Research on Dynamic Hybrid Compensation Technology and Device in Low Voltage Distribution area of Transformer

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Abstract. In order to solve the problem of three-phase unbalance and low power factor caused by distributed power supply to low-voltage distribution network, a hybrid reactive power compensation system based on "intelligent capacitor +SVG" is designed. The system is composed of a small capacity Static Var Generator (SVG) with high precision compensation and several smart capacitors. Firstly, the structure of three-level SVG in the hybrid compensation system is analyzed, and the two-level SVPWM vector synthesis method is applied to three-level compensation. The control mode of intelligent capacitor is analyzed. Then the principle of reactive power distribution in hybrid compensation system is analyzed. Finally, a hybrid reactive power compensation system is designed with TMS320F28335 as the core controller of the hybrid system. The experimental results show that the hybrid reactive compensation system can effectively compensate the reactive current dynamically.

1. Introduction

Low voltage station area refers to the area of low voltage (0.4kV) power supply affected by 35 (10) kV / 0.4kV distribution transformer. The electricity used in Taiwan is generally used by residents, and its quality directly affects residents' lives. However, more and more distributed power sources are connected to the distribution network, which brings power quality problems such as voltage deviations, three-phase imbalances, and abnormal power factors at the assessment points to the distribution network, which will ultimately reduce system economics and threaten system security [1].

In order to effectively solve the above problems, reactive power compensation devices can be used for compensation, which can not only reduce the active loss, increase the output of the transformer and its utilization rate, but also improve the power factor and power quality of the power used in the low-voltage distribution network system. Phase imbalance and terminal voltage drop.

At present, there are three kinds of the most common reactive power compensation devices. Parallel capacitors / inductors can achieve reactive power compensation, but the compensation capacity cannot be smoothly adjusted. The static reactive power compensator (SVC) is a FACTS device that can smoothly compensate the capacity, but with poor accuracy, it is easy to cause under or over compensation, poor followability, and it cannot suppress flicker and imbalance [2]. The static reactive power generator (SVG) adopts self-commutating inverter technology to achieve reactive power compensation, fast adjustment speed, wide operating range, and can suppress harmonic
adjustment of three-phase imbalance. However, the structure is complicated at high capacity, high technical requirements and high cost [3, 4].

Aiming at the problems of a single reactive power compensation device, this paper proposes a hybrid compensation system combining a smart capacitor bank and a three-level SVG for dynamic compensation in low-voltage transformer stations. This device combines the low cost, large capacity, and the advantages of accurate compensation of SVG are compensation for large-capacity and fixed reactive power using switching capacitors; compensation for reactive power with small capacity and under- compensation of capacitors using SVG compensation [5, 6].

This article will first analyze the topology and working principle of three-level SVG, and then study how to convert the three-level space vector synthesis into two-level space vector synthesis to obtain a simplified and easier-to-implement three-level SVPWM algorithm; then The principle of reactive power distribution of smart capacitors and SVG is studied. The correctness and effectiveness of the distribution principle are verified by simulation and experimental results. Based on this, a set of hybrid reactive power compensation device based on smart capacitor + SVG was developed. The experimental results show that the developed device can effectively regulate the three-phase imbalance of the system and compensate the reactive current.

2. Overall structure of hybrid reactive power compensation system

2.1. The overall structure of the system

The dynamic hybrid reactive power compensation device consists of smart capacitors and SVG. The system topology is shown in Figure 1. Among them, smart capacitors are composed of co-complement / sub-complement capacitors. The capacity and number of capacitors can be flexibly configured according to actual needs to meet the steady-state reactive power requirements in the system. SVG consists of three-level power units, DC support units, and filter units. Can achieve rapid adjustment of system dynamic reactive power requirements.

![Figure 1. Overall system results.](image-url)
The hybrid reactive power compensation system uses SVG as the control center. Its controller not only controls the operation of SVG itself, but also controls the switching of smart capacitors. Smart capacitors are preferentially switched during compensation, and then SVG is used for fine compensation.

The following will analyze the composition and working principle of the hybrid reactive power compensation system, mainly focusing on the structure and control principle of the three-level SVG in the system, and the reactive power distribution principle of the overall hybrid reactive power compensation system [1].

2.2. Three-level SVG main circuit topology and basic working principle

2.2.1. Three-level SVG structure

![Three-level SVG structure](image)

The three-level SVG main topology is shown in Figure 2. The three-level studied in this paper is a type-three-level. Each phase contains 4 IGBTs in series. Each IGBT is connected in parallel with a freewheeling diode. At the same time, there are two clamp diodes in each phase. It is used to equalize and support the DC voltage. The AC side is connected to the power grid through an inductor L, and L plays the role of filtering. When the system is working, the current and voltage at the load end are sampled, and then sent to the controller after analysis. The active or reactive capacity that the SVG needs to compensate is calculated. Based on this, a three-level space voltage vector modulation strategy will be used to obtain the driving pulse. Control the on and off of each phase switch, and finally realize the compensation of the reactive power of the load.

For a three-level inverter, assuming the device is an ideal device, ignoring the on-state voltage drop, etc., each phase of the AC output voltage has three potential states, which are equal to + Vdc / 2 positive terminal voltage and -Vdc / 2 negative terminal voltage With zero voltage at the midpoint, the voltage drop experienced by each IGBT when it is turned off is half of the DC bus voltage, and the switching loss is reduced. Compared with the two-level circuit, the harmonic is smaller at the same switching frequency, and the control method is flexible. The electromagnetic interference of the system is also smaller [8, 9].

Figure 3 shows the equivalent circuit diagram and vector diagram of the three-level SVG. $U_s$ is defined as the grid voltage, $R_c$ and $L_c$ are the system equivalent resistance and equivalent inductance, and $U_c$ and $I_c$ are the output voltage and the absorbed current of the SVG, respectively. Analyse the SVG equivalent circuit diagram shown in Figure 3 (a), and equivalent SVG to a voltage-controlled current source (VCCS). When the amplitude of the SVG output voltage $U_s$ and the phase difference from $U_s$ can be adjusted, the SVG can be indirectly adjusted from the grid The direction and magnitude of the absorbed current $I_c$. 

![Three-level SVG structure](image)
Figure 3. SVG equivalent circuit diagram and vector diagram.

Figure 3 (b) shows the system vector diagram. $\delta$ is defined as the phase difference between the grid voltage $U_s$ and the SVG output voltage $U_C$, and $\phi$ is the impedance angle of the equivalent inductance. When the current $I_C$ absorbed by SVG lags the grid voltage $U_s$ 90 °, it indicates that SVG absorbs capacitive reactive power; on the contrary, when $I_C$ leads $U_s$ by 90 °, SVG absorbs inductive reactive power. Since the grid also provides active power for system losses, the phase difference between $I_C$ and $U_s$ is generally slightly less than 90 °, and the deviation angle is represented by $\delta$, as defined above.

2.2.2. Three-level SVPWM Simplification. The PWM modulation method of the multilevel converter is a key part of applying multilevel technology. How to further reduce the $dv/dt$ and THD of the output voltage based on the multilevel topology, reduce the loss of power switching devices, and increase the DC voltage. Utilization, and simplifying the modulation algorithm to facilitate digital implementation, is one of the current research hotspots. The three-level SVPWM that will be discussed in this article mainly corresponds to the three-level space voltage distribution map. The judgment method of the sector where the voltage vector reference value is located, and the corresponding action time of each basic voltage vector are simplified to two levels, and then derived. SVPWM modulation algorithm of three-level SVG.

Figure 4 is a vector diagram of the voltage space of the three-level inverter. Under normal operating conditions, each phase of the three-level inverter has three switching states, so three relative inverters have a total of $3^3 = 27$ switching states. Refer to the two-level space voltage vector theory, that is, the three-level space There are 27 kinds of voltage vectors. As can be seen from Figure 4, in the three-level SVPWM modulation principle, the three-level corresponding reference voltage vector space vector diagram can be divided into 1-6 large sectors, and the small vectors V1, V2, V3, V4, V5, V6, etc. The effect is the zero vector of the two-level SVPWM, and the sector corresponding to the two-level zero vector composed of small regular hexagons. Thus, a specific simplified idea of three-level SVPWM is obtained, that is, the reference space vectors in the 1-6 large sectors are uniformly rotated into the large sector 1, so that the small regular hexagon corresponding to the small vector V1 can be used in the vector diagram. The two-level space voltage vector synthesis rule is used to calculate the action time when the reference space vector is synthesized from each vector [8, 9].
Through the above analysis, it is known that the action time of the three-level space vector SVPWM calculated by using the two-level reference voltage is equivalent. The two-level reference voltage zero vector can be used to determine the sector of the three-level reference voltage vector, the basic voltage vector's action time can be obtained, and then a three-level SVG space voltage vector modulation algorithm can be obtained.

Based on the three-level space voltage vector SVPWM theory, the system control diagram can be obtained as shown in Figure 5. Corresponding to the equivalent circuit diagram shown in Figure 3, SVG is equivalent to a voltage-controlled current source (VCCS). When the amplitude and phase of the SVG output voltage $U_v$ can be adjusted, the SVG sent to or absorbed from the grid side can be indirectly adjusted Current $I_c$, which includes active and reactive currents, is defined as $I_{ca}$ and $I_{cq}$, respectively, and $I_{ca}$ and $I_{cq}$ are linearly related to the active / reactive power sent or absorbed by the SVG, respectively. In the control method shown in FIG. 5, $I_{ca}$ and $I_{cq}$ can complete power decoupling through a PI regulator. This method is not only easy to implement, but also has good dynamic response. At the same time, in order to keep the DC terminal voltage $V_{dc}$ stable, the DC voltage is sampled in real time, and the difference between the reference DC voltage $V'_{dc}$ and the DC terminal voltage real-time sampling value $V_{dc}$ is calculated and sent to the PI regulator. The
corresponding output is the input current active power. The given value of the component $I_{cd}$, so if you want to stabilize the DC terminal voltage, you can control the SVG output or absorbed active power.

2.3. Mathematical Model of Smart Capacitor

Current smart capacitor banks are controlled by thyristors. The principle is shown in Figure 7. Its equivalent Laplace transform mathematical model is

$$U(s) = \left[ Ls + \frac{1}{Cs} \right] I(s) + \frac{U_{c0}}{s}$$

(1)

Where the power supply voltage is:

$$U(t) = U_m \cdot \sin(\omega t + \alpha)$$

(2)

Can be solved from the above two formulas:

$$i(t) = i_{acm} \cdot \cos(\omega t + \alpha) - n[U_{c0} - \frac{n^2 U_m \sin \alpha}{n^2 - 1}]$$

$$\cdot \frac{\sin(\omega t)}{X_L} - i_{acm} \cos \alpha \cos(\omega t)$$

(3)

Where: $\omega$ represents the fundamental angular frequency; $U_{c0}$ represents the initial DC voltage of the capacitor. Meanwhile, the angular frequency is $\omega_n = \frac{1}{\sqrt{LC}} = n \omega$; The resonance order is $n = \sqrt{\frac{X_L}{X_L}}$; The current amplitude is $i_{acm} = \frac{U_m n^2}{X_c (n^2 - 1)}$.

The most important thing for a thyristor switching capacitor is that it does not generate an inrush current when the capacitor is switched. The expression of the capacitor current shown in equation (3) can be divided into three parts. The first part $i_{acm} \cdot \cos(\omega t + \alpha)$ represents the steady-state current, the phase angle between the current and the voltage is 90°, and the second part...
represents the amplitude of the oscillating current that will occur when \( U_{c0} \) is below the optimal precharge voltage; the last part \( i_{c0} \cos \alpha \cos(\omega_n t) \) and the trigger angle \( \alpha \) indicates the amplitude of current oscillation when the trigger angle deviates from the optimal point. If the thyristor does not generate inrush current when switching the smart capacitor, the following two conditions must be met at the same time. The first part of the above formula is equal to zero, that is, the pre-charge voltage of the smart capacitor must reach \( \frac{n^2 U_m \sin \alpha}{n^2 - 1} \). The second is the third part \( \cos(\omega_n t) = 0 \), that is, the trigger point of the thyristor is the positive or negative peak of the power supply voltage.

It is known from the above analysis that in order to achieve switching without inrush current, the trigger point of the thyristor of the smart capacitor should be at the positive or negative peak of the power supply voltage. There are usually two methods to judge the thyristor voltage zero-crossing point: one is to sample the cathode or anode voltage of the thyristor to obtain the zero-crossing signal, and the other is to judge the zero-crossing point by the grid voltage. The first method uses fewer components, lower cost, but is difficult to control. The second method is relatively simple and easy to implement, but uses more components and costs more. The biggest problem is when the capacitor voltage gradually changes with discharge. The detection circuit will produce a large error when the trigger point changes due to the smaller size, so the first method is currently more widely used.

3. System reactive power distribution principle and control method

3.1. Reactive power distribution control method of hybrid reactive power compensation system

Hybrid reactive power compensation system is composed of multiple sets of smart capacitors and a set of SVG to complete reactive power compensation. The compensation principle is shown in Figure 7. It can be seen that the capacity and compensation form of each group of smart capacitors are fixed, that is, the capacity of the smart capacitor is equal to the capacity of the group of capacitors when it is turned on or off. The capacitor is compensated. The SVG switchable capacity is smooth and controllable, so accurate compensation can be achieved. Therefore, the SVG completes the reactive power compensation between stages, and finally realizes the accurate compensation of reactive power. At the same time, in order to avoid frequent switching of the smart capacitor and reduce the life, when the compensation capacity is within the maximum capacity of the SVG, SVG will compensate it.
3.2. Reactive power distribution principle of hybrid reactive power compensation system

Assume that the total capacity of the optional intelligent capacitor plus the maximum capacity of the SVG can fully meet the system's reactive power requirements. According to the actual working conditions that may occur, the reactive power that the system needs to compensate is allocated as shown in Table 1. Among them, \( I_Q \) is defined as the total reactive current of the system that needs to be compensated, \( I_S \) is defined as the output reactive current of SVG, \( I_{S_{\text{max}}} \) is the maximum reactive current that SVG can provide, and it is assumed that the capacity of each smart capacitor is the same, and \( I_C \) is a single smart capacitor. Reactive current that can be compensated, \( N \) is the number of smart capacitors, \( n \) is the number of smart capacitors to be invested, and \( k \) is defined as the largest integer not exceeding \( I_Q / I_C \).

| Table 1. Reactive power distribution scheme |
|---------------------------------------------|
| range                | System reactive current range | Capacitor input number n |
| \( k>N \)            | \( kI_C-I_{S_{\text{max}}} < I_Q \leq kI_C + I_{S_{\text{max}}} \) | N                     |
| \( 0<k<N \)          | \( kI_C-I_{S_{\text{max}}} < I_Q \leq kI_C \) | \( k \)                |
| \( k<0 \)            | \( kI_C-I_{S_{\text{max}}} < I_Q \leq kI_C + I_{S_{\text{max}}} \) | 0                     |

1. When \( k<0 \) and \( kI_C-I_{S_{\text{max}}} < I_Q \leq kI_C + I_{S_{\text{max}}} \), the reactive power component of the system to be compensated is relatively small and smaller than the amount of reactive power that a single smart capacitor and SVG can provide, all compensation can be realized by SVG. Inductive reactive current and capacitive reactive current in under-compensated state.

2. There are two cases when \( 0<k<N \) , if \( kI_C<I_Q \leq kI_C + I_{S_{\text{max}}} \), the system is still under-compensated after the smart capacitor with the number of \( k \) is input, and the remaining reactive power in the range of \( 0 \sim I_{S_{\text{max}}} \) is compensated by SVG; The system is in an over-compensated state after the number of smart capacitors is input, and the remaining reactive power in the range of \( I_{S_{\text{max}}} \sim 0 \) is compensated by SVG.

3. When \( k>N \) and \( kI_C-I_{S_{\text{max}}} < I_Q \leq kI_C + I_{S_{\text{max}}} \), it indicates that the total reactive power demand at this time exceeds the total reactive power provided by all smart capacitors, that is, all capacitors need to be put in and SVG is added for compensation.

In the above-mentioned reactive capacity allocation method, the compensation capacity of the SVG is \( -I_{S_{\text{max}}} \sim I_{S_{\text{max}}} \). If the consideration is to avoid the SVG being in a full load output state and reduce the dynamic output capacity of the SVG, the threshold range can be appropriately reduced.
4. Control prototype development

Figure 8. System control chart.

Figure 8 shows the system control block diagram. It can be seen that the device detects the grid voltage and current and the load-side current signal through the voltage and current sensors, and calculates the reactive current and power factor of the load in real time to obtain the total reactive power of the system that needs compensation. Then control the switching of each compensation branch based on the reactive power distribution method described in section 2.2, that is, calculate the type and number of smart capacitors that need to be switched first, control the switching of the smart capacitor group through the communication unit, and then obtain the inductive or capacitive reactive power that the system still needs to supplement, and control the SVG for fine compensation, and finally realize the system's unbalance adjustment and reactive power compensation.

The SVG in the system also comes with a protection program. By detecting the voltage, current, and temperature of the system in real time, it can determine the system's overvoltage/undervoltage, overcurrent, open circuit, and overtemperature faults, and remove SVG from the system in time. At the same time, each smart capacitor also samples the grid voltage, current, temperature and other signals in real time, and sends them to the internal controller for analysis and calculation to determine whether there are overvoltage, overcurrent, and overtemperature faults, so as to quickly remove the working capacitor and protect the main circuit.

Based on the above technologies, a prototype of an intelligent integrated power distribution device for a low-voltage transformer station area was developed to compensate the system's hybrid reactive power. The total compensation capacity of the system is 120kVA, of which the compensation capacity of SVG is 30 kVA. The smart capacitor is composed of four groups of smart capacitors, namely a group of Δ/0.45-15 • 20 kVA compensating capacitors and a group of Y / Δ-10 • 10 kVA hybrid capacitors, a group of Y /0.25-20 kVA sub-capacitors and a group of Y / 0.25-15 kVA sub-capacitors. The SVG control chip is DSPTMS320F28335, which is a full digital control system with FPGA, which can meet the changes and changes in the capacity of smart capacitors and SVG's own reactive power compensation.
Figure 9. SVG compensation alone.

Figure 9 shows the waveform of the SVG to individually compensate the load. At this time, the reactive power in the load is relatively small. Only the SVG is used for reactive power compensation. The reactive current of the load is 8.8A and the compensated current in the SVG is 8.7A. The current in the power grid is 3.1A, and SVG achieves full compensation for the load.

Figure 10. Mixed compensation waveform.

Figure 10 shows the process of hybrid compensation of smart capacitors and SVG. In Figure 10 (a), the reactive current in the load is 29A, the compensated current in SVG is 11A, and the current in the power grid is 43A. At this time, the capacitor is over-compensated. State, SVG absorbs reactive power. In Figure 10 (b), the reactive current in the load is 56A, the compensated current in SVG is 14A, and the current in the power grid is 42A. At this time, the capacitor is under-compensated, and SVG emits reactive power.
Figure 11 shows the smart capacitor input and removal process. It can be seen that the capacitor input process is relatively smooth and there is no current impact; the capacitor removal process is smooth and there is no over-impact.

5. Conclusion
Aiming at a series of power quality problems caused by distributed power access to the distribution network, this paper proposes a hybrid compensation scheme of smart capacitor bank + SVG, in which smart capacitors compensate for the main reactive power, and SVG is used to assist the compensation of smart capacitors for hierarchical compensation. Compensated reactive power to achieve fast, large-capacity, low-cost continuous reactive power compensation.

Firstly, the structure of the three-level SVG in the hybrid compensation system is analyzed, and the two-level SVPWM vector synthesis method is applied to the three-level compensation to realize the decoupling control of the three-level SVG. The capacitor performs "zero switching" to ensure that there is no inrush current during the switching process, no operating overvoltage, and low power consumption; then the principle of reactive power distribution of the hybrid compensation system is analyzed, and the optimal combination of capacitor switching and switching is selected. SVG compensation points, thereby improving the effectiveness of the entire compensation system. Finally, TMS320F28335 is used as the core controller of the hybrid system, and a hybrid reactive power compensation system is designed. The test results show that the hybrid reactive power compensation system can effectively compensate the reactive current.

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