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RESEARCH ARTICLE

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Research on cascaded multilevel inverter and its application in STATCOM

Abstract Because of the broad application of multilevel converters in the high-power area, a cascaded multilevel voltage-source inverter with phase-shifted SPWM (PS-SPWM) switching scheme is proposed as a static synchronous compensator (STATCOM). This can eliminate the bulky and weighty transformers and reduce power loss. In addition, the equivalent carrier frequency can be doubled and the output harmonics will be reduced compared with the STATCOM being put into operation. The operating principle and control methods are analyzed in detail and the feasibility is validated by simulation with MATLAB.

Keywords multilevel converter, cascaded, PS-SPWM, STATCOM

1 Introduction

Since Nabea A. proposed the three-level inverter during the IAS annual conference in 1980, the multilevel converter, as a new breed of power converter option, has advanced rapidly and has been a hotspot for high-power applications. From previous research, it was shown that the multilevel converter has better performance than conventional converters in output harmonics spectra [1, 2]. There are three reported basic topologies of the multilevel converter: cascaded, diode clamped, and capacitor clamped. Compared with the latter two, the cascaded multilevel converter has many distinct advantages:

1) Switch devices required are less under the same switching frequency and level number.

2) The harmonic content is lower in the output voltage for a given switching frequency.

3) Modularized circuit layout and packaging is possible because each cell has the same structure, and there are no extra clamping diodes as in the case of diode clamped topology, or voltage balancing capacitors as in the case of the capacitor clamped topology [3–7].

Due to the widespread use of high-power switch devices, a lot of reactive and harmonics current are produced, which have a worse effect on electric power equipment. Now, a high-order harmonic current and reactive current compensation are crucial tasks that need to be settled urgently in power systems.

STATCOM is an advanced static var compensator introduced in 1990. It is different from the conventional var compensators such as thyristor-switched capacitors (TSC), thyristor-switched reactors (TCR) and the mechanically switched capacitors. STATCOM is a static var compensator with no rotating parts, and is composed of new-generation high-power force-commutated semiconductor valve based inverters, DC capacitors and output transformers [8–13].

Nowadays, most of the STATCOMs that have been in use at home and abroad are made up of multi-pulse inverters and zig-zag transformers. The first STATCOM in China, which is manufactured by Tsinghua University and the Henan Electric Power Bureau, and put into use in March 1999, is also based on this configuration. The zig-zag transformers:

1) Are the most expensive equipment in the system.

2) Produce about 50 % of the total losses of the system.

3) Occupy a large area of real estate (about 40 % of the total system).

4) Cause difficulties in control due to saturation of the transformers.

Because of the advantages of cascaded multilevel inverters, this paper presents a STATCOM that adopts the cascaded multilevel inverter as the main topology to replace the multi-pulse inverter and bulky transformers used in the conventional STATCOM, and phase-shifted SPWM to replace the fundamental frequency modulation. The PS-SPWM principle, var compensation principle, and control method are analyzed. A simulation system is created with MATLAB and the simulation results validate that the

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cascaded multilevel inverter with PS-SPWM is a better choice for STATCOM.

2 System configuration of STATCOM

2.1 Cascaded inverter structure

Figure 1 shows the *Y*-configured 7-level cascaded inverter used in the STATCOM system. As shown in Fig. 1, one phase of the cascaded inverter consists of (7−1)/2 identical H-bridges, in which each bridge has its own separate DC source, and all the capacitors, switches and diodes have the same voltage and current ratings. The output voltage of each phase is summed by the output voltage of three H-bridge cells. This inverter can:

1) Generate sinusoidal waveform output voltage with the least harmonics.

2) Eliminate transformers used in conventional STATCOM.

3) Make possible a direct connection to the distribution system without any additional transformers. A reactor is required between the system and the three-phase cascaded inverters, which serves as a current smoother to attenuate the high frequency current harmonics that the STATCOM generates.

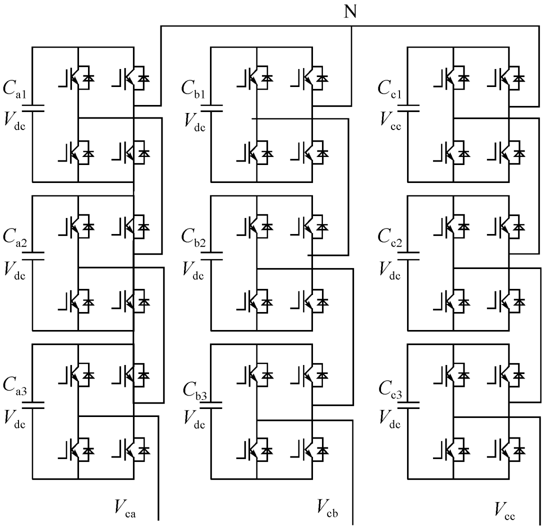

Fig. 1 The 7-level cascaded inverter used in the STATCOM system

2.2 PS-SPWM scheme

A so-called PS-SPWM switching scheme is proposed to operate the switches in the system. The scheme is briefly explained with the aid of Fig. 2 obtained by simulation with MATLAB. Three H-bridge inverters share the same modulating sinusoidal signal $u_a(t)$. The three triangular carrier signals are for three H-bridge inverters, respectively. They are time shifted by θ_{sh}, so that the output of every H-bridge is time shifted, which leads to the equivalent switching frequency of the summed output voltage being increased, then the output harmonic content is reduced without increasing

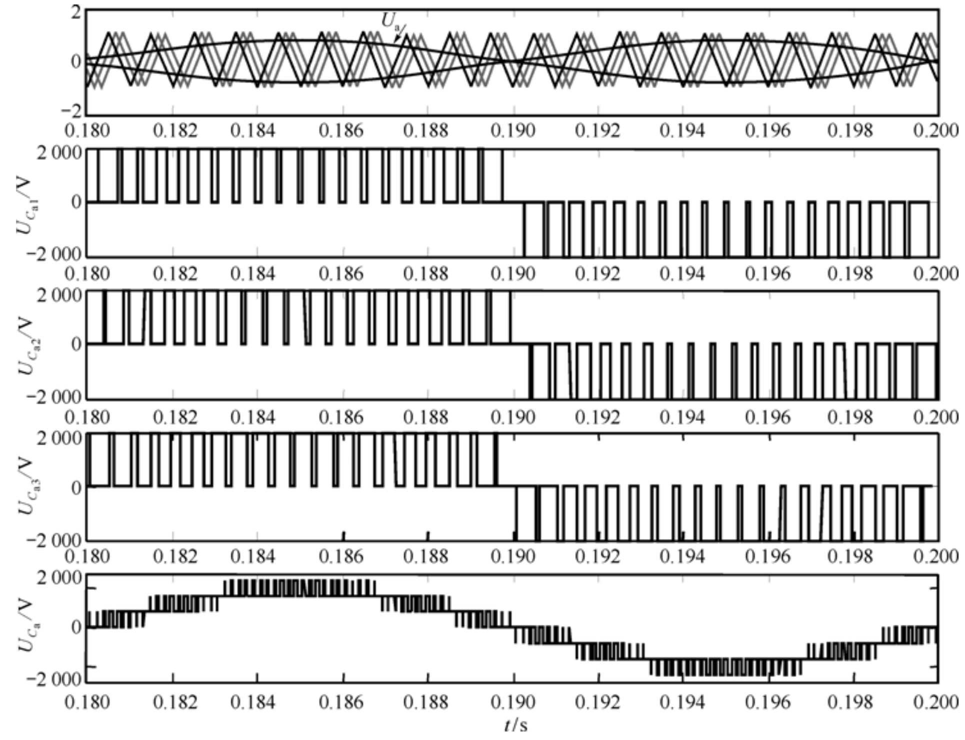

Fig. 2 Principle of PS-SPWM method

the switching frequency. Assuming the frequency ratio of the carrier and modulating sinusoidal signal is k_c ($k_c = f_s/f$, f_s, f are frequencies of carrier and modulating signal $u_a(t)$ respectively), the period of the triangular carrier is $\theta_c = 2\pi/k_c$. The triangular carrier phase shifted for n modules cascaded inverters is $\theta_{sh} = \theta_c/(2n) = 2\pi/(2nk_c)$, then the output voltage equivalent frequency ratio is $k_{eff} = 2nk_c$. In the proposed STATCOM, $n = 3$, so the equivalent switching frequency of the output voltage is increased to $6f_s$.

2.3 STATCOM system dynamic models and control of reactive power

The STATCOM based on cascaded multilevel inverters connects to the system through a current smoothing reactor as shown in Fig. 3.

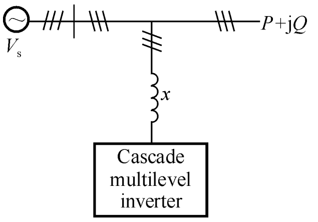

Fig. 3 A conceptual STATCOM based on cascaded multilevel inverter

Figure 4 shows the single phase equivalent circuit of the STATCOM, where V_s is the system voltage, V_c is the generated voltage of the STATCOM, i is the current drawn by the STATCOM, and L and R are the total AC inductance and resistance (including the smoother reactor and the impedance of the cascaded inverter). The exchange of the real power and reactive power between the cascaded inverter and the power system can be controlled by adjusting the amplitude and phase of the inverter output voltage. In the case of an ideal inverter (the inverter need not absorb real power from the power system), the output voltage of the inverter is controlled to be in phase with that of the power system. To operate the STATCOM in capacitive mode, the magnitude of the inverter output voltage is greater than that of the power system, and the current i is leading. On the other hand, to operate the STATCOM in inductive mode, the magnitude of the inverter output voltage is controlled to be less than that of the power system, and the current i is lagging.

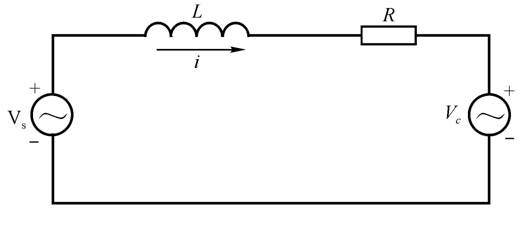

Fig. 4 Single phase equivalent circuit of the STATCOM system

However, in practice, the inverter is associated with internal losses caused by non-ideal power semiconductor devices and passive components. As a result, without any control, the capacitor voltage will decrease. To regulate the capacitor voltage, a small phase shift α between the inverter voltage and the power system voltage is introduced. Figure 5 illustrates the phasor diagram of voltage at a point of common coupling (PCC). The current projection on the power system voltage is i_d, and the vertical one is i_q. The phase and magnitude of the current i is changed by changing the phase shift α or the amplitude of the inverter output voltage V_c, then the reactive exchange between the STATCOM and the power system is controlled.

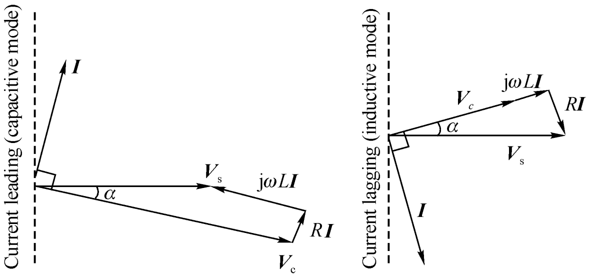

Fig. 5 Phasor diagram of voltage at PCC

From the equivalent circuit of Fig. 4, the model under abc coordinates can be obtained as Eq. (1):

$$L\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} + R\begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix} = \begin{pmatrix} V_{sa} \\ V_{sb} \\ V_{sc} \end{pmatrix} - \begin{pmatrix} V_{ca} \\ V_{cb} \\ V_{cc} \end{pmatrix} \tag{1}$$

where V_{sa}, V_{sb}, V_{sc} are the three-phase voltages of the power system, V_{ca}, V_{cb}, V_{cc} are the three-phase inverter output voltages, and i_a, i_b, i_c are the three-phase inverter currents, whose referenced direction is shown in Fig. 4. Assuming that the power system voltage is ideal and sinusoidal, phase A voltage is $V_{sa} = V_m \sin \omega t$. The synchronous dq coordinates is shown in Fig. 6.

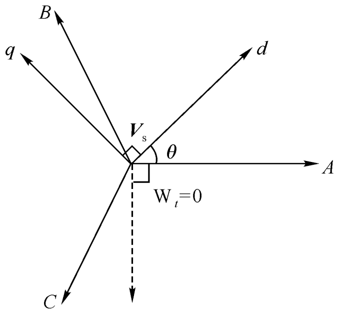

Fig. 6 The synchronous dq coordinates

If $\boldsymbol{T}_{abc\text{-}dq}$ is as follows:

$$\boldsymbol{T}_{abc\text{-}dq} = \sqrt{\frac{2}{3}} \begin{pmatrix} \sin\omega t & \sin(\omega t - \frac{2}{3}\pi) & \sin(\omega t + \frac{2}{3}\pi) \\ \cos\omega t & \cos(\omega t - \frac{2}{3}\pi) & \cos(\omega t + \frac{2}{3}\pi) \end{pmatrix} \tag{2}$$

then one can get the *dq*-coordinate expressions using the synchronous reference frame transformation [$\boldsymbol{T}_{abc\text{-}dq}$].

$$L\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix} i_d \\ i_q \end{pmatrix} + \omega L\begin{pmatrix} -i_q \\ i_d \end{pmatrix} + R\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \begin{pmatrix} V_{sd} - V_{cd} \\ V_{sq} - V_{cq} \end{pmatrix} \tag{3}$$

and

$$\begin{pmatrix} V_{sd} \\ V_{sq} \end{pmatrix} = \begin{pmatrix} \sqrt{\frac{3}{2}}V_m \\ 0 \end{pmatrix} \tag{4}$$

According to the instantaneous reactive power theory, the instantaneous active power p_{c} and the instantaneous reactive power q_{c} can be obtained as:

$$\begin{aligned} p_{\mathrm{c}} &= \sqrt{\frac{3}{2}}V_m i_d \\ q_{\mathrm{c}} &= \sqrt{\frac{3}{2}}V_m i_q \end{aligned} \tag{5}$$

Therefore, the reactive power generated or absorbed by the inverter is directly controlled by adjusting i_q. Likewise, the real power exchange can be controlled by adjusting i_d. As a result, the reactive power and active power can be separately controlled. Then, i_d and i_q are the active current component and reactive current component of the STATCOM: active power flows into the STATCOM when i_d is positive, and flows out when i_d is negative. The STATCOM generates leading reactive power when i_q is positive and lagging reactive power when i_q is negative.

3 Control scheme

As a STATCOM, it should have the characteristics of rapid dynamic response and small steady-state error. To obtain these performances, a feedback decoupling control is proposed, which is shown in Fig. 7. A PI controller is used for both active and reactive current control loops. The equivalent decoupling control diagrams for i_d and i_q can be derived as shown in Fig. 8.

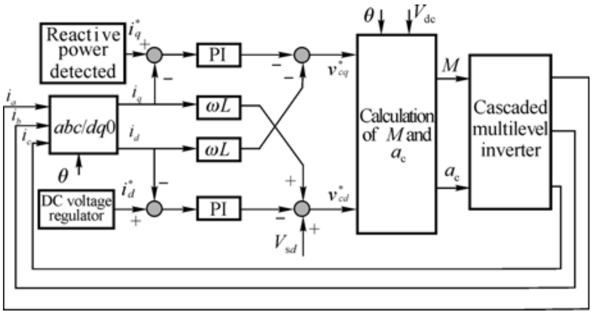

Fig. 7 Feedback decoupling control black diagram of the STATCOM

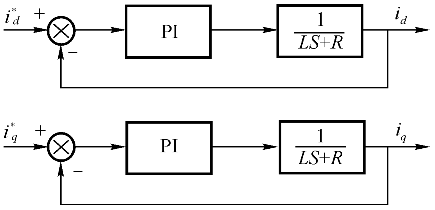

Fig. 8 Equivalent control diagram for i_d and i_q

In the block diagram, M is the modulation index, and α_{c} is the phase of the modulation signal. Their calculation equations are:

$$M = \frac{\sqrt{V_{cd}^2 + V_{cq}^2}}{nV_{\mathrm{dc}}},\ \alpha = \tan^{-1}\frac{V_{cq}}{V_{cd}},\ \alpha_{\mathrm{c}} = \theta - \alpha$$

where, n is the number of cascaded cells.

Since the STATCOM output voltage is always needed to supply a small amount of active power to the STATCOM for component losses, the DC voltage regulator meets the demand of the active current. Interested readers can read Ref. [11] for a detailed description of this regulator.

4 System simulation results

In order to validate the proposed inverter system, computer simulation using the MATLAB power system blockset package is carried out with the main parameters: line-to-line voltage V_{s} = 6 000 V, f = 50 Hz, Q_{var} = ± 9 Mvar, f_{s} = 1 kHz, V_{dc} = 2 000 V, L = 3 mH.

The three-phase simulated system is based on the control scheme shown in Fig. 7. The STATCOM output phase voltage and current is shown in Fig. 9. It is obvious that the phase voltage is lagging behind the phase current by about $\pi/2$. The STATCOM is being operated in capacitive mode and compensating the inductive reactive power of the system .

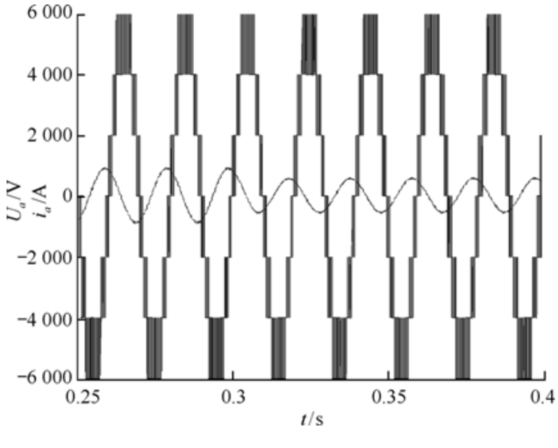

Fig. 9 STATCOM output phase voltage and phase current

Figure 10 is the frequency spectrum of the STATCOM output voltage U_{ca}. It can be seen that the harmonics of the STATCOM output voltage only appear as side-bands centered around the frequency of $6f_s$(6 000 Hz) and its multiples. Therefore, the STATCOM output voltage has very high equivalent switching frequency, which simplifies the design and implementation of the filter.

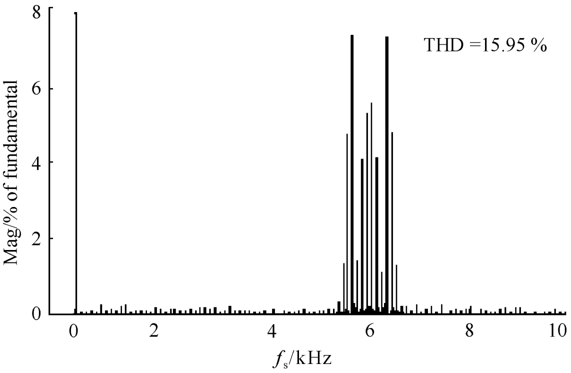

Fig. 10 Frequency spectrum of STATCOM output voltage

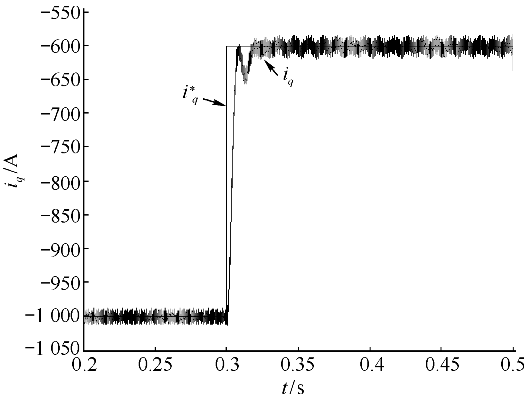

Fig. 11 Step response of the STATCOM

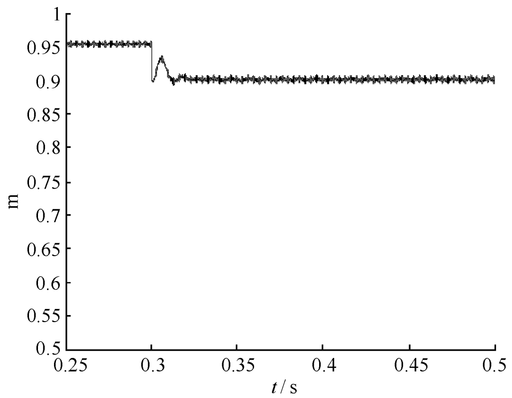

Fig. 12 The dynamic course of modulation index M

Figure 11 shows the simulation results of the dynamic response at a step-change reference of reactive current, which shows excellent dynamic response with a 20 ms time constant to the step change and no steady-error after stabilization. The dynamic course of modulation index M during the step-change is shown in Fig. 12. M is adjusted to be smaller, and then the STATCOM can compensate for less inductive reactive power of the power system when it is operated in capacitive mode.

5 Conclusions

A cascaded multilevel inverter with phase-shift SPWM switching scheme is proposed for use as a STATCOM in this paper. The STATCOM topology offers several advantages over the other types of STATCOM such as reduced power loss, modular layout, the output changing linearly with the input, and so on. Furthermore, high equivalent switching is obtained, which can settle the conflict between devices switching frequency and devices capacity to a certain extent.

These features make the cascaded multilevel inverter a better candidate for static synchronous compensation.

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