Investigation of MMC-HVDC Operation Performance Based on Improved Control Strategy

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Abstract. Modular multilevel converter (MMC), as a new type of topology, has aroused widespread concern in the research on HVDC system. However, there are some problems such as low anti-interference performance and output instability in their internal control systems. Based on these problems, this paper improves pole control on original control strategy. The improved control strategy not only can achieve active and reactive power independent control as well as stability control of the DC voltage, but also can reduce the oscillation amplitude and cut down the recovery time, as a consequence, the transient and steady-state performance are improved efficaciously. This paper establishes MMC-HVDC two AC systems and conducts the contrastive simulation analyses between the improved control strategies and original strategies in the MATLAB/Simulink. The results verify the validity and effectiveness of the theory.

1. Introduction

With the rapid development of HVDC transmission technology, the high voltage direct current based on voltage source converter (VSC-HVDC) has been widely applied to large city load centers, offshore drilling platforms, island power supply, new energy and other HVDC transmission projects because of its independent control of active and reactive power, two-way transmission of energy, adaptability in various transmission occasions, no commutation failure and many other advantages [1-4]. Among them, MMC acts as a new topology of VSC, which has great prospects for development due to its low switching frequency, high waveform quality and scalability [5-6]. For these reason, MMC becomes an important object for the future development of HVDC transmission projects. The MMC is made up of several sub modules controlled by PWM control signals. Any changes of sub module operation parameters will affect the output of the entire waveform. Therefore, compared with VSC-HVDC, MMC control strategy under steady state operation requires additional sub module capacitor voltage balancing control and circulating current suppression control [7], besides the basic control strategy deduced from the AC side mathematical model. The complexity and diversity of control strategy make the control requirement of MMC-HVDC system very strict for all links. A weakness in a link control will inevitably affect other links.

The VSC-HVDC control strategy mainly contains the current inner loop and voltage outer loop control system in [8]. For the two level, three level VSC-HVDC, due to the additional AC side filter with large capacity and the DC side capacitor, the output stability is greatly enhanced, so the traditional control strategy can satisfy the requirements of normal operation. However, the original VSC control
strategy cannot be perfectly applied to the MMC-HVDC system with the increase of the voltage balancing control in the structure. Therefore, the control strategy must be improved to effectively suppress the abnormal conditions and small disturbance waves in the MMC-HVDC system, and reduce the amplitude of the fault oscillation as well as the recovery time after the failure.

According to the above-mentioned requirements for MMC controller, new control elements are added in system control to limit oscillation amplitude and reduce disturbance recovery time, so as to improve the stability and anti-interference of the control system. The MMC-HVDC two AC system based on improved control strategy is built in MATLAB/Simulink environment to simulate steady and transient stage, analyze the operation performance before and after the improvement. The results verify the correctness and validity of the improved control strategy.

2. MMC-HVDC System Control Strategy

At present, the general outer loop controller control is relatively simple, as shown in Fig. 1, $P_{ref}$, $Q_{ref}$, $U_{dc-ref}$ are respectively the reference active power, reactive power and DC voltage value; $P_{meas}$, $Q_{meas}$, $U_{dc-meas}$ are respectively the measurement value of active power, reactive power and DC voltage, $i_{dref}$, $i_{qref}$ are respectively dq reference value of the AC current.

By comparing the actual measured value $P_{meas}$, $Q_{meas}$, $U_{dc-meas}$ with the reference value $P_{ref}$, $Q_{ref}$, $U_{dc-ref}$, the unbalance quantity can be obtained, and then convert it into an inner loop current controller input quantity $i_{dref}$, $i_{qref}$ through the PI controller. The control type belongs to open loop control.

Although the traditional outer loop controller shortens the control response time to a certain extent, its structure is not able to control the abnormal working condition or disturbance accurately, so that the reliability and anti-interference of the system are not guaranteed[14-15].

![Figure 1. The traditional outer loop controller](image)

In this paper, the improved system level control is adopted in view of the above problems, and the concrete structure is shown in Fig. 2. The improvement 1 is aimed at the improvement of the original outer ring controller, and the improvement 2 is an additional control for the design of abnormal conditions such as the transient fault, like the large disturbance.

![Figure 2. The improved external loop controller](image)
The improved constant active power controller increases the closed loop control compared with the traditional outer loop constant active power controller, and adds transient fault control, as shown in Fig. 2 (a) improvement 1 and improvement 2. Among them, \( U_{d\text{ref}} \), \( U_{d\text{meas}} \) is the allowable upper and lower limits of DC voltage, the general allowable voltage fluctuation is less than 5% of the rated value. The DC upper limit is 1.05p.u, the lower limit is 0.95p.u, and the upper and lower limits of active power limiting link are 1p.u and -1p.u respectively.

First, the control principle of the improvement 1 is analyzed in detail. Compared to \( P_{\text{ref}} \) and \( P_{\text{meas}} \), the unbalance value \( \Delta P \) can be obtained, through the PI link the \( \Delta P \) can be changed into \( P' \), through the limiting link, the \( P' \) can be changed into \( P^* \). Under the steady state, \( P' = P^* \), when the system is disturbed, \( P' \) may be higher or lower than the limit, when the \( P' \) is beyond the limit, the system outputs the limit value directly, and the system is normally output when the \( P' \) is not exceeded. At this point, \( P' \neq P^* \), through the adder, \( P' - P^* \) will be fed back to the input end, and compared with \( \Delta P \), the difference will be used to eliminate the disturbance through the PI controller, thus \( i_{d\text{ref}} \) can maintain stable output.

Secondly, the control principle of the improvement 2 is analyzed in detail. Compared to the \( U_{d\text{max}} \) and \( U_{d\text{meas}} \), \( \Delta U_{d1} \) can be obtained, compared \( U_{d\text{min}} \) with \( U_{d\text{meas}} \), \( \Delta U_{d2} \) can be obtained. On the one hand, \( \Delta U_{d1} \) and \( \Delta U_{d2} \) can be changed into \( \Delta P'_{1} \) and \( \Delta P'_{2} \) through the PI controller, on the other hand, \( \Delta U_{d1} \) can be changed into \( \Delta U'_{d1} \) through the limiting link(-1~0), \( \Delta U_{d2} \) can be changed into \( \Delta U'_{d2} \) through the limiting link(0~1). \( \Delta U'_{d1} \) is summed with \( \Delta U'_{d2} \), and \( \Delta P' \) can be obtained through Proportional link. At last, \( \Delta P'' \) can be get through the sum of \( \Delta P'_{1}, \Delta P'_{2} \) and \( \Delta P' \), and \( \Delta P'' \) will be send to improvement 1 in order to adjust the \( i_{d\text{ref}} \) value.

Take the case of the transient fault which occurs at the AC side of the inverter, due to lower active power transmission from receiving end, and unchanged active power transmission from sending end, the surplus active power makes the DC voltage increase. In order to solve this problem, the improvement 2 is created to control the DC voltage. Once the DC voltage is too high, the PI controller will output negative active power, then sum with active power from improvement 1, thereby the receiving end active power will be reductive, eventually the increase of DC voltage is suppressed.

In addition, improvement 2 can be used to suppress DC voltage in transient fault, while the traditional controller can convert constant active power and constant DC voltage converter to control the transient fault effect. In comparison, the additional improvement 2 belongs to direct control, which control more quickly and adjust more conveniently. At the same time, due to the introduction of additional control, the complexity of the control is greatly increased compared with the original outer loop controller’s. However, the additional control has the advantages of simple structure, which can decrease the system complexity compared to the complexity of the mutual conversion control of the constant active power and the constant current voltage converter in the control of transient faults. In addition, the range of DC voltage fluctuation controlled by additional control is less than the range of traditional transient control. Therefore, when transient fault is very serious, it is necessary to transform the constant active power and constant DC to replace the improvement 2.

The improved constant reactive power controller is similar to the improved constant active power controller. It also increases the closed loop control, and adds transient fault control, as shown in Fig. 2(b) improvement 1 and improvement 2. Among them, \( U_{r\text{max}} \), \( U_{r\text{min}} \) are the upper and lower limits of AC voltage respectively which are the same as those of DC voltage limits, and \( Q_{\text{max}} \), \( Q_{\text{min}} \) are the upper and lower limits of reactive power limit which are 0.5p.u and -0.5p.u respectively.

Compared with Fig. 2(a) and Fig. 2(b), the improved constant reactive power controller is basically the same as that of the constant active power controller. It shows that the specific control principle is consistent with the constant active power controller. Only the control volume is converted from active power and DC voltage to reactive power and alternating voltage, and the function is also converted to suppress the fluctuation of AC voltage. Therefore, this article will not repeat it.
The constant DC voltage controller used in this paper is shown in Fig. 2(c), in which the upper and lower limits $U_{dc\_max1}$, $U_{dc\_min1}$ of the DC voltage limiting link are 1.1p.u and -1.1p.u respectively. Because it is aimed at the control of DC voltage, there is no improvement 2, and the function of the improvement 1 is similar to the functions of the above two controllers. It is mainly used to suppress the DC voltage fluctuation under abnormal conditions.

3. Simulation and analysis of operation characteristics of MMC-HVDC system

3.1. A comparative study of steady state stage

In order to verify the superiority of the improved control strategy adopted in this paper, two sets of MMC-HVDC systems are designed, one of which adopts the original control strategy and the other one adopts the improved control strategy. The steady-state performance of the above MMC-HVDC system is simulated to study their operation characteristics under different working conditions and small disturbance states. The operation states of both of them are compared in different states, and the stability and anti-interference of the improved control strategy are analyzed. The details of the control in the steady state are shown in Table 1.

**Table 1. Steady state stage simulation control details**

| Time/s | Action details |
|--------|----------------|
| 1.5-1.64s | The AC voltage of the rectifier is reduced by 0.1 p.u. |
| 2.0s | Active power reference power is reduced by 0.1 p.u. |
| 2.5s | Reactive power of reactive power is reduced by 0.1 p.u. |
| 3s | The inverter side DC reference voltage decreases by 0.05 p.u. |

In accordance with the control details given in the above table, the steady-state simulation of the MMC-HVDC system is carried out. The simulation results are shown in Fig. 3. Sections should be numbered with a dot following the number and then separated by a single space:

According to Fig. 3, the changes of the system before and after the improvement are analyzed.

(1) Active power: as shown in Fig. 3 (a), in 1.5s-1.64s, the sending side AC voltage drops, and the active power oscillates about 0.18p.u. before the improvement, oscillation time is about 0.3s. After the improvement, the active power oscillates about 0.1p.u., oscillation time is about 0.2s. At 2s, the operation condition changes, the reference value of active power is reduced by 0.1p.u. Before the improvement, the active power real value is hard to follow reference value until 2.2s. The actual value of the improved active power changes with the reference value in time, and the waveform of them is almost coincided. At 2.5s, the reference value of reactive power is reduced by 0.1p.u. No matter before or after improvement, the active power is not changed. At 3s, the DC voltage is reduced by 0.05p.u, the active power changes considerably before the improvement, the recovery time is longer, and the
improved system is stable after 0.2s. The above results show that the improved control strategy has greatly improved the control of the active power, the amplitude of the system oscillation and the recovery time.

(2) Reactive power: as shown in Fig. 3 (b), when the AC voltage is decreasing from 1.5s to 1.64s, before the improvement, the oscillation is very frequent only on the basis of its own regulation mechanism. After adopting the improved control strategy, the reactive power decreases by 0.1p.u under the action of the improved control strategy, thus ensuring the stability of active power and DC voltage. The change of the active power reference value at 2s has no effect on the reactive power. At 2.5s, the reference value of reactive power is reduced by 0.1p.u. Before the improvement, the real value of reactive power tracks the reference value slowly, using 0.3s to reaches stability. After improvement, the actual value of reactive power follows the reference value in time, and almost coincides. At the same time, the change of DC voltage has no effect on reactive power. The above comparison shows that the improved control strategy has a significant effect on reactive power control.

(3) DC voltage: as shown in Fig. 3 (c), when the AC voltage is reduced, the fluctuation of DC voltage is larger before improvement, and the fluctuation amplitude and time are improved after using the improvement 1 and 2. When the reference value of active power is reduced, the DC voltage is reduced, however, the DC voltage amplitude of the fluctuation and the recovery time has improved after improvement. The decrease of reactive power has no effect on the DC voltage. When the DC voltage is reduced, the actual value of DC voltage changes slower and the stability time is more than 0.4s before improvement. After improvement, the actual value can track the reference value in time. It shows that the control effect of the DC voltage is obviously adopted after the improved control strategy.

Through the comparison of simulation results before and after the improvement of control strategy, a conclusion can be get: the improved system can not only make the decoupling control of active power and reactive power, but also can reduce the oscillation amplitude, shorten the oscillation time, make the system reliable, enhance the system stability and anti-jamming.

3.2. A comparative study of transient stage

The three-phase short circuit module is set at the AC side of the inverter, which is put in 3.5s and excised at 3.62s. The specific simulation results are shown in Fig. 4.

![Figure 4. Transient state stage waveform](image)

After analyzing the Fig. 4(a), a result can be obtained, when the inverter side occurs three-phase fault, the rectifier side transmission active power is 0.5p.u, the inverter side AC voltage drop to zero, and the active demand drop to 0, at this time, the rectifier side transmission active power is larger than the inverter side active power, the demand imbalance on both sides of the active power will lead to the increase of DC voltage finally, causing damage to the power electronic devices. After using the improved control strategy, the active power of the rectifier side is reduced to 0.25p.u under the action of the controller, which also reduces the harm of the active power imbalance. After the fault is removed, the active power before the improvement always fluctuates at the stable value, but the improved active power is recovered to the stable state after about 0.3s.

After analyzing the Fig. 4(c), a result can be obtained, when three-phase faults occurs, the DC voltage controller works, and controls the maximum amplitude of DC voltage to be 1.16p.u, reduces 0.1p.u.
than that of pre-improved DC voltage amplitude, so after the fault, the improved DC voltage recovery effect is obviously better than the original.

By comparing the simulation results, we can see that the improved control strategy adopted in this paper can reduce the transmission of the active power of rectifier side in time, and control the DC voltage within the allowable range, so as to ensure the safety of power electronic devices. After the fault is removed, the improved system will quickly return to the steady state and there is no obvious fluctuation. The degree of fluctuation and the recovery time of the fault are far less than the time before the improvement, and can be restored to the steady state in time.

4. Conclusion
In this paper, an improved control strategy is adopted in the MMC-HVDC system, which solves the problem of low anti-interference and unstable control in the past. On the platform of MATLAB/Simulink, a simulation model of two side MMC-HVDC system is built. The steady state and operation characteristics of transient stage before and after adopting the improved control strategy are compared.

According to steady state, in the stationary case, the outer loop control is change into closed loop from open loop, which is a certain degree of delay in the control response speed, but the control effect is remarkable. To a certain extent, the improved system can enhance the ability of interference suppression. In the abnormal condition of the system, it can reduce the amplitude of oscillation, shorten the recovery time of system after disturbance, and has good stability and anti-interference.

(1) For transient conditions, the improved control strategy can start without starting conversion control mode, reduce the transmission of rectifier active power in time, so as to effectively suppress the DC voltage increased, and also has a good protective effect on power electronic devices. In addition, the fault recovery time has also been significantly improved.

(2) After using the improved control strategy, although the complexity of MMC-HVDC system control is increased a little, the reaction speed control strategy is reduced, but the advantages are great, the improved system can be more efficient to control the DC system, and provide a more effective basis platform in the research on operational characteristics of AC/DC system for the following research.

5. References
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