Research on restraining low voltage of distribution power network using STATCOM

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Abstract. In order to solve the problem of low voltage in distribution power network, this paper proposes a novel static synchronous compensator (STATCOM) based on modular multilevel converter. When the bus voltage of distribution power network changes rapidly, the MMC-STATCOM can quickly provide reactive voltage support and maintain the stability of bus voltage. Firstly, this paper introduces the operating principle of the MMC-STATCOM, and then propose three-level control strategies including device-level-, converter-level- and system level-control. Finally, based on the data of a power station in the distribution network, Simulation is carried out in the power system analysis and synthesis program (PSASP). The simulation results show that the MMC-STATCOM control function is reasonable and can respond quickly to the system reactive power change. It can effectively realize the voltage support and ensure the safe and stable operation of the power network.

1. Introduction
In recent years, with the application of electric power devices in distribution power network more and more widely, the power load has a large number of equipment with frequent changes of reactive power, such as welding machine, rolling mill and rectifier equipment [1-3]. Once, the distribution power network lacks the support of dynamic reactive voltage, the power grid voltage will fluctuate violently, and even cause the large area collapse of the power grid voltage [4]. In particular, a large number of impact loads will cause typical power quality problems such as voltage fluctuation, flicker, harmonic and three-phase imbalance, which may pose a serious threat to the safety and stability of the power system. A new generation of dynamic reactive power compensation equipment of static reactive power compensator (STATCOM) is constructed using power electronic devices [5-6]. It has the following advantages: fast dynamic response, strong compensation ability, and small power consumption. The STATCOM is considered as the most effective way to solve the voltage fluctuation and flicker.

The basic principle of STATCOM is that the self-commutating circuit is comprised by high power electronic devices and it is connected in parallel with power grid [7]. Then, the STATCOM can absorb or provide dynamic reactive power by appropriate adjustment ac output voltage amplitude and phase, or direct control of the ac current. Doing so, compensating reactive power dynamically into power grid is achieved. However, with the increasing of reactive power which needs to be compensated, the traditional topology of two-level or three-level converter can’t not meet the requirements. Therefore, this paper suggests the modular multilevel converter (MMC) is as the topology of STATCOM. MMC is a new multilevel topology proposed by German scholars in 2002 [8]. This topology can realize high-voltage output by using low-voltage power devices, and has the advantages of low harmonic output and easy expansion.
2. Application of MMC-STATCOM

As shown in Figure 1, the 220kV substation is one of the important voltage points in the local area. There is a main transformer in the station, and there are four feed-in and outlet lines, of which #1 and #2 provide power for the traction substation high-speed railway. Influenced by the intensive operation of electrified railway, 220kV bus line has obvious voltage fluctuation and flicker and needs large capacity reactive power compensation. However, the traditional manual switching of capacitors cannot solve the above-mentioned problem. Therefore, the MMC-STATCOM as a new generation of dynamic reactive power compensator is used in this substation.

Figure 1. Wiring diagram of MMC-STATCOM in distribution power network.

Figure 2 gives the topology of MMC-STATCOM. It can be seen that MMC is composed of six bridge arms, and each bridge arm is composed of several interconnected sub-modules with the same structure in series. The upper and lower bridge arms form a phase unit. The six arms are symmetrical, and the electrical parameters and reactance of each submodule are the same. A sub-module of MMC is shown in the upper right part of Figure 2. Each sub-module is composed of two IGBTs, D1 and D2 are anti-parallel diodes. UC is the capacitive voltage of the submodule, USM and iSM are the output voltage and current of the submodule respectively.

At any time, the dc side voltage \( U_{dc} \) is shared by the sub-modules in the output state of each phase upper and lower bridge arm and the two reactors LS. Namely to satisfy the following equation [9-10]:

\[
U_{dc} = L_o \frac{d}{dt}(i_{px} + i_{nx}) + \sum_{j=1}^{n_x} (u_{px} + u_{nx}) \quad (x=a, b, c)
\]  

(1)

Where, \( U_{dc} \) is the bus voltage of the dc side, \( i_{px} \) and \( i_{nx} \) are the upper and lower bridge arm current of phase x (x=a, b, c) respectively.

Theoretically, the number of submodules in the output state of each phase in MMC is constant and is half of all submodules in the phase, namely, \( n_x \). If \( M_x \) is set as the number of submodules in the output state in the upper bridge arm of phase x, and \( P_x \) is the number of submodules in the output state in the lower bridge arm of phase x, then

\[
M_x + P_x = n_x
\]  

(2)

During normal operation, uneven energy distribution between three phases of MMC will generate phase circulation. Let the circulation flowing through phase x be \( i_{cx} \), as shown in Figure 2. Due to the strict symmetry of MMC structure, it can be regarded as energy sharing equally in upper and lower bridge arms. Thus the following equation can be obtained:
The following expression can be obtained based on KVL equation:

\[
\begin{align*}
\frac{U_{dc}}{2} - \sum_{i=1}^{n} u_{px} - L_s \frac{di_{px}}{dt} &= u_{so} \\
- \frac{U_{dc}}{2} - \sum_{i=1}^{n} u_{nx} - L_s \frac{di_{nx}}{dt} &= u_{so} \\
\end{align*}
\]

\[u_{so} = \frac{1}{2} \left( \sum_{i=1}^{n} u_{nx} - \sum_{i=1}^{n} u_{px} \right) - \frac{L_s}{2} \frac{di_{x}}{dt} \quad (x = a, b, c)
\]

The above equation is the dynamic mathematical model of output voltage of MMC. The required three-phase ac voltage is output by controlling the input state of sub-modules of upper and lower bridge arms. When the converter operates at steady-state, the fluctuation of dc voltage and the voltage drop of inductance are ignored. The errors caused by them are corrected through the closed loop of the control system.

3. Control strategy of MMC-STATCOM

There are three operating modes of MMC-STATCOM, namely open-loop commissioning operation, constant-reactive power operation and voltage stable operation. The operation mode can be selected according to the operation requirements. Among them, open-loop commissioning mode is only used for pre-operation debugging, so it will not be considered in this paper.

(1) Constant reactive power operation mode: the STATCOM can output constant reactive power under this operation mode. And the reference value of output reactive power can be set arbitrarily from rated capacitive reactive power to rated inductive reactive power.

(2) Voltage stable operation mode: due to the variation of daily load and the influence of other power grid factors, the system voltage will fluctuate to some extent. The regulation of system voltage fluctuation and maintenance of voltage level can be realized within a certain range depend on the automatic control and quick response function of STATCOM.
In order to achieve better control of MMC-STATCOM, the control strategy is divided into three levels: system-level control, converter-level control and device-level control, as shown in Figure 3.

3.1. System-level control
System-level control layer is in the highest level of the MMC-STATCOM control system. It is the dispatching center responsible for receiving the amount of active and reactive power in setting value and scheduling control instruction. The reactive quantity reference value is produced by regulating control in dispatching center and then is sent to converter-level layer by control bus. At the same time, running information of system is feedback to the dispatch center.

When STATCOM is in voltage stable operation mode, system voltage is as the control target and make the system voltage stable within the allowable error range by changing its output reactive power. When STATCOM is running in constant reactive power mode, the remote communication interface is adopted to receive the reactive power instruction from the dispatching center or AVC master control unit.

3.2. Converter-level control
The converter-level control layer is the core control layer of MMC-STATCOM control system. It is the bridge between the system-level control layer and the device-level control layer. The converter-level control layer is mainly responsible for receiving the reference values of active and reactive power commands from the system-level control layer. The modulation ratio M and the phase shift Angle are transmitted to the device level control layer through the control of the device level control layer. The control strategy mainly includes direct current control and indirect current control.

3.3. Device-level control
Device-level control layer is the lowest control layer in MMC-STATCOM control system, which is also called executive control layer. It mainly controls the switching devices of MMC, and realizes the specific execution and operation of various instructions. The control instructions including modulation ratio M and phase-shifting Angle are received from the converter-level control layer. And then generate the bridge arm voltage reference. The switching devices turn on or off by PWM modulation trigger pulse. The control strategies includes: generation of reference voltage of bridge arm, selection of modulation strategy, capacitor voltage balance control, phase circulation suppression, fault protection control, etc.

Figure 3. Control diagram of MMC-STATCOM

4. Simulation
Based on the data model of a substation mentioned above, the simulation model of MMC-STATCOM is established in the power system analysis and synthesis program (CPSASP). The control protection device consists of system-control layer, converter-control layer, device-control layer and monitoring layer. The system-control layer is mainly responsible for the system-level control strategy of MMC-STATCOM, which generates the reference reactive power signal. The converter-level control layer is mainly responsible for receiving the instructions from the system-level layer and obtaining the
required modulation waveform. The device-control layer is mainly responsible for generating PWM modulation signal, capacitor voltage balancing and phase current instruction.

4.1. Voltage stable operation control
In order to verify the dynamic response characteristics of STATCOM in the voltage stability control mode, the 220kV side bus voltage is set as the main voltage control target. Referring to the field test of substation, simulation results of the voltage fluctuation by switching reactor and capacitor in the substation, the output reactive power is set within the range of \((-80, +80)\) MVA in CPSASP test. In the initial state, the 220kV bus voltage is the rated voltage, namely 220kV. After 0.2s, the reactive power of 60Mvar is injected into power grid. The bus voltage variation and output characteristic of MMC-STATCOM were observed.

![Simulation results of 220kV bus voltage](image1)

(a) Simulation results of 220kV bus voltage

![Simulation results of output reactive power](image2)

(b) Simulation results of output reactive power of MMC-STATCOM.

![Simulation results of output reactive current](image3)

(c) Simulation results of output reactive current of MMC-STATCOM

**Figure 4.** Simulation results when the reactor is put into system.

Figure 4(a) gives simulation waveforms of 220KV bus voltage before and after MMC-STATCOM are connected into grid. It can be seen that the 220 kV bus voltage drops by about 10% without MMC-STATCOM. However, once the MMC-STATCOM is connected to power grid, the 220kV bus voltage keep at 219kV due to the capacitive reactive power is injected to grid instantaneously. It indicates the MMC-STATCOM has the good ability to restrain voltage fluctuation. Figure 4(b) and (c) show the output reactive power and three-phase output current waveform of MMC-STATCOM. According to Figure 4(b), the reactive power stabilizes rapidly after a small overshoot through a very short response time. Figure 4(c) shows that the output current waveform is good quality and low THD, and the harmonic can be effectively filtered by using a small filtering device.

![Simulation results of 220kV bus voltage](image4)

(a) Simulation results of 220kV bus voltage

![Simulation results of reactive power](image5)

(b) Simulation results of reactive power.
At 0.2s, replacing the 60Mvar reactor with the 60Mvar capacitor, the simulated waveform is shown in Figure 5. the 220kV bus voltage increases by 10% due to the input of capacitors when the MMC-STATCOM is not used. Once the MMC-STATCOM is used, the inductive reactive power is quickly injected into grid to suppress the rise of voltage. Therefore, the bus voltage eventually stabilizes around 222kV. Figure 5(a) and (b) respectively show the output reactive power and three-phase current waveform of STATCOM. It can be seen that the overshoot is slightly larger than the overshoot that inhibits the switching of inductive load. This is because the transient process voltage changes greatly due to the large rate of current change in the switching of capacitor.

4.2. Constant reactive power operation control

The purpose of this mode is to change the reactive reference value of STATCOM, and observe the accuracy and corresponding characteristics of the output reactive power. The simulation condition is as follows: the rated voltage is 220kV and the reactive power of STATCOM is limited to (-80, 80) Mvar. At 0.2s, the reference value of reactive power changes from +30Mvar to -30Mvar. Figure 6(a) shows the active and reactive power waveform of MMC-STATCOM. It can be seen that the MMC-STATCOM can quickly track the reactive power changing, accurately output the corresponding reactive power, and has good dynamic response characteristics. Figure 6(b) shows the three-phase output current waveform of the MMC-STATCOM. It can be seen that the three-phase output current is rapidly in a stable state after a short fluctuation. Figure 6(c) shows that the rapid change of output reactive power has a small impact on bus voltage, which can be ignored.

5. Conclusion

Based on the actual operation of a substation, this paper studies the operation control strategy of the MMC-STATCOM. According to the actual parameters of the substation, the control model of
STATCOM is built in PSASP software. Simulation results verify the dynamic response characteristics of the MMC-STATCOM under constant voltage control and constant reactive power control respectively. Simulation results show that the MMC-STATCOM can not only effectively solve the problems of the bus voltage fluctuation, but also can automatically track the system's reactive power changing, dynamically and adjust the reactive power output rapidly.

6. References

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