Design of High Voltage Static Reactive Power Generator Based on SPWM Technology

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Abstract. In order to verify the compensation effect of high voltage static var generator. The system structure of cascaded H-bridge is adopted. The bipolar CPS-SPWM and monopole frequency doubling CPS-SPWM modulation modes are compared by simulation. The instantaneous reactive power detection principle is derived theoretically. The reactive power can be compensated quickly by using monopole frequency doubling CPS-SPWM modulation mode and instantaneous reactive power detection. Using Matlab/Simulink to build 10kv High-voltage SVG, the fast and accurate reactive power compensation is realized under the switching of inductive reactive power and capacitive reactive power. The reliability of the design is verified by simulation.

1. Introduction

With the continuous development of our society, long-distance high-voltage transmission systems such as west-east power transmission are being built. With the rapid development of electric energy, the demand for power quality of power grid is increasing day by day. A large number of nonlinear and impact loads increase, which puts forward higher requirements for power quality control. Reactive power has the same status and plays an important role in ensuring stable operation of power system, reducing power consumption and ensuring safe operation of power grid. If the reactive power of the power grid is out of balance, the voltage of the users will be unstable, which will seriously cause damage to electrical equipment, casualties and other destructive accidents. Therefore, reactive power plays a crucial role in power system, so the research on reactive power compensation is significant and far-reaching.

Static var generator (SVG) plays an important role in improving power quality and compensating reactive power due to its advantages of good compensation effect, fast response speed, small size of energy storage components and low harmonic content. Among them, series h-bridge multi-power SVG has attracted much attention due to its advantages of easy modularization expansion, independence of each inverter unit, no need for multiple transformer access, and few switching devices required at the same output level. Scholars at home and abroad have proposed many control methods for the control of high-voltage SVG to realize fast and accurate reactive power compensation. Literature [1] compares and analyzes the decoupling control and non-decoupling control of the current, and concludes that the double closed-loop of the decoupling control can achieve no static difference, good steady-state voltage and higher power factor, which is suitable for the occasions requiring high voltage stability on...
the dc side. Literature [2,3] analyzed the carrier phase shift SPWM technology under different modulation modes, and compared and analyzed the harmonic content, switching frequency and sine wave effect under three modulation modes: bipolar modulation, monopole modulation and monopole frequency doubling. It is concluded that the single-pole octave CPS-SPWM modulation mode has the most obvious advantages. In this paper, the control method of static reactive power generator for 10KV power grid is deeply studied. Monopole frequency doubling cps-spwm modulation and h-bridge cascade structure are used to suppress the generation of harmonics to a great extent, and the output voltage and output current of h-bridge cascade SVG are fed forward to achieve fast and dynamic adjustment. Finally, the correctness of the control method is verified by simulation [4].

2. Structure of star-connected h-bridge cascading SVG control system
The main circuit structure of h-bridge cascade SVG is shown in figure 1. A, B, and C three-phase star connection, each phase is composed of N identical h-bridge modules in series, and then connected to the power grid by connecting reactor $L$. In the figure, $u_{sa}$, $u_{sb}$ and $u_{sc}$ are three-phase power grid voltage respectively [5,6]. $I_{ca}$, $I_{cb}$ and $I_{cc}$ are series multi-level SVG three-phase output current respectively. $L_{i} (i=a, b, c)$ is the incoming inductance when SVG is connected to the power grid. $U_{dc_{ik}} (i=a, b, c; k = 1,2..., N)$ is the equivalent loss and dc side capacitance of each H bridge module.

![Figure 1. main circuit structure of star-connected H bridge cascading SVG](image)

Figure 2 shows the overall control model of cascade h-bridge STATCOM system. Strictly speaking, the STATCOM double closed-loop control strategy is divided into two parts, in which the current inner loop adopts direct current control and has good dynamic performance, which can realize the decoupling control of active and reactive power components and realize real-time compensation of reactive power. The voltage outer ring realizes the balanced control of the whole voltage, so that the
whole average voltage of the dc side capacitance tracks the given value, and provides the active power component reference for the current inner ring.

![Figure 2](image-url)

**Figure 2.** System general control block diagram

### 3. Star-connected h-bridge cascading SVG modulation strategy

For type cascade multilevel converter modulation strategies are mainly optimized PWM technology, carrier phase-shifting sinusoidal pulse width modulation (CPS SPWM) modulation and space vector modulation technology, the optimization method solving process of PWM technology is complex, difficult to be realized, and the action time of space vector modulation methods are difficult to determine, the wider application is carrier phase-shifting SPWM modulation strategy [7, 8]. Among them, bipolar cps-spwm and monopole octave cps-spwm are two commonly used modulation methods.

The angle frequency of bipolar CPS-SPWM is WS, and the angle frequency of each H-bridge unit is WC triangular carrier. The phase of each triangular carrier is staggered by \( \frac{1}{N} \) of the period of triangular carrier. For each H-bridge unit, if the modulated wave signal is greater than the carrier signal at a certain time, the high level \( E \) is output, otherwise the low level \(-E\) is output. Finally, the output waveform of bipolar CPS-SPWM with \( N + 1 \) levels can be obtained by superposing the outputs of N H-bridge units.

Monopole frequency doubling CPS-SPWM: the so-called monopole refers to that the SPWM wave signal only contains the positive half cycle or negative half cycle information of the sine signal. At any time of the positive half wave of the modulation wave, the carrier signal \( \geq 0 \). If the modulation wave signal is greater than the carrier signal, the H-bridge unit outputs high level \( E \), otherwise 0; at any time of the negative half wave of the modulation wave, the carrier signal \( \leq 0 \), if the modulation wave signal is greater than the carrier signal, H-bridge unit outputs low-level \(-E\), otherwise output 0. N H-bridge inverter units use a pair of modulation waves with opposite phase, and the frequency of modulation wave is WS. The triangle carrier phase of N H-bridge staggers \( 1 / 2N \) of carrier period in turn. The output voltage of cascade inverse monopole frequency doubled CPS-SPWM modulation mode with \( 2N + 1 \) level can be obtained by superposing the output of each inverter unit.
Figure 3 is a simulation model built by 12 H-bridges in cascade, comparing the input voltage of bipolar CPS-SPWM and monopole frequency doubled CPS-SPWM; it can be seen that the output voltage of bipolar CPS-SPWM is 13 \((N+1)\) switching frequency increased by \(N\) times; the output voltage of monopole frequency doubled CPS-SPWM is 25 \((2N+1)\) switching frequency increased by \(2n\) times; the output waveform of monopole frequency doubled CPS-SPWM is closer to sine wave than that of bipolar CPS-SPWM It is better to eliminate harmonic.

4. detection of reactive power

The instantaneous power theory transforms the voltage and current from the abc coordinate system to the dq coordinate system for detection, which is suitable for the three-phase system in the time domain, not only for the steady state but also for the transient state. In this paper, the detection algorithm based on instantaneous power theory is used. The current components of each part are obtained by coordinate transformation, and the AC is converted into DC for control [9,10].

Firstly, the load three-phase current abc is collected and transformed into two-phase orthogonal static coordinate system \(\alpha\beta\) by matrix \(C_{abc-\alpha\beta}\).
\[
\begin{bmatrix}
i_{\alpha} \\
i_{\beta}
\end{bmatrix} = C_{abc-\alpha\beta}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]  

(1)

Among them:

\[
C_{abc-\alpha\beta} = \frac{2}{3}
\begin{bmatrix}
1 & -\frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{3}} \\
0 & \frac{2}{\sqrt{3}} & -\frac{2}{\sqrt{3}}
\end{bmatrix}
\]

(2)

Then the two-phase static orthogonal coordinate system is transformed into two-phase rotating coordinate system by \(C_{\alpha\beta-dq}\), which is expressed as:

\[
\begin{bmatrix}
i_{d} \\
i_{q}
\end{bmatrix} = C_{\alpha\beta-dq}
\begin{bmatrix}
i_{\alpha} \\
i_{\beta}
\end{bmatrix}
\]

(3)

Where the transformation matrix \(C_{\alpha\beta-dq}\) is:

\[
C_{\alpha\beta-dq} = \begin{bmatrix}
\sin(\omega t) & -\cos(\omega t) \\
\cos(\omega t) & \sin(\omega t)
\end{bmatrix}
\]

(4)

Then the transformation matrix \(C_{abc-dq}\) from abc coordinate system to dq coordinate system is:

\[
C_{abc-dq} = C_{\alpha\beta-dq}C_{abc-\alpha\beta} = \frac{2}{3}
\begin{bmatrix}
\sin(\omega t) & -\cos(\omega t) \\
\cos(\omega t) & \sin(\omega t)
\end{bmatrix}
\begin{bmatrix}
1 & -\frac{1}{2} & -\frac{1}{2} \\
0 & \frac{2}{\sqrt{3}} & -\frac{2}{\sqrt{3}}
\end{bmatrix}
\]

(5)

It can be simplified as follows:

\[
C_{abc-dq} = \frac{2}{3}
\begin{bmatrix}
\sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\
\cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3})
\end{bmatrix}
\]

(6)

Therefore, according to the calculation of three-phase load current, the formula of positive sequence component is expressed as follows:

\[
\begin{bmatrix}
i_{d} \\
i_{q}
\end{bmatrix} = \frac{2}{3}
\begin{bmatrix}
\sin(\omega t) & \sin(\omega t - \frac{2\pi}{3}) & \sin(\omega t + \frac{2\pi}{3}) \\
\cos(\omega t) & \cos(\omega t - \frac{2\pi}{3}) & \cos(\omega t + \frac{2\pi}{3})
\end{bmatrix}
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix}
\]

(7)

The positive sequence component obtained by the above calculation method also contains harmonic component. It is necessary to add filtering link to filter to obtain the fundamental component of current positive sequence active power and reactive power \([I_d^* \ I_q^*]\). Since the matrix \(C_{abc-dq}\) is orthogonal, its inverse matrix and transpose matrix are the same, so the inverse transformation matrix from dq coordinate system to abc coordinate system is expressed as:
The reactive power detection flow chart of the load is as shown in Figure 4.

\[ C_{dq-abc} = \frac{2}{3} \begin{bmatrix} \sin(wt) & \cos(wt) \\ \sin(wt - \frac{2\pi}{3}) & \cos(wt + \frac{2\pi}{3}) \\ \sin(wt + \frac{2\pi}{3}) & \cos(wt - \frac{2\pi}{3}) \end{bmatrix} \]  

(8)

The reactive power detection flow chart of the load is as shown in Figure 4.

**Figure 4.** flow chart of reactive power detection

5. Simulations
In order to verify the accuracy of theoretical derivation in this paper, a simulation model of multi-level SVG of star connected series H-bridge is built by using Matlab / Simulink simulation tools; the simulation parameters are shown in Table 1.

| parameter | numerical value | parameter | numerical value |
|-----------|-----------------|-----------|----------------|
| Three phase system line voltage / kV | 10 | Switching frequency / kHz | 24 |
| Grid frequency / Hz | 50 | Connecting reactance / mH | 3 |
| Number of cascade modules of each phase n | 12 | DC side voltage reference value / V | 850 |
| DC side capacitance value / μf | 5000 | | |

The simulation platform is built to carry out simulation experiments when the load is capacitance or inductance, and observe the effect of reactive power compensation and the response speed of compensation.
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Figure 5. Capacitive load

The figure 5 above shows the voltage and current diagram of the common connection point (PCC) with the load of capacitance. It can be seen that (a) the current is 155.5A when $C = 20 \times 10^{-5}$ F; figure (b) the current is 125A when $C = 10 \times 10^{-5}$ F; the current phase leading voltage phase is capacitive reactive before 0.1s. SVG is put into operation at 0.1s. After less than one cycle, the voltage and current reach the same phase, and the load reactive power is compensated.
Figure 6 is the voltage and current diagram of PCC point under inductive load, and the current lagging voltage is inductive reactive power before 0.1s. In less than a period of 0.1s, SVG can achieve the same phase of voltage and current, which verifies the effect of reactive power compensation.

In order to verify the rapidity and compensation ability of SVG, build an initial load $R = 50 \, \Omega$, $L = 100e^{-3} \, \text{H}$ and switch the load type to $R = 50 \, \Omega$, $C = 10e^{-5} \, \text{F}$ at 0.2s. Observe the voltage and current of PCC at this time, as shown in Figure 7. Before 0.1s, the current lags behind the voltage. When 0.1s, the reactive power compensation quickly reaches the same phase of voltage and current. When 0.2s is switched to capacitor, it can be seen that the current phase is ahead of the voltage in a short time, and then immediately reaches the same phase through the reactive power compensation. The rapidity is verified.

Figure 7. inductive load switching capacitor load

6. Conclusions
In this paper, the high voltage static generator is analyzed. Firstly, the cascade H-bridge has the characteristics of large capacity and high efficiency. For the control of cascaded H-bridge, the characteristics of bipolar CPS-SPWM and unipolar frequency doubling CPS-SPWM are compared and analyzed. It is clear that unipolar frequency doubling CPS-SPWM can reduce the harmonic content and effectively control each H-bridge module. The classical instantaneous reactive power theory is
used to detect the reactive power, and the principle and process of the detection are analyzed. The simulation results show that the proposed control strategy can realize fast and accurate reactive power compensation under both inductive reactive power and capacitive reactive power. This design realizes the fast and accurate compensation of reactive power by high voltage static var generator, and provides reference for the control of high voltage static var generator.

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