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Study on SVG Control Method Based on Reactive Open Loop

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Abstract. Aiming at the series of problems of power quality such as low power factor, large reactive power deficiency and the presence of harmonic interference leading to high harmonic content, which are caused by non-linear load in the system, a reactive power open loop control strategy is proposed in this paper. This control strategy improves the conventional indirect current control method, and uses the voltage outer loop of reactive power control to control the power factor parameter. The basic method is as follows: the reactive current of the system is controlled by a series of controls after comparison of a given ideal power factor with the actual power factor. Finally, the involved system is simulated and modeled by PSCAD tool. The simulation results show that, with this improved control strategy, the SVG can compensate the reactive power of the system through accurately responding to the dynamic changes of reactive power in the system.

Keywords. Power quality, static VAR generator, open loop, power factor

1. Introduction

With the development of industrial modernization, users have increasing demands for power quality. The problems such as low power factor and deficient reactive power presented in the power network reduces the effective utilization rate of the power generation and supply equipment and increases the loss on the electric transmission line, causing huge economic loss to the country and society. Because the load in the system changes over time, the dynamic reactive power compensation is great significance for maintaining the stable operation of the system and effectively improving the power quality. The Static Var Generator (SVG) is more and more widely used in reactive power compensation due to its advantages of faster regulating speed, wide range of operation, low harmonic content and small volume and low cost etc., and has broad prospects for R&D and application [1,2].

The factors affecting SVG control precision are as follows: detection method of reactive current, PWM modulation method and control strategies of reactive power compensation etc. In recent years, many scholars have conducted in-depth studies on the above aspects.

In the aspect of reactive current detection, literature [3] indicates that in case of asymmetric network voltage, the traditional reactive current detection method can not

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accurately extract the reactive current in the system and extract the phase A positive sequence voltage as the input of the phase-locked loop. The precision of reactive current can be increased with improvement. Literature [4] proposes a method of extracting positive sequence voltage phase without phase-locked loop, which is suitable for network voltage distortion and asymmetric. It eliminates the influence of phase-locked loop on current detection and improves the precision of current detection.

As to the PWM modulation method, literature [5] analyzes and models the bipolar CPS-SPWM modulation method and the unipolar frequency doubling CPS-SPWM modulation method respectively. Simulation analysis shows that the output waveform of the unipolar frequency doubling CPS-SPWM modulation method is closer to sine wave than that of the bipolar one, and the equivalent switching frequency is high, which has better harmonic wave elimination characteristics. Literature [6] investigates a space vector pulse width modulation method based on 60° coordinate system, which reduces the imbalance of capacitor voltage. The DC voltage utilization of SVPWM is 15.47% higher than that of the SPWM, but SVPWM is typically limited to circuits of less than five levels.

In the control strategy of reactive power compensation, reactive current control is typically divided into direct current control and indirect current control. Indirect current control is mainly suitable for high-power and high-voltage devices with good static characteristics, but due to the complex implementation methods, the control accuracy is often not high, and the dynamic response speed is relatively slow, which is suitable for high-capacity and high-voltage occasions. Direct current control can realize fast tracking of instantaneous current value, has the advantages of high control precision and fast dynamic response speed, and can meet the requirements of the system quickly, which is suitable for low-voltage and small-capacity occasions [7].

Aiming at the problems of power quality such as low power factor, large reactive power deficiency and high harmonic content caused by non-linear load in the system and adopting the topological connection of chain H-bridge star connection, a direct control method for power factor is proposed in this paper. In this method, the voltage outer loop under reactive power control is controlled with power factor parameter, an ideal power factor is given and compared with actual power factor to control the reactive current of the system through a series of controls, and its theory is deducted. Finally, simulation validation is carried out on PSCAD. The results show that the control method is effective and can dynamically and rapidly compensate the reactive power in the system.

2. Main Circuit Structure and Working Principle of Chain H-Bridge SVG

The circuit structure of SVG can be divided into two types: voltage type bridge circuit (VSI) and current type bridge circuit (ISI). Current type bridge structure is commonly used taking account of operating efficiency.

The main circuit structure of chain H-bridge SVG is shown in figure 1. Star connection is adopted for SVG main circuit. Where i_{si}, i_{li} *and* i_{ci} ($i = a,b,c$) are the network-side current in the system, the load side current and the current flowing into SVG respectively.

Each phase is composed of n H-bridge power units in series. IGBT with self-turning-off capability is selected as switching device. SVG is connected between power network and load through inductance L and resistance R. DC side of each power unit of SVG adopts capacitor C as energy storage element and voltage support element.

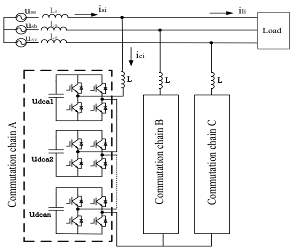
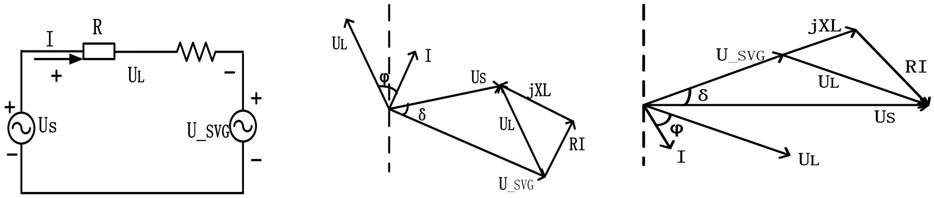


Figure 1. The Main Circuit Structure of Chain H-Bridge SVG.

During normal operation, SVG can convert DC side voltage into AC voltage of the same frequency with AC power grid through inverter by controlling the opening and turning off of IGBT [8]. The working principle of SVG can be represented by a single-phase equivalent circuit diagram in figure 2(a). The network voltage and the AC voltage output by the SVG are expressed by Us and U_SVG respectively, where R is the loss of the converter during operation, L is the connection inductance between the SVG and the power network, UL is the voltage on the connection reactance, I is the current absorbed by the SVG from the power network, δ is the phase difference between Us and U_SVG. δ is positive when U_SVG leads Us.



(a) Single-Phase Equivalent Circuit; (b) Current Lead Vector Diagram (c) Current Lag Vector Diagram

Figure 2. Single-Phase Functional Diagram of SVG.

Figure 2(b) and figure 2(c) are vector diagram of current lead and current lag, respectively. Since SVG itself does not consume reactive power, the phase difference between U_SVG and I is 90°. The phase of system voltage Us and current I is no longer 90°, but δ degree smaller than 90°, which indicates that the system provides part of active power to compensate for the loss in the circuit, so as to maintain the voltage stability on the DC side of SVG.

3. SVG Control Strategy

3.1. Feedback Decoupling Control

The voltage of SVG three-phase output expression is written as a matrix and processed by transformation matrix C to obtain:

$$\frac{d}{dt}\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 \\ 0 & -\frac{R}{L} \end{bmatrix}\begin{bmatrix} i_d \\ i_q \end{bmatrix} + \frac{1}{L}\begin{bmatrix} u_{sd} - u_{cd} + \omega L i_q \\ u_{sq} - u_{cq} - \omega L i_d \end{bmatrix} \tag{1}$$

The control strategy of v_{cd} and v_{cq} can be obtained from equation of state as follows:

$$\begin{cases} u_{cd} = -k_{dp}\left(i_d^* - i_d\right) + u_{sd} + \omega L i_q \\ \quad -k_{di}\int\left(i_d^* - i_d\right)dt \\ u_{cq} = -k_{qp}\left(i_q^* - i_d\right) + u_{sq} - \omega L i_d \\ \quad -k_{qi}\int\left(i_q^* - i_d\right)dt \end{cases} \tag{2}$$

Where, k_{dp} , k_{dq} , k_{di} and k_{qi} are all parameters of the PI regulator. i_d^* and i_q^* are the given values of active current and reactive current, respectively. According to this expression, the decoupled control block diagram can be drawn, as shown in Figure 3.

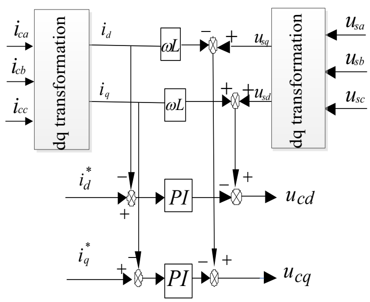


Figure 3. Control Block Diagram of SVG AC Side Feedback Decoupling.

3.2. DC Capacitor Voltage Control

Due to different device manufacturing processes of each module in practice, the operating characteristics of each device are not identical, that is, the power loss of the three-phase inverter is different from the switching loss of each switching device, and the pulse of the switching device is delayed. Various factors make the DC side capacitor voltage of the three-phase in whole and each phase unbalanced. The DC side voltage imbalance will cause the given value of the active current to be indeterminate and affect the current following performance of the whole system.

Based on the above situation, the hierarchical control strategy is adopted herein to solve the capacitor voltage imbalance of the DC side [9]. The first layer controls the total active current, and the second layer controls balance of each capacitor voltage of the DC side.

The energy relationship of the DC side capacitor can be expressed as:

$$\frac{d}{dt}\left(\frac{1}{2}cu_{dc}^2\right) = u_{ca}i_a + u_{cb}i_b + u_{cc}i_c \tag{3}$$

Equation (3) can be performed abc/dq transformation to obtain:

$$\frac{du_{dc}}{dt} = \sqrt{\frac{3}{2}}\frac{M}{C}\left(i_d \cos\delta + i_q \sin\delta\right) \tag{4}$$

M is the modulation ratio, and C is the total voltage of the capacitor on the DC side.

Since δ is very small, u_{dc} and i_d can be regarded as linear relationship in Equation (4). Therefore, the control block diagram of DC side voltage can be expressed as follows. Where u_{dcsi} is the DC side voltage value of each phase of abc, *s = a, b, c; I = 1, 2....12.*

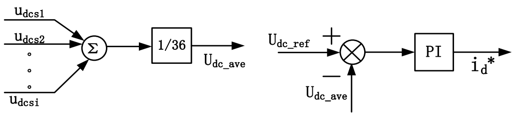


Figure 4. Active Current Given Value Control Block Diagram.

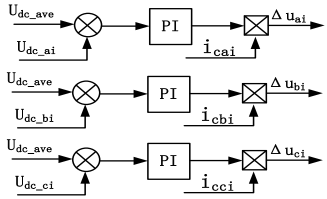


Figure 5. DC Side Capacitor Voltage Balance Control Diagram.

Figure 4 shows the upper layer control of capacitor voltage on DC side, which can be designed as active current outer loop control. The given value of the active current is obtained by PI control through the difference between the given value and the average value of the DC side voltage.

Figure 5 shows the voltage balance strategy designed for the difference in DC side voltage loss of each phase, that is, the low-level control strategy of DC side voltage control.

Where, the adjustment amount of the obtained modulation wave voltage is related to the bridge arm current [10], that is, get the difference and make comparison between the actual value of the DC side voltage and the average value of the DC side capacitor voltage in each phase, and after being adjusted by a PI controller, the obtained value is multiplied by the current of the bridge arm H-bridge module unit in each phase, and the fine tuning command data of the modulation wave in each phase of SPWM is obtained. The fine-tuning command data is added to the modulation wave obtained by the modulation strategy to obtain the modulation wave in practical application, so as to maintain the DC side capacitor voltage balance.

3.3. The Control Strategy

The control strategy of this paper is shown in figure 6. Where, the given value of active current i_d^* is obtained from figure 4, and the voltage balance control is obtained from figure 5. The given value of reactive current i_q^* is obtained by using the given power factor method in this paper, that is, the given power factor is cosφ*, according to Ps and Qs at the incoming line of the system, the given value of reactive power from the incoming line Qref = Ps*tanφ* is obtained, where Qs is the sum of load side reactive power, the filter reactive power and the reactive power generated by SVG itself. Therefore, the reactive power command signal Q* to be sent by the SVG is shown in figure 7.

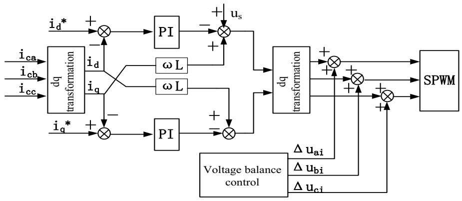


Figure 6. Structure Diagram of SVG Control System.

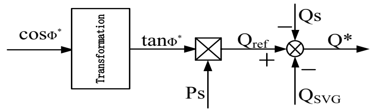


Figure 7. SVG Reactive Power Command Diagram.

The instantaneous reactive power, instantaneous active power and the given value of reactive current are expressed as follows:

$$\begin{aligned} p &= u_{sd} i_d + u_{sq} i_q = u_{sd} i_d \\ q &= u_{sd} i_q - u_{sq} i_d = u_{sd} i_q \\ i_q^* &= q^* / u_{sd} \end{aligned} \tag{5}$$

4. Simulation Analysis

In order to verify the feasibility of the control strategy proposed in this paper, an H-bridge cascade SVG model is built in PSCAD simulation software. Specific model parameters are shown in table 1 below. The values set in this document are per-unit value.

Table 1. Simulation Parameters of cascaded H-Bridge SVG.

Parameter	Network Voltage (kV)	Number of SVG Cascade Units	SVG Capacity (Mvar)	Filter Inductance L (mH)	DC Side Inductance C (μF)	DC Side Capacitor Voltage (V)	Rated Output Current (A)
Value	10	12	6	3	3000	830	346

In practice, a power factor of about 0.95 complies with the practical requirement, so the power factor set in this paper is 0.95. SVG unlocks after 0.1s, and the load adopts star connection (active power of 4 MW, reactive power of 3 Mvar). The AC current value at SVG inverter side is shown in figure 8.

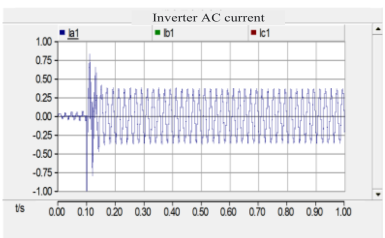


Figure 8. Current at SVG Inverter AC Side.

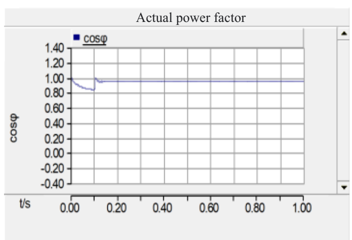


Figure 9. Power Factor at System Side.

It can be seen from figure 9 that before 0.1s, the capacitive reactive power gradually increases due to the charging of the load side capacitance, leading to the gradual decrease of the power factor of the system, while the power factor of the system remains at 0.95 after the SVG is put into operation, reaching the required target.

In figure 10, there is a deviation between the DC voltage outer loop current and the ideal current before 0.1s. After SVG is put into operation at 0.1 s, the two currents are the same, and the outer loop current can follow the ideal value.

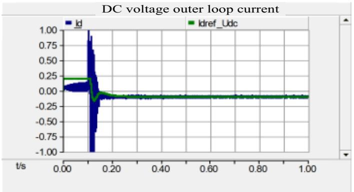


Figure 10. DC Voltage Outer Loop Current.

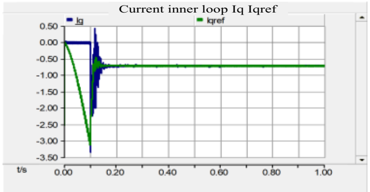


Figure 11. Inner Loop Current.

It can be seen from figure 11 that the given value of reactive current decreases before 0.1 s, which is consistent with the control strategy in this paper. The given reactive current before 0.1 s is directly proportional to the reactive power in the system. After SVG is put into operation at 0.1 s, the two currents are the same, and the inner loop reactive current can follow the ideal value.

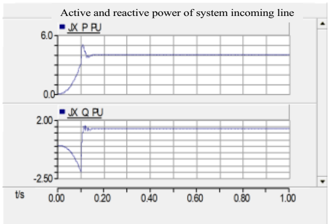


Figure 12. Active Power and Reactive Power of Incoming Line of the System.

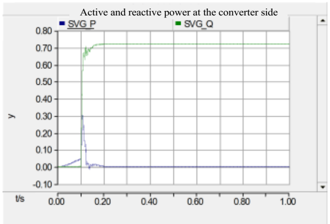


Figure 13. SVG Output Side Active Power and Reactive Power.

It can be seen from figure 12 that, for the active power and reactive power of the network side incoming line of the system, the active power increases gradually and the reactive decreases gradually before 0.1 s, and the main reason is that the inductance and capacitance of the system are charged at the beginning. The active power and reactive power of the system are maintained at constant values after 0.1 s, corresponding to the system side power factors in figure 9.

It can be seen from figure 13 that the value of SVG output side active power and reactive power change after 0.1 s, and the SVG output side reactive power is dynamically compensated according to the demand of the system. It can be proved that the control strategy used in this paper can achieve better control effect.

5. Conclusion

This paper studied and analyzed the working principle and mathematical model of chain H-bridge SVG, and proposed the control strategy of improved SVG to complete the dynamic reactive power compensation of the system. Through the simulation on the PSCAD simulation platform, the results showed that the control method was effective and can dynamically and rapidly compensate the reactive power in the system.

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