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Matrix converter based virtual synchronous generation technology

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Abstract: Energy is an important driving force for social development. The shortage of natural resources urgently promotes the research of energy and the development of related technologies. Meanwhile, the distributed generation is one of the most important approaches. Virtual synchronous generator (VSG) technology, as a kind of control strategy that can participate actively in grid power regulation, has drawn much attention. Traditional VSG technology uses the two-level inverter as the main circuit. Based on the theory of VSG and the matrix converter (MC) as the main circuit of the VSG, the control system can imitate synchronous generator's characteristics such as inertial characteristics, frequency response characteristics and frequency modulation. The method provides a feasible solution for the power conversion of the distributed generation, which is the AC output, omitting the procedure of AC–DC–AC. Through the simulation, it is verified that the VSG technology can be applied to the MC, which provides a new idea for the exchange transformation in distributed generation.

1 Introduction

At present, because of the shortage of natural resources and the environmental pollution, the demand for renewable resources is increasing. Distributed energy, as an important part of renewable energy, has also been receiving considerable attention [1].

With the development of distributed power generation technology, the capacity of distributed energy that participates in the grid is largely growing. The original control method in response to the increasing capacity of distributed energy will influence the power system stability and security [2]. As a result, the demand for distributed energy improves. Under this condition, some scholars put forward the droop control method that simulates traditional droop characteristics of a synchronous motor, making the distributed power supply according to the amplitude and frequency of power fluctuations and achieving the purpose of regulating the output of active and reactive powers [3]. However, the droop control does not simulate the inertia of the synchronous generator. When the power grid is in unbalance, the lack of inertia in distributed power supply will lead to the lack of regulation in the grid fluctuation. Therefore, based on droop control, some scholars proposed the virtual synchronous generator (VSG) technology, which can make the grid-connected inverter to simulate the running mechanism of the synchronous generator. Specifically, the grid-connected inverter can be compared with the conventional synchronous generator from the viewpoint of operating mechanism and external characteristics by simulating the characteristics of the synchronous generator's main body model, active frequency modulation and reactive power voltage regulation [4]. The matrix converter is different from the conventional AC–DC–AC converter. Compared with the traditional two-level converter, the matrix converter (MC) has many advantages, namely, without energy storage units, can achieve four-quadrant operation, has small size and light weight and is the unit of power factor input [5, 6].

Based on these excellent characteristics of the MC, the virtual synchronous power generation technology is combined with MC. In the VSG field, such circuit is rare. It can be applied to new energy sources such as wind and tidal power output, eliminating the exchange of DC and then conversion into AC.

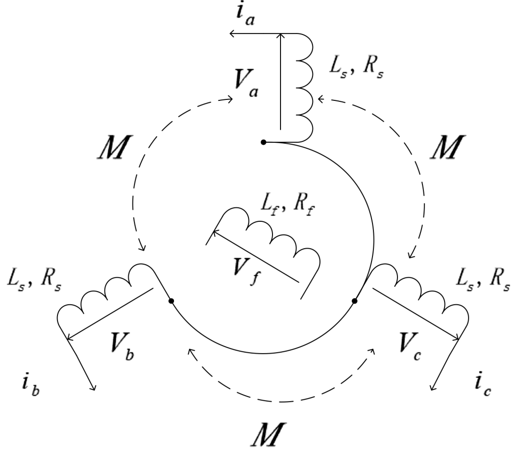

Fig. 1 *Structure of a three-phase synchronous motor*

2 MC based on the principle of VSG

The structure of a three-phase synchronous motor is shown in Fig. 1, and it is assumed that the surface of the motor rotor is smooth enough and the electromagnetic leakage inductance is ignored. Here, the stator winding is simplified as inductance of self-inductance L_s and mutual inductance $-M$. The currents and voltages flowing through the three-phase stator windings are i_a, i_b, i_c and V_a, V_b, V_c, respectively.

In order to facilitate the analysis, the following equations are proposed:

$$v = \begin{bmatrix} v_a & v_b & v_c \end{bmatrix}^{\mathrm{T}} \tag{1}$$

$$e = \begin{bmatrix} e_a & e_b & e_c \end{bmatrix}^{\mathrm{T}} \tag{2}$$

$$\Phi = \begin{bmatrix} \Phi_a & \Phi_b & \Phi_c \end{bmatrix}^{\mathrm{T}} \tag{3}$$

$$\tilde{\sin}\,\theta = \begin{bmatrix} \sin\theta \\ \sin\left(\theta - \frac{2\pi}{3}\right) \\ \sin\left(\theta - \frac{4\pi}{3}\right) \end{bmatrix} \tag{4}$$

$$i = \begin{bmatrix} i_a & i_b & i_c \end{bmatrix}^{\mathrm{T}} = i_0 \tilde{\sin}\,\varphi \tag{5}$$

$$L_s = L + M \tag{6}$$

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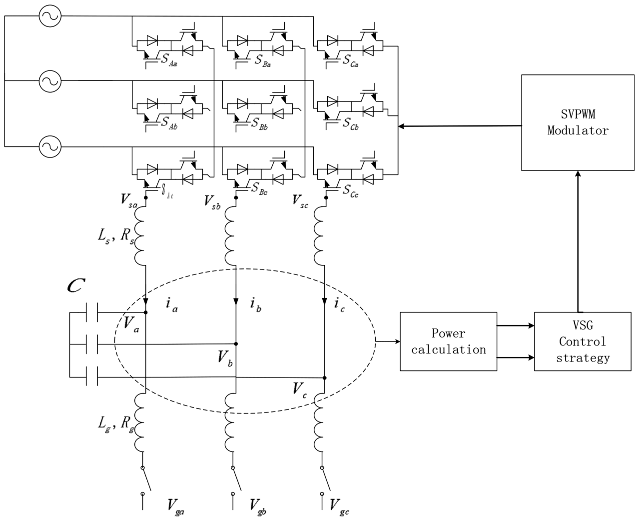

Fig. 2 *MC-based VSG main circuit topology and control structure*

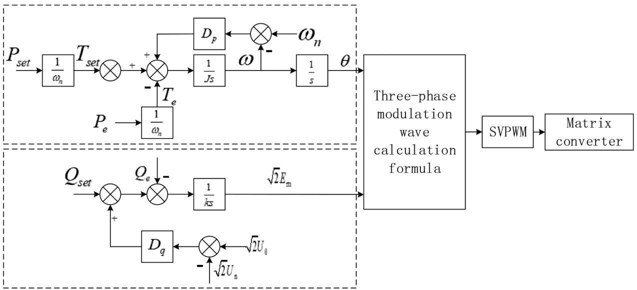

Fig. 3 *Control strategy of VSG*

where Φ is the stator inductance, i is the stator current, v is the terminal voltage of the synchronous motor and e is the stator voltage of the synchronous motor. The relationship between the terminal potential of the synchronous motor and its stator inductance, stator current and internal potential is as follows [7]:

$$v = -R_s i - \frac{\mathrm{d}\Phi}{\mathrm{d}t} = -R_s i - L_s \frac{\mathrm{d}i}{\mathrm{d}t} + e \tag{7}$$

Fig. 2 shows the MC-based VSG main circuit topology and control structure; the traditional topology of VSG is a two-level inverter. The main circuit part $S_{\mathrm{Aa}} - S_{\mathrm{Cc}}$ has a total of nine switches of the MC, and an output-side inductor L_s, a filter capacitor C and the network-side inductor L_g form LCL-type filter.

According to the circuit theory, the output active power P_e and reactive power Q_e of the VSG can be obtained by orthogonal projection of the voltage and current vectors, that is,

$$P_e = \frac{3}{2}\sqrt{2}E_m \dot{\omega} i_0 \cos(\theta - \varphi) \tag{8}$$

$$Q_e = \frac{3}{2}\sqrt{2}E_m \dot{\omega} i_0 \sin(\theta - \varphi) \tag{9}$$

The control strategy of VSG is shown in Fig. 3. As can be seen from Fig. 3, the active loop of VSG simulates the inertia and primary frequency modulation characteristics of the synchronous generator. The reactive power loop simulates the primary voltage regulation of the synchronous generator [8].

The mathematical equations for the VSG active and reactive rings are as follows [9]:

$$T_{\mathrm{set}} = T_e + J\frac{\mathrm{d}\dot{\omega}}{\mathrm{d}t} - D_p(\dot{\omega}_r - \dot{\omega}) \tag{10}$$

$$P_{\mathrm{set}} = T_{\mathrm{set}}\dot{\omega} \approx T_{\mathrm{set}}\dot{\omega}_r \tag{11}$$

$$P_e = T_e\dot{\omega} \approx T_e\dot{\omega}_r \tag{12}$$

where P_{set} and Q_{set} are given for the active power and reactive power, respectively, T_{set} is the torque reference, T_e is the electromagnetic torque, D_p is the active power–frequency droop coefficient, D_q is the reactive power-voltage droop coefficient, $\dot{\omega}$ is the VSG angular frequency, $\dot{\omega}_r$ is the reference angle frequency, U_0 is the output voltage, U_n is the reference voltage and J is the virtual moment of inertia [9].

From the above analysis, the VSG active loop and reactive power loop simulate the characteristics of synchronous generators. Then, the three-phase modulation wave expression is

$$\begin{cases} U_{ma} = \sqrt{2}E_m\dot{\omega}\sin\theta \\ U_{mb} = \sqrt{2}E_m\dot{\omega}\sin\left(\theta - \frac{2\pi}{3}\right) \\ U_{mc} = \sqrt{2}E_m\dot{\omega}\sin\left(\theta + \frac{2\pi}{3}\right) \end{cases} \tag{13}$$

A three-phase modulated wave U_{ma}, U_{mb}, U_{mc} and a drive signal are switched by the MC after space vector pulse width modulation (SVPWM) modulation. Under the control of MC, finally, it can get the corresponding output waveform [10].

3 New strategy of SVPWM

The SVPWM based on the traditional MC needs both two quantities of voltage and current to determine the switching state. However, the control strategy in the VSG has only given voltage. Therefore, a new SVPWM control strategy is proposed in this paper, which only needs the state of a given voltage to realise the corresponding SVPWM.

Set the current output voltage vector as $U_{\max}$. Though Table 1, on the same straight line can be drawn from six size of the voltage vector, corresponding to the instantaneous input voltage U_{ab}, $-U_{ab}$, U_{bc}, $-U_{bc}$, U_{ca}, $-U_{ca}$ is six values, and the largest voltage space vector in those six voltage is selected. Every corresponding vector has a corresponding switch state; there is only one vector that can meet both demands about the maximum vector and the corresponding direction, so the corresponding switch state can correspond to Table 1.

Three-phase instantaneous voltage space vector can be synthesised by pulse width modulation. When the desired output voltage of the rotating space vector $\boldsymbol{U}$ is in some sectors, V_α and V_β are available to compound the desire output voltage.

The real-time modulation of SVPWM signals requires the components of α and β axes, V_α and V_β, the PWM periodic T_{PWM} and the magnitude of the output voltage. According to the principle

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Table 1 Corresponding switch state

Maximum voltage	Sector					
	1	2	3	4	5	6
U_{ab}	−4,1	−5,2	−6,3	4,−1	5,−2	6,−3
U_{bc}	−5,2	2,−8	3,−9	−1,7	−2,8	−3,9
U_{ca}	−6,3	−8,5	−9,6	7,−4	8,−5	9,−6
$-U_{ab}$	4,−1	5,−2	6,−3	−4,1	−5,2	−6,3
$-U_{bc}$	5,−2	−2,8	−3,9	1,−7	2,−8	3,−9
$-U_{ca}$	6,−3	8,−5	9,−6	−7,4	−8,5	−9,6

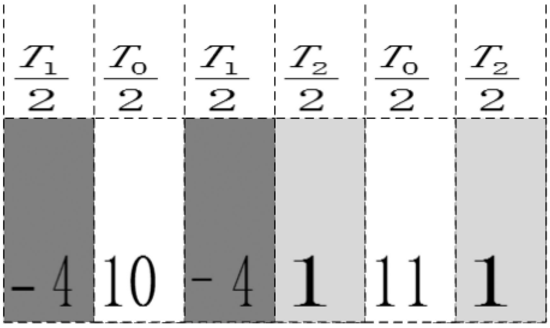

Fig. 4 *Switch combination in a single modulation cycle*

of area equivalence, the relationship between the output voltage and the switching state in a sector is

$$V_\alpha = \frac{T_1}{T_{\text{PWM}}}\frac{1}{\sqrt{3}}|V_1|\cos\frac{\pi}{6} + \frac{T_2}{T_{\text{PWM}}}|V_2|\cos\frac{\pi}{6} \tag{14}$$

$$V_\beta = \frac{T_1}{T_{\text{PWM}}}|V_1|\left(-\sin\frac{\pi}{6}\right) + \frac{T_2}{T_{\text{PWM}}}|V_2|\sin\frac{\pi}{6} \tag{15}$$

$$T_1 = \frac{T_{\text{PWM}}}{|V_1|}\left(\frac{1}{\sqrt{3}}V_\alpha - V_\beta\right) \tag{16}$$

$$T_2 = \frac{T_{\text{PWM}}}{|V_2|}\left(\frac{1}{\sqrt{3}}V_\alpha + V_\beta\right) \tag{17}$$

If T_1 and T_2 are greater than the periodic values in one period, the time of the two adjacent vectors in one cycle is

$$T_1 = \frac{T_1}{T_1 + T_2} \tag{18}$$

$$T_2 = \frac{T_2}{T_1 + T_2} \tag{19}$$

$$T_0 = 0 \tag{20}$$

If the sum of T_1 and T_2 in a period is less than the periodic value, its action time is

$$T_1 = \frac{T_{\text{PWM}}}{|V_1|}\left(\frac{1}{\sqrt{3}}V_\alpha - V_\beta\right) \tag{21}$$

$$T_2 = \frac{T_{\text{PWM}}}{|V_2|}\left(\frac{1}{\sqrt{3}}V_\alpha + V_\beta\right) \tag{22}$$

$$T_0 = T_{\text{PWM}} - T_1 - T_2 \tag{23}$$

In order to reduce the harmonic component of the input line current and the output line voltage, the symmetrical space vector modulation strategy is adopted. Assuming the current maximum voltage is U_{ab}, in the first sector, as shown in Fig. 4, in a single modulation cycle, the above switch combination is halved, according to $-4 \rightarrow 10 \rightarrow -4 \rightarrow 1 \rightarrow 11 \rightarrow 1$ and lead time sequence $(T_1/2) \rightarrow (T_0/2) \rightarrow (T_1/2) \rightarrow (T_2/2) \rightarrow (T_0/2) \rightarrow (T_2/2)$.

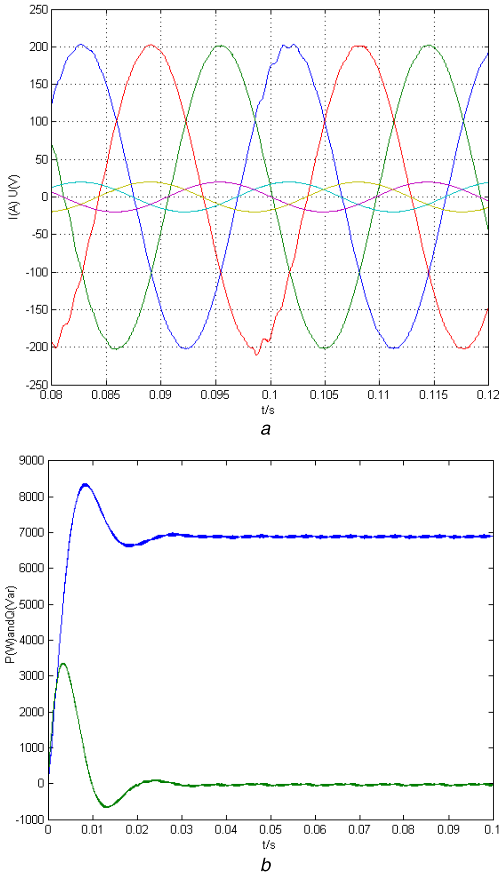

Fig. 5 *The waveform of the synchronous inverter when P_{set} = 7 kW, Q_{set} = 0 kvar*

(a) Steady-state phase current and voltage, ***(b)*** Active (blue) and reactive (green) powers when P_{set} = 7 kW, Q_{set} = 0 kvar

The control concept in this paper is different from indirect space vector modulation algorithm mode, but the basic modulation algorithm is based on the principle of SVM; its advantage is that without sampling current, it can control the output voltage, greatly simplifying the control strategy.

4 Simulation results and analysis

As can be seen from Fig. 5, the phases of the current and voltage are basically the same, indicating that the output of the synchronous inverter meets the power setting requirements and only outputs the active power. As can be seen from Fig. 6, there is a certain phase difference between the voltage and the incoming current. It shows that the synchronous inverter output meets the power setting requirements, and both the active power and the reactive power are outputted.

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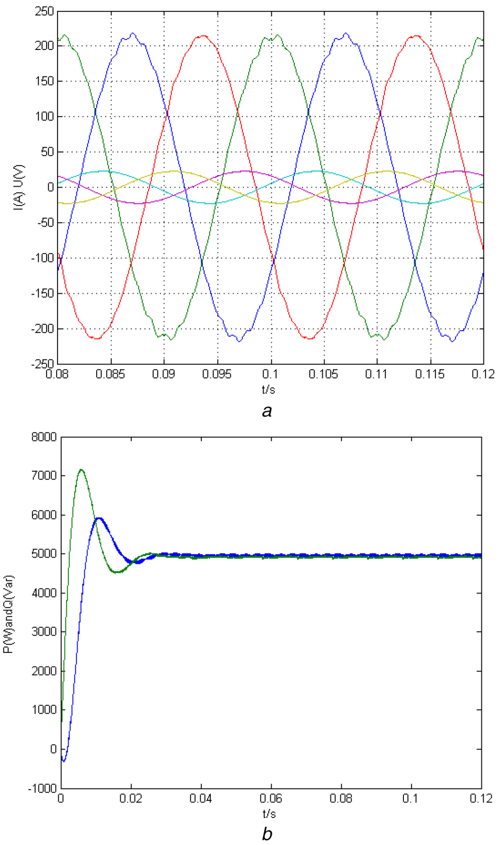

Fig. 6 *The waveform of the synchronous inverter when P_{set} = 5 kW, Q_{set} = 5 kvar*

(a) Steady-state phase current and voltage, ***(b)*** Active (blue) and reactive (green) powers when P_{set} = 5 kW, Q_{set} = 5 kvar

5 Conclusions

The VSG technology is expected to solve the problem of stability caused by the large-scale access to distributed power grids and has drawn wide attention. The VSG technology based on matrix converter proposed in this paper is aimed at the application of a distributed generation system with AC output such as wind power generation. It can directly convert electric energy and carry out exchange transformation, and it also eliminates the need of AC–DC conversion and DC–AC conversion. A 10 kW simulation model based on a matrix converter VSG is built in MATLAB/Simulink. The simulation results show that VSG can be used in the matrix converter.

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