery is neglected. In our work, the voltage control will be adaptively adjusted, depending on the state of converters. Case studies based on simulations in PSCAD/EMTDC show that the proposed strategy can improve the performance of fault recovery from CF.

1. Introduction

Commutation failures are very common in traditional LCC-based HVDC systems [1], which will inevitably cause temporary interruption of power transmission, voltage fluctuation, etc. Once the fault is cleared, the HVDC system should be able to recover from CF. Otherwise, continuous CFs may induce converter block, which largely threatens the system security. It is important to improve the recovery performance to avoid the converter block, and many previous works have been dedicated to this topic.

The commutation process relies on the stable commutating voltage provided by the ac-side system, meaning that the transient voltage support ability is closely related to the immunity against CFs [2]. To counter CFs, many studies concerning about DVSs have been done. Authors in [3] pointed out that the synchronous compensators installed at HVDC converter stations can reduce the system risk caused by CFs. Paper [4] discussed the impact of dynamic var sources on transient voltage stabilities and CFs, where the multi-infeed effect was considered. To maximize the benefit of dynamic var sources, paper [5] proposed a dynamic var reserve optimization model to prevent the onset of CFs, considering the constraints of commutating voltage. In [6], the location effect of dynamic var sources on CFs is investigated, and the results showed that more dynamic var sources will lead to better immunity against CFs.

Synchronous compensator is one typical dynamic var sources, which can provide transient voltage support during CFs [7]. The exciter can regulate the filed voltage to maintain the system voltage at the specified level. However, the current strategy of automatic voltage regulator may not be suitable for the synchronous compensator allocated nearby the converter. The main reason is that the dynamic var demand of converters during the CF transients is neglected.
In our work, a novel coordinated control of exciter for synchronous compensator located nearby converters was proposed, without any communication channels. Based on the captured commutating voltage phase angle information from the terminal voltage, the CF state was judged and then sent to the exciter to adjust the control strategy to improve the transient performance.

The rest of this paper was organized as follows: the transient behaviours of converters and synchronous compensator were analysed in section 2, and the proposed control method was introduced in section 3, followed by the case studies. At last, the conclusion was presented in section 5.

2. The CF transient behaviour analysis

2.1 The dynamic var demand of converters

2.1.1 The demand under normal operations

For the LCC-based converter, the dc voltage and dc current during the normal operation can be expressed as [8-9]:

\[
\begin{align*}
I_d &= \frac{\sqrt{6}U_m}{2\pi\omega_c} \left[ \cos \alpha - \cos(\alpha + \mu) \right] \\
U_d &= \frac{3\sqrt{6}U_m}{2\pi} \left[ \cos \alpha - \cos(\alpha + \mu) \right]
\end{align*}
\]

where \(U_d\) and \(I_d\) are the dc voltage and dc current respectively; \(U_m\) is the ac voltage; \(L_c\) is the commutation inductance; \(\alpha\) is the firing angle; and \(\mu\) is the commutating angle.

From the energy conservation law, we have

\[
U_d I_d = 3U_m I_a \cos \phi
\]

where \(I_a\) is ac-side current and \(\phi\) is the power factor angle.

For the ac-side current and dc-side current, the following relation holds:

\[
I_a = \frac{\sqrt{6}}{\pi} I_d
\]

Thus, the var demand of converter during the commutation process can be expressed as

\[
Q_{\text{var}} = U_d I_d \tan \phi
\]

where \(Q_{\text{var}}\) represents the var demand of converter.

2.1.2 The demand under CF

When CF occurs, the valves cannot be operated following the firing command, because at least one valve cannot be closed as expected. In consequence, the dc-side will have a short-circuit fault, with the positive pole and negative pole conducted directly. Meanwhile, the abnormal operation of valves will lead to the open-circuit of ac-side [10]. At this moment, both the power injection and var demand of converter are zero.

It should be pointed out that the filter and capacitance compensation are still provide reactive power during CF [11], which may result in transient overvoltage.

2.2 The traditional exciter response under CF

2.2.1 The traditional AVR control

The exciter of synchronous compensator is expected to respond to the voltage changes at the stator terminal, and a proper level of field voltage is produced to maintain the stator terminal voltage at a specified value [12]. Figure 1 shows one simplified AVR control loop, where \(V_{\text{ref}}\) represents the voltage reference, \(E_{\text{ext}}\) is the external control signal, \(T_A\), \(T_B\) and \(T_E\) are the control time constants, \(K\) is the exciter gain, \(E_{\text{max}}\) and \(E_{\text{min}}\) are the upper limit and lower limit of exciter output respectively, and \(E_f\) is the filed voltage.
2.2.2 The transient behaviour of AVR during CF
From the discussion in subsection 2.1.2, the var demand of converter during CF is almost zero, while the filter and capacitance compensation are still injecting var into system. Thus, overvoltage may occur before the converter var demand recovers to the level of normal operation. From (4), the var demand of converter will rise with the dc current increased. The total var injected from converter station will be decreased, resulting in a lower voltage.

For the synchronous compensator, the var output will be regulated with reference to the stator terminal voltage, i.e., the commutating voltage. Therefore, the var output will be reduced at the beginning of CF recovery, because the field voltage will be reduced due to overvoltage. With the var demand of converter recovering, the voltage will go down, to support which more var should be injected into system. However, the var output of synchronous compensator largely depends on the rotor current, and the rotor current cannot be changed instantaneously due to the inductance effect. The previous reduction of var output may induce the failure of CF recovery.

3. The proposed methodology

3.1 Fast judgement of CF state
Assume that, in a single-infeed system a converter station is connected to an infinite system via a reactance of $X_s$, where the voltage magnitude and phase angle are $U_s$ and $0$ respectively. Then, the following expression with regard to commutating voltage should hold:

$$
\begin{align*}
& P_s = \frac{U_s U_m}{X_s} \sin \theta \\
& Q_s = \frac{U_m^2}{X_s} - \frac{U_m U_s}{X_s} \cos \theta 
\end{align*}
$$

where $P_s$ and $Q_s$ are the active and reactive power injection of converter station respectively, and $\theta$ is the voltage phase angle.

From (5), the voltage phase angle largely depends on the active power injection of HVDC system. When CF occurs, the ac-side system can be regarded as open-circuit and power transmission is suspended. At this moment, the phase angle $\theta$ will decrease suddenly, which can be regarded as an indicative index for judging the state of CF.

If the change rate of phase angle exceeds a critical value, the occurrence of CF can be regarded:

$$
\lambda_{CF} = \begin{cases} 
1, & \text{if } \dot{\theta} \geq \dot{\theta}_c; \\
0, & \text{if } \dot{\theta} < \dot{\theta}_c,
\end{cases}
$$

where $\lambda_{CF}$ denotes the state of CF, and $\dot{\theta}_c$ is the critical value of voltage phase angle.

One major advantage of the judgement is that the facilities nearby converters can gain the state information of converter directly from the bus voltage, without any communication systems.
3.2 The proposed exciter coordination control

\[ V_{\text{ref}} \xrightarrow{\lambda_{\text{CF}}} \frac{1}{1+sT_A} E_{\text{ref}} \xrightarrow{\frac{K}{1+sT_E}} \frac{K_{\max}}{1+sT_E} E_{\text{ref}} \xrightarrow{\text{S/H}} E_f \]

Fig. 2. The proposed coordination control.

Figure 2 shows the proposed control method. Firstly, the CF state is judged with reference to the stator terminal voltage by (6), where the phase angle change rate is captured by phase lock loop. Once the CF state is triggered, a monostable signal with high level is produced and then remains high for a pulse duration. Then, this signal is sent to a sample and hold control block to adjust the output of exciter. When the CF state signal transition from 0 to 1 is detected, the output of exciter is held at that input sample value. After the CF state is over, the traditional exciter control output is passed to the output.

The main idea of proposed control is that, the exciter output is switched to maintain the exciter output stable. Under traditional control strategy, the dramatic change of commutating voltage will definitely induce a dramatic variation of exciter output. The var output reduction in the beginning recovery stage will cause bad effects on the following recovery process, which desires a large amount of var increment. To overcome the shortage of dynamic var ramping rate, the exciter output is forced to maintain a stable value with reference to the pre-fault situation.

4. Case studies

In our work, the effectiveness of proposed method is validated based on the CIGRE_benchmark model established in PSCAD/EMTDC environment [13]. Here, a synchronous compensator with capacity of 300 MVA is connected to the commutation bus via a transformer with reactance of 0.18j (p.u), shown as Figure 3.

For the synchronous compensator, the exciter control parameters are listed as follows: \( T_A = 0.1s, T_B = 0.2s, T_E = 0.065s, K = 25, E_{\text{max}} = 10 \) and \( E_{\text{min}} = -10 \) respectively. For the synchronous machine, the inertia constant is 1.988s, the armature resistance is 0.00001 p.u., the unsaturated reactance \( X_d \) is 1.56 p.u., the unsaturated transient time \( T_{\text{d0}} \) is 1.1s, the unsaturated transient reactance \( X_d' \) is 0.3 p.u., and the unsaturated reactance \( X_q \) is 1.56 p.u.

Fig. 3. The single-infeed system used in case studies.

4.1 Discussion of CF state judgement

Firstly, the CF state judgement method was validated with two different fault levels. At the time of 0.2s, a three-phase fault was applied at the commutation bus, and cleared after 0.02s.
Figure 4 depicted the voltage phase angle and active power comparison under the fault level of 400 W with no synchronous compensator connected. It can be seen that the phase angle had a similar response compared to the active power. When the fault happened at $t=0.2s$, CF occurred. The dc-side and ac-side were with short-circuit and open-circuit respectively, so the active power injection decreased very fast to zero. From subsection 3.1, the phase angle was mainly determined by the active power injection. Thus, the phase angle had a dramatic change when CF occurs. In our work, this characteristic is used to indicate the state of CF.

Figure 5 showed the simulation results under the 1000 $\Omega$ fault level. In this case, the CF did not happen because the voltage dip induced by ac system fault was not big enough to trigger CF. Therefore, the power injection would sustain, rather than be suspended. The change rate of power injection and voltage phase angle were much smaller than that under CF. That means the CF state can be judged with reference to the change rate of voltage phase angle, if a proper critical value was given.

4.2 Effectiveness validation

To show the effectiveness of the proposed method, the comparison between the traditional AVR method and the proposed method was performed, where the three phase fault level was set to 400 $\Omega$.

Fig. 6. The var output of synchronous compensator and ac voltage response under the traditional method.
As shown in Figure 6, the var output ramped from the steady state output to 40 Mvar within 0.05s, once the fault happened. After the fault was cleared, the ac voltage would rise to a higher value, due to the low var demand of converter and large var injection from filters and compensation capacitors. Thus, the synchronous compensator would decrease the var output to counter the overvoltage, which may have a negative effect on the CF recovery. During the CF recovery, the synchronous compensator had a lower var output than the steady state did. In this case, the continuous CF occurred at $t = 0.4s$, and then the followed overvoltage would induce a further var output deduction.

Therefore, the traditional AVR method cannot cooperate with the CF recovery, because the overvoltage in the beginning state and the dramatic var demand increase were neglected.

Figure 7 gave the responses under the proposed method. It can be seen that, the var output of synchronous compensator still had a variation during the transients, because of the fluctuation of the stator terminal voltage. But, the variation of var output was much smaller than the response under traditional method, which means the synchronous compensator can provide voltage support in the period of CF recovery. During the period between 0.4s and 0.7s, the var output of synchronous compensator had a higher output than the steady state did, because the voltage was lower than the specified value and the CF recovery was in the late stage.

Figure 8 showed the comparison of extinguishing angle $\gamma$ between the traditional method and the proposed method. As seen, the traditional method cannot give enough support to the CF recovery, and the converter had a following CF during the CF recovery process. For the proposed method, the extinguish angle was over the hard limit of critical angle and no continuous CF occurred. That means, the proposed method can effectively improve the performance of CF recovery.

5. Conclusion
A novel coordination control method was proposed to improve the performance of CF recovery, where no further communication was desired between the synchronous compensator and converters. The CF state was judged by the change rate of voltage phase angle, and the voltage phase angle information can
be captured from the stator terminal voltage of synchronous compensator. Then, the field voltage was adaptively controlled with reference to the signal of CF state. Once the CF state is on, the field voltage would hold until the CF state is off. Case studies based on the CIGRE benchmark model showed that the proposed method can improve the CF recovery performance, where the CF state judgement method can indicate the CF state effectively.

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References
[1] Rahimi, Ebrahim, et al. "Commutation failure analysis in multi-infeed HVDC systems." IEEE Transactions on power delivery 26.1 (2010): 378-384.
[2] Wang, Yuhong, et al. "Impact of AC system strength on commutation failure at HVDC inverter station." 2012 Asia-Pacific Power and Energy Engineering Conference. IEEE, 2012.
[3] K. Zhang, Y. Cui, Z. Yang, Y. Feng, Q. Zhang, and Y. Yu, “Analysis of the influence of synchronous condensers on receiving-end grid with multi-infeed HVDC,” in Proc. IEEE Int. Conf. Power Syst. Technol., (2016).
[4] K. Saichand and K. R. Padiyar, "Analysis of voltage stability in multi-infeed HVDC systems with STATCOM," 2012 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES, 2012).
[5] B. Zhao, Z. Hu, Q. Zhou, Y. Song, and C. He, “Online dynamic reactive power reserve optimization for power system with multi-infeed HVDC systems,” in Proc. Int. Conf. Power Syst. Technol (2014).
[6] F. De Lillo, F. Cecconi, G. Lacorata, A. Vulpiani, EPL, 84 (2008).
[7] S. Teleke, T. Abdulahovic, T. Thiringer and J. Svensson, "Dynamic Performance Comparison of Synchronous Condenser and SVC," in IEEE Transactions on Power Delivery, vol. 23, no. 3, pp. 1606-1612, (July 2008).
[8] S. Mirsaeidi, X. Dong, D. Tzelepis, D. M. Said, A. Dyško and C. Booth, "A Predictive Control Strategy for Mitigation of Commutation Failure in LCC-Based HVDC Systems," IEEE Transactions on Power Electronics, vol. 34, no. 1, pp. 160-172, (Jan. 2019).
[9] Khazaemi, Javad, et al. "Review of HVDC control in weak AC grids." Electric power systems research 162 (2018): 194-206.
[10] Muthusamy, Arunkumar. Selection of dynamic performance control parameters for classic HVDC in PSS/E. MS thesis. (2010).
[11] Xue, Ying, and Xiao-Ping Zhang. "Reactive power and AC voltage control of LCC HVDC system with controllable capacitors." IEEE transactions on power systems 32.1 (2016): 753-764.
[12] Ibraheem, Ibraheem Kasim. "A digital-based optimal AVR design of synchronous generator exciter using LQR technique." Al-Khwarizmi Engineering Journal 7.1 (2011): 82-94.
[13] M. Szechtmian, T. Wess, C.V. Thio, "First Benchmark Model for HVDC Control Studies", Electra, No. 135, (1991).