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Control to compensate reactive power at medium voltage load nodes to improve performance and load voltage stabilization based on modular multilevel converter

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ABSTRACT

This paper will present a reactive power control method for medium voltage power grids based on the modular multilevel converter (MMC) structure. In particular, the MMC converter applies control algorithms to operate as a D-STATCOM device. A proportional–integral (PI) controller combined with an improved nearest level modulation (NLM) method performs the system control process. The purpose is to create sinusoidal voltage levels on the alternating current (AC) side to generate or absorb reactive power according to load requirements. This will ensure that the amount of reactive power for the load node is always within the allowable value and improve voltage quality, increasing the power factor for the load. Verifying and evaluating results are performed on MATLAB/Simulink software.

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1. INTRODUCTION

Power quality for electrical equipment directly connected to the medium voltage grid is essential. However, loads of this type are often affected by many causes, such as phase imbalance, transient incidents, or switching processes in the power grid [1]–[4]. Among them, temporary voltage fluctuations are the most common causes. In addition, the lack of reactive power supplied to the load also causes electrical equipment to operate inefficiently [5], [6]. Therefore, reactive power compensation will become necessary to improve the power factor and better voltage regulation [7]. Reactive power compensation devices will supplement the required amount of reactive power. The parallel reactive power compensation structure adjusts the reactive power at the connection point. This process is done by changing the amplitude and phase angle between the voltage on the compensation device and the voltage on the power grid [8], [9], stabilizing the voltage, and balancing the load for the phase. Reactive power compensation solutions have been widely researched and focused on directions such as two-way compensation, fixed compensation, or flexible compensation using synchronous compensators, capacitors, and static var compensator (SVC) [10]–[12]. There have not been many studies on using modular multilevel converter (MMC) in reactive power compensation to achieve reactive power compensation effects. In this article, we will focus on researching an improved nearest level modulation (NLM) modulation method, a control system applied to MMC that operates like a D-STATCOM device to compensate reactive power for load nodes of medium voltage power grids. The main goal is to improve the power factor and stabilize the voltage at the load node. The MMC multi-level converter has outstanding advantages compared to other multi-level converters because it has a simple structure and can work with high voltage ranges and high power [13]. The MMC structure is very suitable for correct power compensation for medium voltage loads to adjust the amount of reactive power shortage or excess; this is especially important when ensuring the performance of high-capacity motors [14]. In this paper, the control process for D-STATCOM is based on the proportional–integral (PI) control method combined with the improved NLM modulation method. These methods are simple, easy to apply, and of good quality when applied to MMC. The simulation results of the proposed system performed on MATLAB/Simulink software have proven the algorithm's effectiveness.

2. MODEL OF STATCOM BASED ON THE MMC STRUCTURE

2.1. MMC converter structure

The modular multilevel converter can meet the conversion requirements with large voltage and high power [15], [16]. MMC has the advantage of power range expansion and simple configuration [17], and it can generate any desired voltage level with good harmonic quality. Only one direct current (DC) voltage source is used at the input without transformers and filters, making the structure compact and economical [18]. The structure of D-STATCOM based on MMC is shown in Figure 1. In which, Figure 1(a) is the power circuit structure of D-STATCOM based on MMC and Figure 1(b) is the diagram of D-STATCOM replacement in the grid connection model.

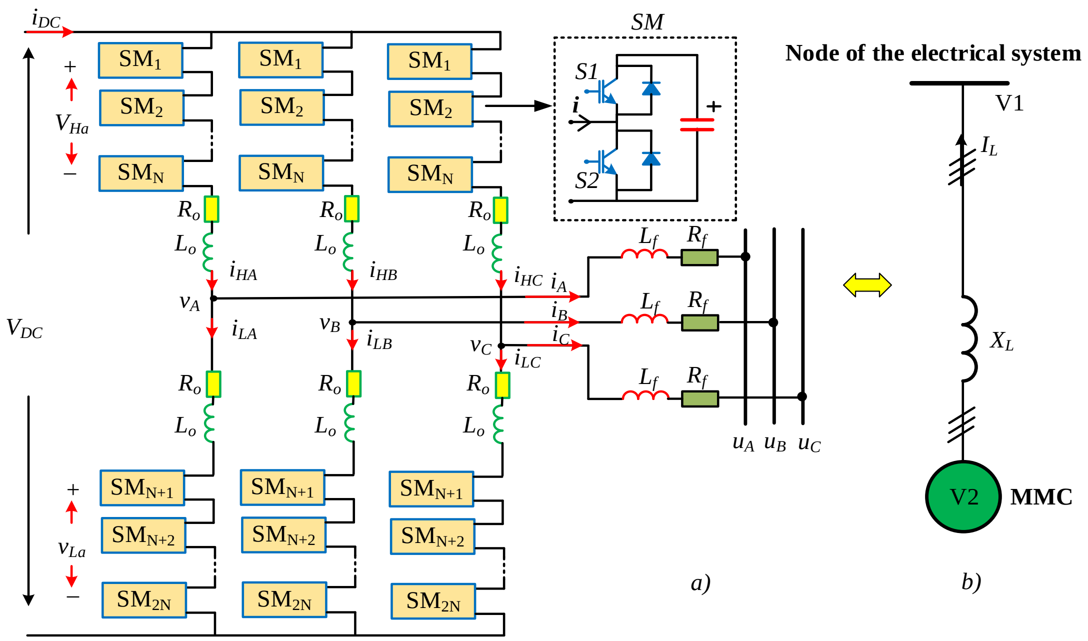


Figure 1. Schematic diagram of D-STATCOM based on MMC connect grid (a) power circuit structure of D-STATCOM based on MMC and (b) alternative diagram of D-STATCOM in grid connection model

In this diagram, each phase of the MMC comprises two branches with the same number of N of submodules (SMs) connected in series. The alternating current (AC) voltage on each phase is taken at the midpoint between the two L_o reactors of each branch; the resistor R_o in each branch limits external shock currents into the MMC [19]. The MMC's DC input voltage is supplied by a single voltage direct current (V_{DC}) source. Each SM will switch at different times from control commands so the converter can achieve high efficiency and reduce harmonic distortion [20]. The number of SMs of the MMC converter depends on the voltage level requirements on the AC side. Theoretically, the number of SMs can be increased indefinitely to meet any requirement for output voltage level on the AC side [21]. The specific working states of SM depend on the state of valves S_1, and S_2 and the direction of the current. When the current i in the circuit has a positive direction, valve S_1 is ON and valve S_2 is OFF, the voltage on the AC side of the SM is $V_{SM} = V_C = V_{DC}/N$. This state is called the SM-inserted state. On the contrary, if valve S_1 is OFF and valve S_2 is ON, the voltage on the AC side of the SM is $V_{SM} = 0$. This state is called the SM bypass state. When the current i in the circuit has a negative direction. In this case, the inserted state also occurs when valve S_1 is ON and S_2 is OFF; The bypass state also occurs when valve S_1 is OFF, and valve S_2 is ON.

2.2. The operation of MMC follows the improved NLM modulation method

The improved NLM method is used to generate the number of levels of the output voltage of the MMC as $2N + 1$ [22]. Figure 2 illustrates the operating principle of the improved NLM method. This method is used to modulate for MMC converter with 10 SMs per valve branch and applied in the D-STATCOM model [22].

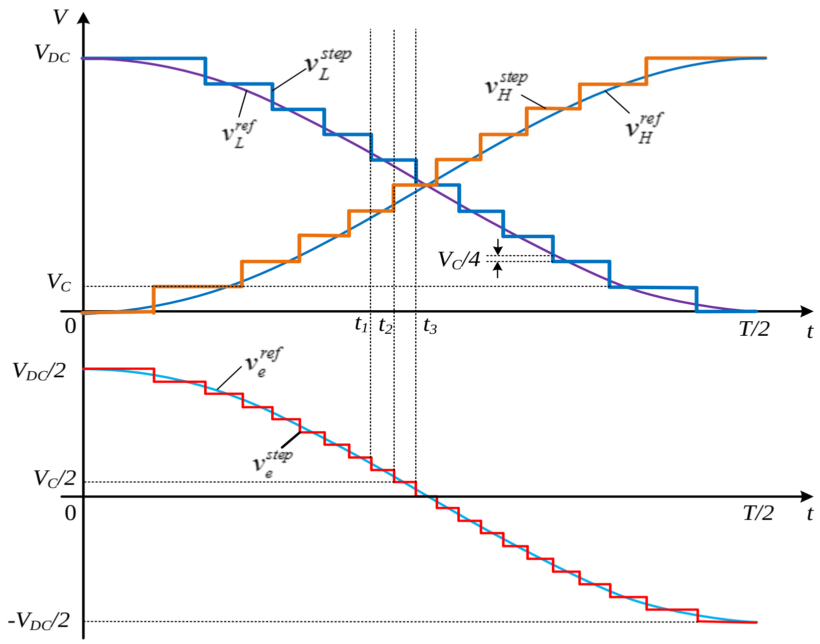


Figure 2. Principle of the improved NLM method

The diagram in Figure 2 uses two sine waves v_L^{ref} and v_H^{ref} to make the set signals and are created as (2). Next, the step waves v_L^{step} and v_H^{step} will be created by the rounding function and are determined as (3). Then, we can synthesize the sine wave set v_e^{ref} and the stepped wave v_e^{step} at the AC output in Figure 2, equivalent to (4) and (5). Details of the processes are explained as follows:

The round function determining the number of SMs inserted during the working cycle is expressed as (1):

$$\begin{cases} N_L = round_{0.25}\left\{\frac{V_{DC}}{2V_C}[1 - m\cos(\omega t)]\right\} \\ N_H = round_{0.25}\left\{\frac{V_{DC}}{2V_C}[1 + m\cos(\omega t)]\right\} \end{cases} \tag{1}$$

The round function $round_{0.25(k)}$ means that the k value is rounded to the nearest integer value depending on the decimal part of k. If the decimal part of k is more significant than 0.25, then k is rounded up to the next specified value; otherwise, k is rounded down to the previously determined value. The improved NLM method analysis considers two time periods from t_1 to t_2, from t_2 to t_3 in Figure 3. The first case is the period from t_1 to t_2. Suppose $v_L^{step} = MV_C$, the set value of branch voltage and AC output voltage at t_1 is determined according to (2):

$$\begin{cases} v_L^{ref} = (M + 0.25)V_C \\ v_H^{ref} = [(N - M - 1) + 0.75]V_C \\ v_e^{ref} = (M - 0.5N + 0.25)V_C \end{cases} \tag{2}$$

According to the rounding function, the step waveform of the branch voltage and AC voltage in the first case is determined as (3):

$$\begin{cases} v_L^{step} = MV_C \\ v_H^{step} = (N-M)V_C \\ v_e^{step} = (M-0.5N)V_C \end{cases} \tag{3}$$

The second case is from t_2 to t_3. The set value of the branch voltage and AC voltage at t_2 is determined by (4).

$$\begin{cases} v_L^{ref} = [(M-1)+0.75]V_C \\ v_H^{ref} = [(N-M)+0.25]V_C \\ v_e^{ref} = (M-0.5N-0.25)V_C \end{cases} \tag{4}$$

The stepped waveform of the branch voltage and AC voltage, in this case, is determined:

$$\begin{cases} v_L^{step} = MV_C \\ v_H^{step} = (N-M+1)V_C \\ v_e^{step} = (M-0.5N-0.5)V_C \end{cases} \tag{5}$$

Comparing (3) and (5), it can be seen that the step size in is 0.5 V_C. The most significant deviation between v_e^{ref} and v_e^{step} appears during step change (t_1, t_2 and t_3). Comparing in (3), (4), and (5), we see that the maximum deviation is 0.25 V_C. This process will cause the output voltage to have several levels of $2N+1$, as shown in Figure 4.

2.3. Model of D-STATCOM is based on MMC

D-STATCOM is based on MMC converters connected in parallel to the distribution grid and can adapt to highly variable power sources [23], [24]. This device works like a voltage source to produce an AC output voltage from a DC voltage source [25]. When performing control for MMC as a D-STATCOM device, this system adjusts the voltage or power at the installed location by changing the amplitude and phase angle between the voltage on D-STATCOM and the voltage on the grid node. Then, the current passing through D-STATCOM can be slower or faster than the upstream voltage, bringing the voltage at the node to its rated value and compensating for the amount of reactive power as required. The central part of D-STATCOM is the MMC converter, which converts the voltage source from DC to AC and vice versa through control laws. The special feature of this configuration is the quick response to generate or absorb reactive power to control the flow of reactive power at the compensated node, preventing flickering of the power grid [26].

3. THE OPERATION OF D-STATCOM IS BASED ON MMC

3.1. Connection D-STATCOM with power system node

Figure 1(b) shows the D-STATCOM diagram using an MMC converter parallel to the power grid. One end of D-STATCOM is connected to the secondary side of the transformer (when you want to raise the voltage value to the appropriate voltage level), and the other is connected to a DC energy storage device. This system is often placed at the node to supply power to the load, limiting harmonics in large-capacity motors and metallurgical technology. It is also placed in buildings to reduce signal distortion and enhance electrical equipment's power quality and operational reliability [25].

3.2. Modeling the MMC converter in reactive power compensation mode

The converter model for grid connection, as shown in Figure 1(a), includes an MMC converter to convert electricity from DC to AC; R_f and L_f are the resistance and inductance between the MMC circuit board and the grid, u_x ($x = A, B, C$) is denoted as grid voltage, v_x is the output voltage of the circuit breaker, vex is the internal electromotive force of the circuit breaker, i_x is the output current of the MMC. It has the direction from MMC to the grid. When sending energy to the grid, MMC works in inverter mode and transfers energy from the DC circuit to the grid.

Applying Kirhoff's law to the circuit, the equation connecting the output voltage and the elements of the MMC is as (6):

$$\begin{cases} v_A = v_{eA} - \frac{R_o}{2} i_A - \frac{L_o}{2}\frac{di_A}{dt} \\ v_B = v_{eB} - \frac{R_o}{2} i_B - \frac{L_o}{2}\frac{di_B}{dt} \\ v_C = v_{eC} - \frac{R_o}{2} i_C - \frac{L_o}{2}\frac{di_C}{dt} \end{cases} \quad (6)$$

The relationship between the output voltage and the grid voltage through the resistance and inductance of the grid is written as (7):

$$\begin{cases} v_A = u_A + R_f i_A + L_f \frac{di_A}{dt} \\ v_B = u_B + R_f i_B + L_f \frac{di_B}{dt} \\ v_C = u_C + R_f i_C + L_f \frac{di_C}{dt} \end{cases} \quad (7)$$

From (6) and (7), it is deduced:

$$\begin{cases} v_{eA} = u_A + (R_f + \frac{R_o}{2}) i_A + (L_f + \frac{L_o}{2})\frac{di_A}{dt} \\ v_{eB} = u_B + (R_f + \frac{R_o}{2}) i_B + (L_f + \frac{L_o}{2})\frac{di_B}{dt} \\ v_{eC} = u_C + (R_f + \frac{R_o}{2}) i_C + (L_f + \frac{L_o}{2})\frac{di_C}{dt} \end{cases} \quad (8)$$

Set $R = R_f + \frac{R_o}{2}$, $L = L_f + \frac{L_o}{2}$ in (8) is rewritten as (9).

$$\begin{cases} v_{eA} = u_A + R i_A + L \frac{di_A}{dt} \\ v_{eB} = u_B + R i_B + L \frac{di_B}{dt} \\ v_{eC} = u_C + R i_C + L \frac{di_C}{dt} \end{cases} \quad (9)$$

In (9) is for controller design purposes if the MMC is applied and connected to the power grid to compensate for reactive power. Use the transformations of ABC coordinates to $0dq$ coordinates through PARK coordinate transformations like in (10):

$$\begin{cases} L\frac{di_d}{dt} = -Ri_d + \omega L i_d - u_d + u_d \\ L\frac{di_q}{dt} = -Ri_q - \omega L i_q - u_q + u_q \end{cases} \quad (10)$$

Active power and reactive power are represented by (11):

$$\begin{cases} P = \frac{3}{2} Re\{u.i^* \quad \} = \frac{3}{2}\left(u_d i_d + u_q i_q\right) \\ Q = \frac{3}{2} Im\{u.i^* \quad \} = \frac{3}{2}\left(-u_d i_q + u_q i_d\right) \end{cases} \quad (11)$$

The relationship of power balance between AC input and DC output is written as (12):

$$P = \frac{3}{2}\left(u_d.i_d + u_q.i_q\right) = V_{DC}.I_{DC} \quad (12)$$

where V_{DC} and I_{DC} are the voltage and current on the DC side.

3.3. Reactive power compensation principle of D-STATCOM

Active power and reactive power at the power system node in Figure 1(a) are shown in (13).

$$P_1 = \frac{V_1 V_2 \sin\delta}{X_L}; Q_1 = \frac{V_1(V_1 - V_2\cos\delta)}{X_L} \quad (13)$$

In which V_1 and θ_1 are the voltage amplitude and phase angle at the power system node; V_2 and θ_2 are the voltage amplitude and phase angle of D-STATCOM; δ is the phase difference angle between the grid and the compensator; X_L is the reactance between the grid and the compensator. From (13), it is seen that reactive power can be adjusted by adjusting the amplitude of the AC voltage or the phase angle so that D-STATCOM can change the absorption or emission of reactive power.

The desire of D-STATCOM is only to provide or consume reactive power. If you adjust the phase angle, it will affect the current of active power exchange. Therefore, the reactive power is adjusted by controlling the phase difference angle of the phases of V_1 and V_2 to zero and simultaneously adjusting the voltage amplitude of V_2. Then, in the reactive power compensation operating mode, V_2 is in phase with V_1 ($\delta = 0$); at the voltage node, only reactive power transmits in (13) becomes (14).

$$P_1 = 0; Q_1 = \frac{V_1(V_1 - V_2)}{X_L} \tag{14}$$

From (14), we see that reactive power Q is proportional to $(V_1 - V_2)$. If $V_1 > V_2$, then $Q > 0$ exists a voltage component V_{12}, corresponding to the inductance current IL being out of phase with V_1 and V_2 at an angle $\pi/2$. Then, D-STATCOM absorbs reactive power. If $V_1 < V_2$, then $Q < 0$, the voltage component V_{12} exists, corresponding to the IC capacitive current being in phase with an angle $\pi/2$; the grid will receive reactive power from the compensator. Then, D-STATCOM generates reactive power for the grid. If $V_1 = V_2$, then $Q = 0$, MMC does not absorb or emit reactive power.

4. CONTROL SYSTEM FOR STATCOM

The control design of the MMC converter in D-STATCOM in this section must address issues such as applying the D-STATCOM control structure based on NLM modulation for MMC, using loops to control the amount of reactive power to be compensated in the dq coordinate system to achieve the requirements for the power value to be compensated. The design process must ensure instantaneous control of reactive power mobilised according to the set amount. The set value of reactive power is calculated instantaneously from the difference between the voltage value at the electrical system connection point and the desired reference voltage at the output of the MMC. From the analysis of the principle of reactive power compensation above, in the active power control system, the active power is always controlled to zero, meaning the controller will not exchange active power with the grid. Then, in the control system, only the control circuit emits or absorbs reactive power; the process of absorbing and generating reactive power depends on comparing the voltage value of the output voltage and the grid voltage. as analyzed in (15).

$$V = V_{ref} + X_S I \tag{15}$$

In which: V is the positive sequence voltage; I is the reactive current ($I > 0$ is the inductive current, $I < 0$ is the capacitive current); X_S is slope resistance. The V voltage value is always measured from the system and compared with the set voltage V_{ref}. The reactive current will be adjusted within the current value range $(-I_{Max}, I_{Max})$ when $V < V_{ref}$, and the controller will increase the voltage V to the V_{ref} value. On the contrary, when $V > V_{ref}$, the controller will adjust the system until $V = V_{ref}$. Therefore, a DC-side voltage controller is necessary to design reactive power compensation. The relationship between DC voltage and AC active power is in the form (16) and (17):

$$V_{DC}^2 C_{DC} = \frac{3}{2} u_d i_d = P \tag{16}$$

$$i_d^{ref} = \frac{3u_d}{2V_{DC}} \frac{1}{sC_{DC}} V_{DC}^{ref} \tag{17}$$

Figure 3 is the control system structure diagram for D-STATCOM. The system includes two control loops: an external control loop to control DC voltage and reactive power; the output of the reactive power controller is if current, which is the current perpendicular to a voltage that controls the reactive power flow. The output of the DC voltage regulator is the i_{dref} current, which is the current in phase with the voltage that controls the active power flow. An internal control loop is used to control the current based on the parameters provided by the external controller after performing control signals. The controller output value is the amount of setting necessary to put into the modulation stage to determine the valve switching state of the MMC. Compared to voltage source converter (VSC) compensation structures, this structure is simple to implement because it uses linear PI regulators.

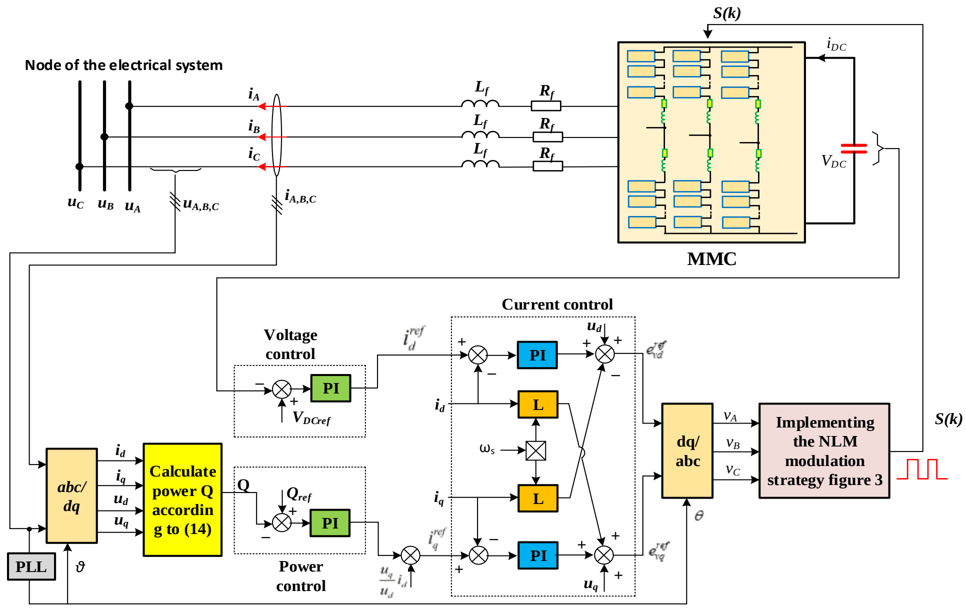


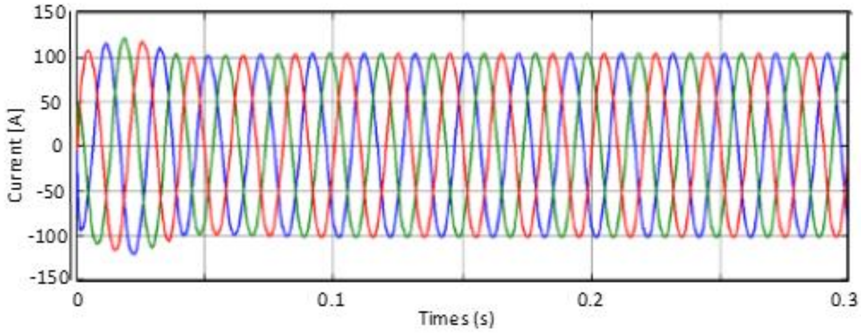
Figure 3. Structure diagram of D-STATCOM control system based on MMC controller

5. SIMULATION AND EVALUATE THE RESULTS

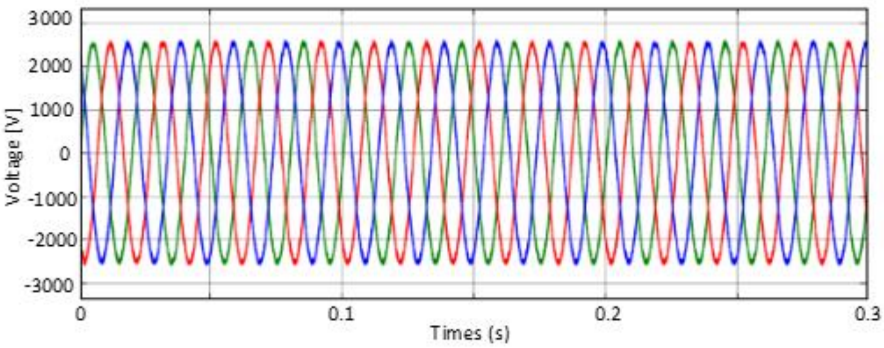
Simulation parameters for the MMC control system are shown in Table 1. Figure 4 shows the results of the MMC switch's AC output current and voltage when operating in reactive power compensation mode, in which Figure 4(a) is the current result on three phases on the AC side, Figure 4(b) is the voltage result on three phases on the AC side. The results show that the current and voltage have a standard sinusoidal shape, abnormal transient phenomena do not appear in the sine wave of current and voltage when the MMC operates in normal mode. Figure 5 shows the reactive power response of the power system at the survey time from 0 to 0.3 s; the compensated reactive power always tracks to the set value after 0.03 s, this is a very small time interval showing very quick response of the controller to stabilize the reactive power value as required. Because MMC operates in reactive power compensation mode, the active power supplied to the grid is always zero according to a preset amount. Figure 6 shows the *d-axis* and *q-axis* current in the *dq* coordinate system. The values of these two currents will correspond to the amount of active power and reactive power of the system. The results show that the power of the tracking effect is set to 0, so the *d-axis* current also has a corresponding value of 0. The *q-axis* current has a negative value corresponding to the value of reactive power pumped to the grid. When using MMC to compensate reactive power for the power system, it brings certain effects on the stability of the compensated power system, such as a wide reactive power adjustment range and quick response to generate power. reactance to control the reactive power flow at the compensated node; DC power value is always stable around the rated value in normal operating mode; can prevent grid fluctuations caused by a shortage of reactive power, thereby improving the stability and power quality of the distribution grid. In particular, it stabilizes the voltage value of the load within the allowable limit to improve the life and performance of the machine. In reactive power compensation mode, MMC's parameters and technical indicators are guaranteed stable throughout the working process.

Table 1. Simulation parameters for the MMC control system

Simulation parameters	Symbol	Value
Load resistance	R	70 Ω
Load inductance	L	5.10^{-3} H
Branch resistors	R_o	0,5 Ω
Branch inductance	L_o	$4,2.10^{-3}$ H
Capacitor per SM	C	100 F
DC voltage	V_{DC}	6000 V
Number of SMs per branch	N	13 SM
Voltage across capacitor	V_C	1000 V
Fundamental frequency	f	50 Hz
NLM modulation frequency	f_{mNLM}	300 Hz
Modulation coefficient	m	0.95
System capacity	S	500 kVA



(a)



(b)

Figure 4. Current and voltage responses of D-STATCOM when connected to the power system node in (a) current output and (b) voltage output

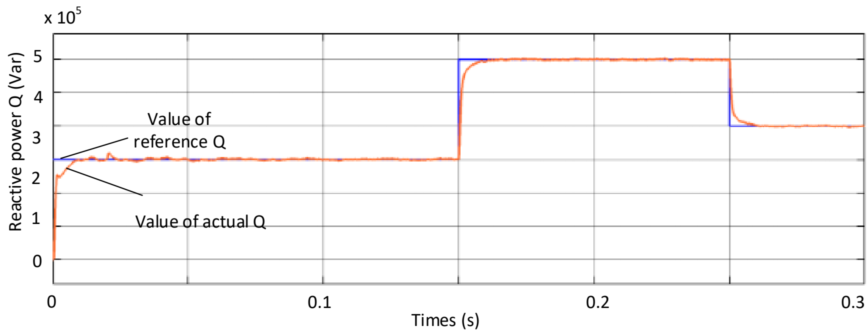


Figure 5. Response of reactive power when MMC compensates reactive power

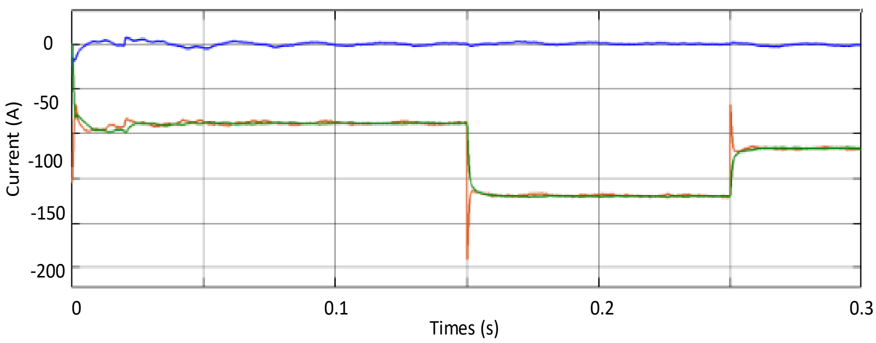


Figure 6. Responses of current on the *d*-axis and *q*-axis

6. CONCLUSION

This paper has chosen the NLM modulation method and the operating structure of D-STATCOM based on MMC to compensate for reactive power. Issues regarding operating principles and reactive power control principles based on MMC converters are analysed, evaluated, and designed. Simulation results of D-STATCOM's operations have been presented and objectively evaluated. The results show that the current and voltage of D-STATCOM are stable and of quality, which ensures the THD index and control requirements. At the same time, the results also reflect the performance quality of the MMC converter based on the application of NLM modulation methods to the PI control algorithm proposed for the system's control structure. From there, we see that it is possible to flexibly control the amount of reactive power at the power grid node to ensure the necessary amount of power and that the node voltage does not exceed the allowable value according to actual operating regulations. economics of the power system.

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