Optimization modelling of HCMC-STATCOMs for offshore wind power based on PSCAD

Fei Dou¹, Weiyuan Wang¹, Kai Xia², Xuan Yu²,³, Lijun Wang² and Yiqing Xu²

¹ State Grid Jiangsu Electric Power Co., Ltd., Nanjing 210000, China;
² East China Electric Power Design Institute Co., Ltd., Shanghai 200063, China
³ Email: 2324@eeepdi.com

Abstract. Under normal circumstances, the voltage fluctuation of the wind farm's grid connection point is mainly caused by the volatility of wind power output. In recent years, with the clustering development of offshore wind power, the voltage fluctuation brought by the output fluctuation of wind power is becoming more and more notable. The main method of improving the reactive voltage problem of wind farms is to add more static and dynamic reactive power compensation devices. Hybrid cascaded multilevel converter STATCOMs (HCMC-STATCOMs) don’t need transformers to increase the device capacity and decrease the harmonics on the output voltage, which is effective in reducing the device cost and volume. This paper firstly introduces the topology and operation principles of an HCMC-STATCOM and then carries out a comparative study on HCMC-STATCOMs and traditional cascaded STATCOMs. Finally PSCAD/EMTDC is applied to model and simulate HCMC-STATCOMs. The simulation result shows that the reactive power of HCMC-STATCOMs can accurately vary according to the system’s demand on reactive power. This means that HCMC-STATCOMs have good dynamic performance and the harmonic contents in the output phase voltage and AC current are quite small. As a dynamic reactive power compensation device, HCMC-STATCOM can be adjusted in real time according to the system's reactive power requirements, and has the advantages of small volume and low cost. The simulation results show that the properties of HCMC-STATCOMs are advantageous for the operation and control of the system and applicable for the dynamic reactive power configuration of offshore wind power.

1. Introduction

Under normal circumstances, the voltage fluctuation of the wind farm's grid connection point is mainly caused by the volatility of wind power output [1-2]. In recent years, with the clustering development of offshore wind power, the voltage fluctuation brought by the output fluctuation of wind power is becoming more and more notable. However, most of the local power grids with wind power grids are at the end of the regional power grid. They are weakly connected to the regional power grid. They have less regional load, and have poor self-regulation ability. They cannot rely solely on the grid side for reactive power regulation. The main method of improving the reactive voltage problem of wind farms is to add more static and dynamic reactive power compensation devices.

As a type of dynamic reactive power compensation devices, the static synchronous compensators (SVCs) are studied due to their good dynamic performance [3-5]. Current topological structures of STATCOMs mainly include transformer-based multi-pulse inverters, diode-clamped multilevel inverters, flying-capacitor multilevel inverters and H-bridge cascaded multilevel inverters [6-8].
Transformer-based multi-pulse inverters utilize a great number of phase shifting transformers, which as a result raises the device cost to a large extent and the power loss and floor areas at the same time. Although diode-clamped and flying-capacitor multilevel inverters effectively overcome the shortcomings of transformer-based multi-pulse inverters, the number of clamping diodes and capacitors rises evidently with that of levels increasing. The design and control would also become quite difficult. H-bridge cascaded multilevel inverters are modularly structured and consequently easy to extend with a low content of harmonics and convenient to realize redundancy and control [9-11]. However, high-voltage big-capacity H-bridge cascaded STATCOMs are in need of many submodules and heavy DC capacitors [12-15].

Hybrid cascaded multilevel converter STATCOMs (HCMC-STATCOMs) don’t need transformers to increase the device capacity and decrease the harmonics on the output voltage, which is effective in reducing the device cost and volume [13,14]. This paper firstly introduces the topology and operation principles of an HCMC-STATCOM and then carries out a comparative study on HCMC-STATCOMs and traditional cascaded STATCOMs. Finally, PSCAD/EMTDC is applied to model and simulate HCMC-STATCOMs. The simulation result shows that the reactive power of HCMC-STATCOMs can accurately vary according to the system’s demand on reactive power. This means that HCMC-STATCOMs have good dynamic performance and the harmonic contents in the output phase voltage and AC current are quite small.

With the large-scale development of offshore wind power, due to the strong voltage fluctuation of wind power and the high cost of offshore platforms, it is particularly important to stabilize voltage fluctuations while limiting costs. As a dynamic reactive power compensation device, HCMC-STATCOM can be adjusted in real time according to the system's reactive power requirements, and has the advantages of small volume and low cost. The simulation results show that the properties of HCMC-STATCOMs are advantageous for the operation and control of the system and applicable for the dynamic reactive power configuration of offshore wind power.

2. Topology and basic principles

2.1. Topology of an HCMC-STATCOM

The basic topology of an HCMC-STATCOM is illustrated in Figure 1, which consists mainly of two parts: 1) a rectifier circuit formed by cascaded H-bridges; 2) a conventional two-level converter.

![Figure 1. Topology of the HCMC-STATCOM.](image-url)
In Figure 1, \( v_a, v_b, v_c \) and \( i_a, i_b, i_c \) are the voltages and currents of a three-phase AC system; \( v_{sa}, v_{sb}, v_c \) are the three-phase output AC voltages of the HCMC-STATCOM; \( L \) is the connecting inductor; \( R \) is the equivalent resistor; \( u_{aO}, u_{bO}, u_{cO} \) are the three-phase terminal voltages of the rectifier circuit; \( u_{a0}, u_{b0}, u_{c0} \) are the phase voltages of the two-level converter on the AC side; \( U_{dc} \) is the rated DC voltage of the two-level converter; \( I_{dc} \) is the DC current of the two-level converter; \( C_T \) is the capacitance of the two-level converter; \( C_H \) is the capacitance of H-bridge submodules; \( U_c \) is the rated voltage on the capacitors of H-bridge submodules.

2.2. Operation principles of an HCMC-STATCOM

When the HCMC-STATCOM operates in a steady state, the two-level converter cyclically and alternately turns on and off each bridge arm. The rectifier circuit makes the output AC voltage approach the expected sinusoidal reference wave by putting the submodules of cascaded H-bridges into operation and cutting them off. Figure 2 shows the equivalent circuit of an HCMC-STATCOM and the reference output voltage waveforms of the two-level converter, the rectifier circuit and the HCMC-STATCOM. The output AC voltage of the HCMC-STATCOM is superposed from the output voltages of the two-level converter and the rectifier circuit. The turn-on switches on each arm of the two-level converter is modulated by a square wave of fundamental frequency, so that the expected waveform shown in Figure 2 (b) \( u_{aO} \) can be generated in Phase A. On the other hand, the rectifier circuit produces a multilevel voltage that approaches the waveform shown as \( u_{wa} \) by inserting and cutting off submodules.

Take Phase A as an example. The basic properties of an HCMC-STATCOM can be determined by formulae (1) ~ (5) when Figure 1 and Figure 2 are combined:

\[
v_a(t) = U_m \sin \omega t \quad (1)
\]

\[
i_a(t) = I_m \sin(\omega t + \pi/2) = I_m \cos \omega t \quad (2)
\]

\[
v_a(t) = u_{wa}(t) + u_{aO}(t) \quad (3)
\]

\[
u_{aO}(t) = M_s U_{dc} \quad (4)
\]

\[
u_{wa}(t) = \sum_{k=1}^{N} G_{k(a)} U_{ck(a)} \quad (5)
\]
where $U_m, I_m$ stands for the amplitudes of the output phase voltage and AC current of the HCMC-STATCOM; $w$ is the system’s angular frequency; $M_a$ is the switching factor that is determined by the switching signals of the two-level converter (e.g. in Phase A, when the upper arm is turned on, $M_a=1/2$; when the lower arm is turned on, $M_a=-1/2$); $U_{ck(a)}(k=1,2,...,N)$ is the capacitor voltage of the $k$th H-bridge submodule of Phase A in the rectifier circuit; $G_{ck(a)}(k=1,2,...,N)$ is the switching function of the $k$th H-bridge submodule of Phase A in the rectifier circuit that corresponds to its operation mode, i.e. positive insertion ($G_{ck(a)}=1$), negative insertion ($G_{ck(a)}=-1$) and cut-off ($G_{ck(a)}=0$).

3. HCMC-STATCOMs and cascaded STATCOMs

With different topological structures, HCMC-STATCOMs and cascaded STATCOMs are distinguished in terms of the number of H-bridges and power devices as well as the capacitance and number of DC capacitors and the energy stored in them.

3.1. Comparison of output levels and power devices

When redundant modules are not considered, the number of needed H-bridge submodules $N_{old}$ in each phase of cascaded STATCOMs is

$$N_{old} = \frac{U_m}{U_c}$$

(6)

where $U_c$ is the rated DC capacitance of H-bridge submodules. The ripple voltage of DC capacitors is 10% of the rated voltage. To simplify the analysis, $U_c$ is set as the rated voltage of the IGBTs in H-bridges.

Therefore, the number of needed IGBTs, capacitors and diodes in each phase of cascaded STATCOMs is $4N_{old}$, $N_{old}$, and $4N_{old}$, respectively. The maximum output level is $2N_{old}+1$, while the number of output levels in practical operations $N_{L,old}$ is

$$N_{L,old} = 2 \frac{U_m}{U_c} + 1$$

(7)

The number of needed IGBTs in each phase of the HCMC-STATCOM $N_{new}$ is the sum of the IGBTs in both the H-bridge submodules of the rectifier circuits and the two-level converter, i.e.

$$N_{new} = 4N + 2 \frac{U_{dc}}{U_c} = 4 \frac{U_m}{U_c}$$

(8)

The number of output levels of HCMC-STATCOMs in practical operations $N_L$ is

$$N_{L,new} = 2\left(\frac{U_{dc}}{2U_c} + \frac{U_m - \frac{U_{dc}}{2}}{U_c}\right) + 1 = 2 \frac{U_m}{U_c} + 1$$

(9)

According to (9), the maximum output level of HCMC-STATCOMs is $2U_m/U_c+1= 4N+1$.

With the analysis above, it can be drawn that when the number of output levels is the same, i.e. the quality of output waveforms is the same, the number ratio of needed H-bridge submodules and IGBTs/diodes in HCMC-STATCOM rectifier circuits and cascaded STATCOMs is 0.5 and 1, respectively.

3.2. Comparison of stored energy in DC capacitors

From 2.1, when the number of output levels is the same, the number of needed H-bridge submodules in an HCMC-STATCOM is half of that of a cascaded STATCOM, which means that the number of DC capacitors in H-bridge modules is reduced by half. However, the topology brings in an extra two-level converter, so a DC capacitor for the converter is added, the capacitance, rated voltage of which is different from that of the DC capacitor in H-bridge modules.

The DC capacitance in a cascaded STATCOM is
The energy stored in all DC capacitors of an HCMC-STATCOM $S_{new}$ can be written as

$$S_{new} = S_1 + S_2 = \frac{3}{2} NC_{H} U_c^2 + \frac{1}{2} C_T U_{dc}^2$$  \hspace{1cm} (11)

Suppose ripple voltage $\Delta u_c = 0.1 U_c$, $\Delta u_{dc} = 0.1 U_{dc}$. By combining (7), (8), (9) and (11), it can be drawn that

$$S_{new} = \left[ \frac{15}{8} + 5\left(1 - \frac{\sqrt{3}}{2}\right) \right] \frac{U_m J_m}{\omega} = 2.54 \frac{U_m J_m}{\omega}$$  \hspace{1cm} (12)

Similarly, the energy stored in all DC capacitors of a cascaded STATCOM $S_{old}$ can be written as

$$S_{old} = \frac{3}{2} N_{old} C_{H, old} U_c^2 = 7.5 \frac{U_m J_m}{\omega}$$  \hspace{1cm} (13)

By comparing (12) and (13), the ratio of energy stored in all DC capacitors in an HCMC-STATCOM and a cascaded STATCOM is 0.34.

4. Modelling and simulation

To verify the feasibility of the topology of HCMC-STATCOMs, a simulation model of a 35kV/±100Mvar HCMC-STATCOM using PSCAD is constructed. The simulated topology is shown in Figure 1. Simulation parameters are as follows: the voltage of the AC system is 35kV and the rated reactive power is ±100Mvar. The connecting inductance is 5.85mH, and the connecting resistance is 0.36 $\Omega$. Suppose the rated capacitor voltage of submodules $U_c = 2kV$. According to what are stated in Section 2, it can be calculated that the number of H-bridge submodules in each phase is 9 and the capacitance is 9283μF. The rated DC voltage of the two-level converter is 32.9 kV and the capacitance is 302μF. The modulation methods of the rectifier circuit and the two-level converter are nearest level modulation and symmetric square wave modulation, respectively [14-16].

![Figure 3. Waveforms on steady-state operation.](image-url)
Figure 3 illustrates the output waveforms of an HCMC-STATCOM operating in the steady state (Phase A), namely the output voltages of the HCMC-STATCOM, the terminal voltages of the rectifier circuit and the two-level converter. As can be seen from the figure, the output voltage agrees with theoretical analysis. The peak values of the output voltage of the rectifier circuit and the two-level converter are ±17.5kV.

Figure 4 illustrates the system waveform when the output reactive power varies, namely the output reactive power of the HCMC-STATCOM, the output voltage of Phase A, the AC current of Phase A and the system voltage. The AC current of Phase A in the figure is amplified 10 times larger in order to be observed more easily. The output reactive power of the HCMC-STATCOM is +100Mvar before 0.4s and -100Mvar after. The accurate variation of reactive power can be seen from Figure 4, implying good dynamic performance. Before 0.4s AC current leads AC voltage by 90° and lags after 0.4s by 90°, indicating that the HCMC-STATCOM is equivalent to a capacitor before 0.4s that generates reactive power and to an inductor after 0.4s that absorbs reactive power. When the system operates in the steady state, the harmonic content in the output phase voltage of the HCMC-STATCOM is small (distortion rate is 0.82%) as well as in the AC current (distortion rate is 1.16%).

5. Conclusions
This paper firstly introduces the topology and operation principles of an HCMC-STATCOM and then carries out a comparative study on HCMC-STATCOMs and traditional cascaded STATCOMs. Finally, PSCAD/EMTDC is applied to model and simulate HCMC-STATCOMs. The simulation result shows that the reactive power of HCMC-STATCOMs can accurately vary according to the system’s demand on reactive power. This means that HCMC-STATCOMs have good dynamic performance and the harmonic contents in the output phase voltage and AC current are quite small. The properties of HCMC-STATCOMs are advantageous for the operation and control of the system and applicable for the dynamic reactive power configuration of offshore wind power.

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