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Research on the HVC Contactor Switched Capacitor at the Zero-crossing Point Based on Expert Decision-making Analysis

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Abstract—**This paper takes the high voltage power system dynamic reactive power compensation at the conditions of the mine load smooth changes, studies the negative effects inhibition of the HVC contactor switched capacitors reactive power compensation device in ambient temperature perturbation. The basic principles and structure of intelligent reactive power compensation device based on contactor zero-crossing switching control and the response time compensation method for different ambient temperature and operating voltage are proposed, and the expert decision-making switched control strategy is given. The research can effectively eliminate the adverse effects of capacitor inrush current and voltage flicker in the moment of switching, and ensure safe and stable operation of the grid under conditions that satisfy the system reactive power compensation.**

Keywords- intelligent reactive power compensation; HVC; zero-crossing control; expert decision-making

I. INTRODUCTION

Dynamic characteristics of the power system are influenced by plenty of electrical equipments, such as asynchronous motors, electric arc furnace, DC hoist and so on. These devices will produce large amounts of reactive power during operation to the grid causing a great deal of burden, seriously affect the power system stability[1]. At present, the main reactive power compensation devices are FC, HVC, SVC, SVG. The structure of static compensation devices FC is simple, so that reactive dynamic regulation of the system can not be achieved; Static var compensator using thyristors as a switching device can realize the dynamic reactive power compensation and fast response, but the voltage rating of the thyristor limites its application in high-voltage area. Static var generator can achieve a continuous reactive power compensation, short response time, eliminate certain harmonic, but SVG has a high cost for using the full controllability of devices such as IGBT or GTO as switching device[2].

Contactor switched capacitor bank reactive power compensation device has been widely used in the field of power quality because of its relatively low cost, high voltage and power levels. However, the contactor switched capacitor will produce many negative effects such as surge impact, voltage flicker and light-load oscillation at the switching moment, which endanger the insulation breakdown of high voltage power supply devices, and the instant temporary state process of switched capacitor will result in some power electronic equipment malfunction and cause the production process to a standstill resulting in huge economic losses[3]. Therefore, this paper presents a zero-crossing switching control strategy affected by the response time comprehensively considering the capacitor connection, ambient temperature and operating voltage; a control system based on expert decision-making control to suppress the negative effect of the capacitor bank reactive power compensation device.

This paper studied an intelligent reactive power compensation device based on the contactor switched capacitors at the zero-crossing point, aimed at a capacitor explosion of shunt capacitor reactive power compensation device in a coal mining enterprise at the capacitor switching moment. The device made a real-time detection and compensation for the active power, reactive power and harmonic factor of the power supply system to reduce the over-voltage and surge current of shunt capacitor banks at switching moment, thereby reduce the impact on the insulation damage of the capacitors and other equipments, and ensure grid a stable operation, providing ideas for the urgent need for the high-voltage, high-power and low-cost of grid.

II. SYSTEM STRUCTURE OF HVC

The structure diagram of the contactor synchronous switched capacitor system was shown in Figure 2-1. Three-phase voltage and current signals of the grid pass through the voltage and current sensors, and after signal conditioning, they enter the control chip with the voltage range of the signal which the conversion control chip can withstand. Analyzing the time required from the switched instructions of the control chip to the contact device to produce the response action, using the temperature chambers between -20℃ to 50℃, we get the change of the response time during the range. A database of the response time with the change of the outside temperature is established as a basis for adjusting the contactor

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response time according to the ambient temperature dynamically. Considering the influence of the working temperature on the contactor response time during operation, the response time history of the contactor is recorded in the control system as a switching signal reference.

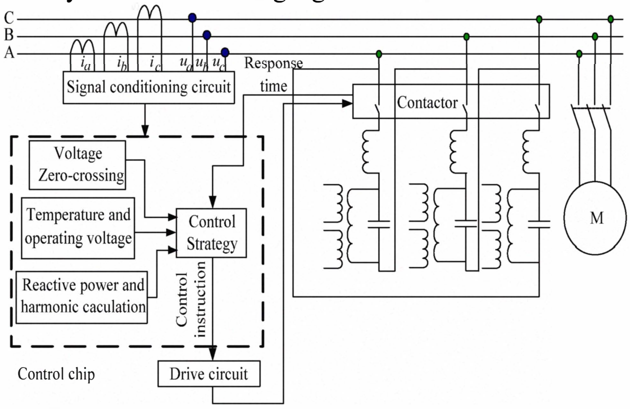

Fig.2-1 System structure of contactor switched capacitor

In the system to control the switching of the capacitor using the contactor, A phase voltage (B, and C phase can also be) is chosen as the reference voltage in this paper. After A-phase voltage go through zero-crossing detection circuit, the zero-crossing phase information will enter the control chip. The control chip detects the reference phase zero-crossing signal in real time[4]. After that, using the instantaneous reactive power algorithm, it calculates the reactive power, current distortion rate and other parameters. We determine the system capacitor switching time based on expert decision-making control strategies. When the system needs for reactive power compensation, the controller uses reference voltage phase zero-crossing signal as a benchmark to calculate the response time compensation amount according to response time data in the database of the corresponding temperature and operating voltage. In the meantime, considering the stored values of the contact device response time history with corresponding number, after a certain delay time, the controller sends out instructions to switch capacitor. The controller instruction controls the contactor after going through an intermediate relay. Switching instructions sent out by the control chip need to go through the uplift circuit to determine the action of the relay, and then control the movement of the contactor, and finally complete the process of capacitor switching process[5].

III. CONTROL STRATEGY

A. The structure of whole control system

Compared to the traditional compensation equipment, the control strategy of the contactor synchronous switched capacitor system proposed in this paper is more complicated. It is mainly reflected in the harmonious control of multiple capacitors and the control of switching time of each capacitor, which assures the normal running and avoids the damage to the electrical network. To solve the problems of the system control, a control method based on the specialist decision-making is proposed. It coordinates the running of the multiple capacitors by using the decision-making information, which has an excellent control effect. The intelligent reactive power compensation device based on contactor zero-crossing switching designed in this paper is shown as Figure 3-1.

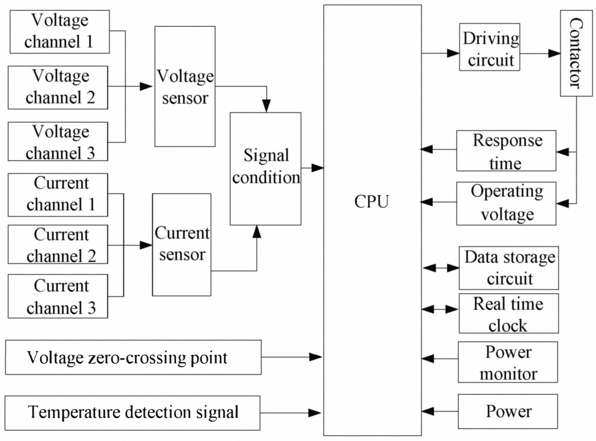

Fig 3-1 Block diagram of HVC control system

Due to the voltage range limit of the control chip, the reactive load three phase voltage and current signal go through the Hall voltage and current sensor, and enter the signal conditioning circuit. After being transformed to the 0~3.3V DC signal, it can be input to the AD port of the control chip. A-phase reference voltage zero-crossing signal is input to the control chip after voltage dividing. The control chip first transforms the sample signal to the digital signal. Then it processes the signal with corresponding algorithm and detects the active power, reactive power and harmonic wave. It controls the switch of contactor based on corresponding control strategy, in order to determine the switching of the shunt capacitor banks.

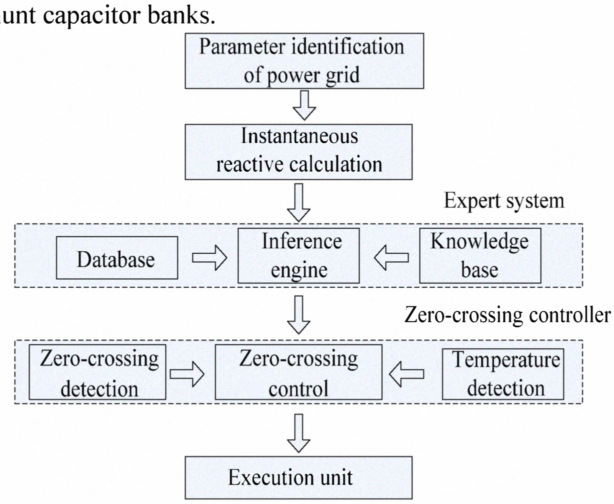

Fig 3-2. Flow chart of system control strategy

The system control strategy is shown in Figure3-2. The necessary compensation of reactive power in the electric network is first detected. After the reasoning based on the specialist decision-making, the compensation capacity of capacitor, namely the number of the switched capacitor, is determined. And the switching signal is send to executive capacitors. In this paper, the sending of the control switching signal is referred to A-phase zero-crossing point. Based on the real-time detecting A-phase zero-crossing point, the response time of the contactor will also be predicted, in order to determine the delay time of controller when sending the signals. The delay time determines whether the capacitor can switch at the zero-crossing point, namely whether can accomplish the goal of suppressing the surge current and overvoltage. So it is important. But during the actual running, the response time of contactor is great related to the circumstance temperature. So using the temperature-measuring circuit to measure the temperature, which can get the real-time temperature when to switch the capacitors, in order to decide the response time of the contactor and minor the difference of the response time. The control signal sent by the controller drives the middle control relay after going through the signal lifting circuit. The switching of the relay controls the contactor connecting to the system[6].

B. Expert decision-making control

In this paper, the system control means switching the reactive power compensation device and adjusting the on-load transformer tap. These control means are discrete variables, and these devices have different priority of actions in different operating conditions, resulting in a mathematical model of the system can't be given. As a result, expert system technology which become more sophisticated has very good prospects in the reactive power control. The expert system is a computer program in specific areas to simulate a human expert to solve practical problems, the actual issue is there is no precise mathematical model of the object, you need to rely on the experience and knowledge of experts and historical data to solve[7]. The Expert System flow chart is shown in Figure 3-3.

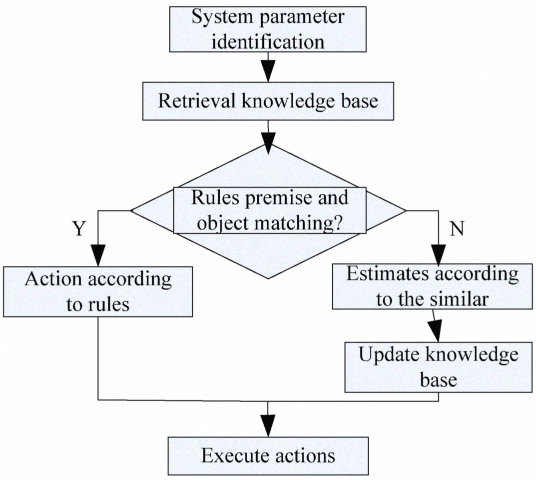

Fig 3-3. Reasoning flow chart of expert system

The database is mainly to save the real-time data of the controlled object and working conditions, including the grid data such as voltage, current, power factor and active and reactive power. The addition also includes the working state of the system devices such as the number of movements of load voltage regulation, switching state and the number grade of capacitor banks, the intervals of the two adjacent actions, and time of each action.

Knowledge is the main results storage of voltage and reactive power data of the controlled object while successful action, as well as the conditions and results of the implementation of the action[8]. Knowledge stored large rules of thumb and historical data in the system during operation, such as voltage and reactive power is in a specific range, the system's action (switching contactor or adjusting the transformer tap), the results achieved in the implementation of the action(changes of reactive power and voltage, the occurrence of shock).

The inference engine's role is mainly to test the existing facts, to determine the path, to call the rules in the knowledge base to infer conclusions. By detecting the network parameters, system call the knowledge base of rules to select the most appropriate strategy for reactive power compensation system and update the knowledge base after a successful action[9]. The system's reasoning mechanism can be expressed as $A=f(I,K)$, where $I=(i_1,i_2,\ldots,i_n)$ is input set of the system, including the real-time voltage and current detected, as well as the reactive power calculated by instantaneous reactive power theory; $K=(k_1,k_2,\ldots,k_n)$ is Knowledge Base set, consists of the relevant rules I search out; $A=(a_1,a_2,\ldots,a_n)$ is the set of the output of the system, including the conclusions of the inference engine got, f is the operator, the basic form of it is IF I AND K THEN A

C. Switched control of the capacitor at zero-crossing point

In order to eliminate surge current and over voltage at the switching moment, the closing and opening time should be controlled , so that the contact of a contactor connect or disconnect accurately in the need time. For switching capacitor, it should be controlled in the voltage zero crossing on and in the current zero crossing off, thereby realizd no inrush current inputting and no arc breaking[10].

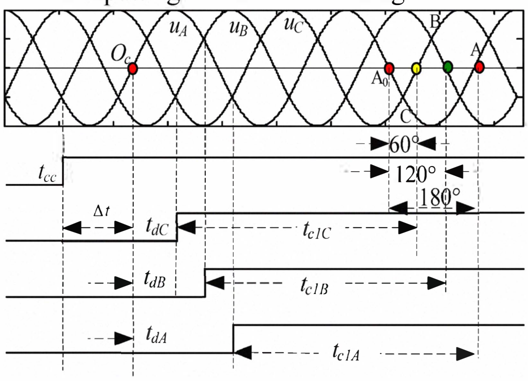

Fig 3-4. Synchronization switched plan of star neutral grounding

As is shown in Figure 3-4, control chip real-time detects zero crossing point of A phase voltage, after receiving the closing instruction at random time t_{cc}, detects zero crossing point of reference voltage (phase A)in order to achieve purposeful minimum delay time at zero-crossing point, based on predicting the required operation time from trigger signal to the contactor action:

$$t_{\mathrm{dx}} = \frac{n}{2f} - t_{clx} + t_{obx} \tag{3-1}$$

t_{dx}(x=A,B,C) is purposeful minimum delay time at zero-crossing point, t_{clx}(x=A,B,C)is responding time of contactor, t_{obx}(x=A,B,C)is phase lag time compared to the reference phase, f is the grid frequency, n is the smallest integer to guarantee $t_{dx} \geqslant 0$, so the purposeful minimum delay time of contactor is:

$$\begin{cases} t_{dA} = n/2f - t_{clA} + 8.33 \\ t_{dB} = n/2f - t_{clB} + 5 \\ t_{dC} = n/2f - t_{clC} + 1.67 \end{cases} \tag{3-2}$$

The required operation time from trigger signal to the contactor action is:

$$\begin{cases} t_{atA} = \Delta t + t_{dA} + t_{c1A} \\ t_{atB} = \Delta t + t_{dB} + t_{c1B} \\ t_{atC} = \Delta t + t_{dC} + t_{c1C} \end{cases} \tag{3-3}$$

If the time from contactor coil power on to the contactor closure t_{clx}(x=A,B,C) can be known, the purposeful delay time t_{dx}(x=A,B,C) can be dynamically adjusted ,projecting into the corresponding ideal cut-off point, made the impact to power network of reactive compensation capacitor device at switching instant to a minimum, in order to achieve the desired switching effect[11].

IV. SIMULATION AND EXPERIMENTAL RESULT ANALYSIS

A. Testing and calculation of contact response time compensation amount

Change of contactor parameters or environmental factors will lead to change in operating time, such as: the control voltage, ambient temperature, contact ablation, the cumulative number of runs. Moreover, the impact of various parameter change on the other parameters and the whole dynamic process is more complex, and therefore a more precise determination of the action time in different environments is needed. Experimental methods as follows: insert normal-open contact of intermediate control relay in the contactor coil circuit; contactor's main contact connect the power supply and resistive load; to power up the middle of the relay coil power (power down); use an oscilloscope to observe the time difference between the control instructions issued to the contactor response, the experimental circuit is shown in Figure 4-1.

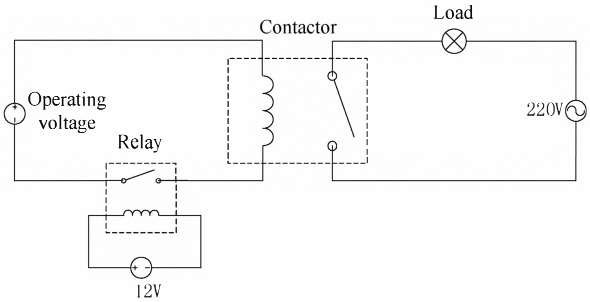

Fig 4-1. Contactor response time detection circuit

Turn-on and turn-off time from the oscilloscope detection waveform is shown in Figure 4-2 and Figure 4-3, in which channel 1 stands for the relay coil voltage(oscilloscope contact attenuation of 10 times), channel 2 stands for the current flowing through the load (detected by current clamp). The time difference from the control commands issued to the contactor response read from the oscilloscope is the contactor response time.

Fig 4-2. Opening time waveform

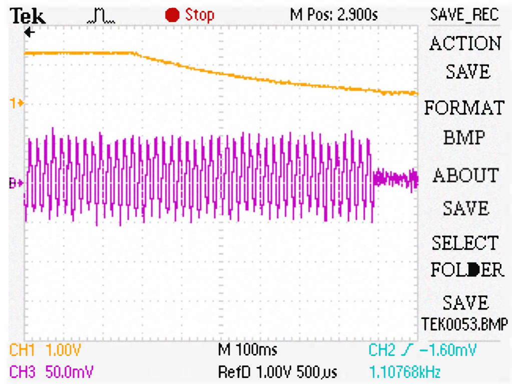

Fig 4-3. Closing time waveform

Fix the operating voltage in 220V,and use High-Low Temperature Test-Box to control the temperature from -35℃ to 40 ℃ temperature to order the repeated action of the contactor, record the response time of each action. The response time curve is shown in Figure 4-4. Meanwhile, at room temperature(20 ℃)measure 190V-240V operating voltage response time of the contactor as shown in Figure4-5. Figure 4-6 is the operating voltage grid under two comprehensive consideration.

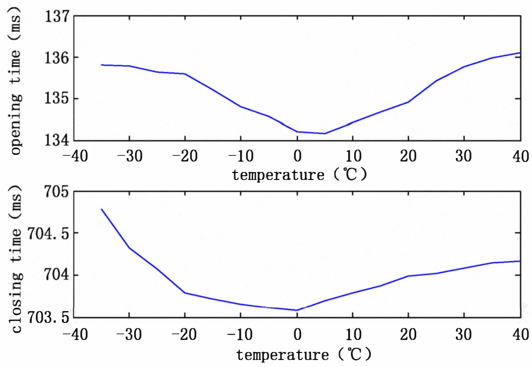

Fig 4-4. The response time on different temperature

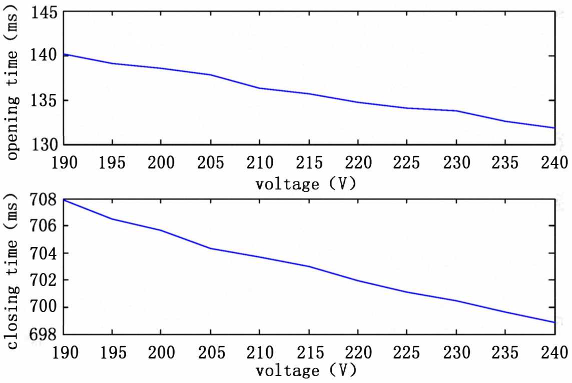

Fig 4-5. The response time on different operating voltage

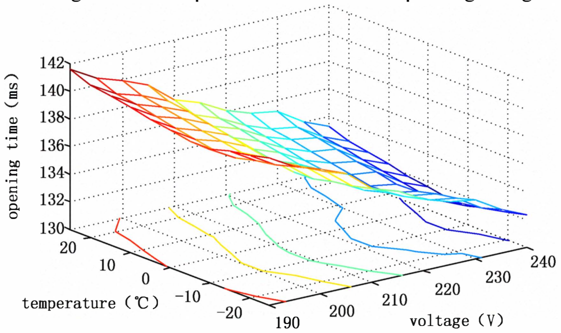

Fig 4-6. The response time under the comprehensive consideration of operating voltage and temperature

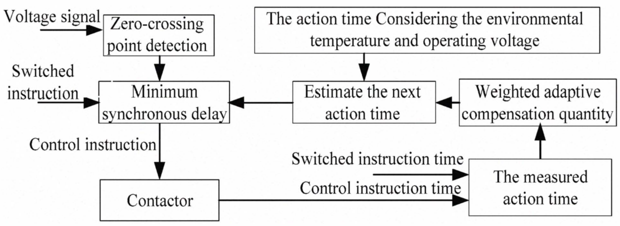

Fig 4-7. The diagram of adaptive contactor switched time

With the measurement data as the initial value of contact response time database, adopt adaptive compensation method based on past operating time, as the block diagram shown in Figure(4-7). In figure(4-7), process the n times history of the measured action records by weighted method and obtain the (n+1) compensation time of switched capacitor bank, and consider the amount of compensation caused by the ambient temperature and operating voltage, which is introduced into the next calculation of minimum synchronization delay as the basis of switching operation time[12]. Thus it has taken into account the response time fluctuations caused by external factors such as ambient temperature, operating voltage, mechanical wear.

B. Simulation and results analysis

Establish contact-switched capacitor simulation model In matlab. In the model the power supply side line voltage is 6300V. Load-side is four groups of three-phase load, and circuit breaker control the time of loads' access to the grid to simulate the loads' changes in the grid. Two sets of capacitors are inserted into the grid by contactor in parallel. In the simulation experiment the active and reactive power in the system are calculated in real-time. With system reactive power as the basis of the capacitor switching, using expert decision-making control strategy for signal switching, respectively simulate the conditions in which switch the capacitor immediately at the moment of receiving input signal and in which switch the capacitors precisely at the zero-cross-over moment of the three-phase voltage. In the simulation oscilloscope is used to measure system power factor, the voltage and current of the grid side and the current flowing through the capacitor at the switching moment. Simulation results are as follows shown in the figure below respectively.

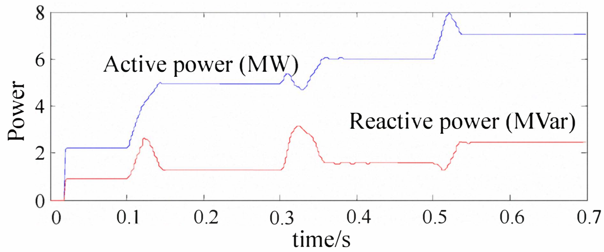

Fig 4-8. the active power and reactive power of the system

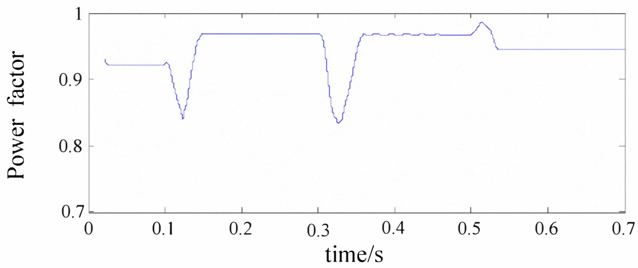

Fig4-9. Power factor of the system

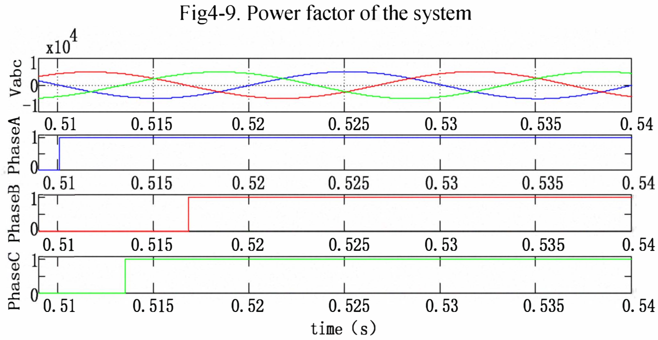

Fig 4-10. Three phase voltage zero-crossing point detection

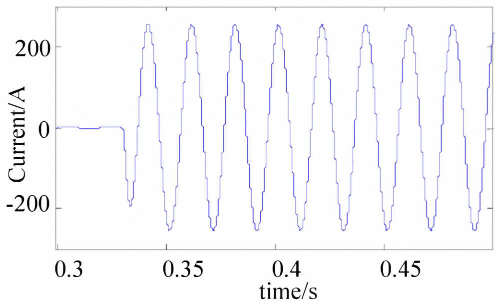

Fig 4-11. A phase capacitor current at the zero-crossing point

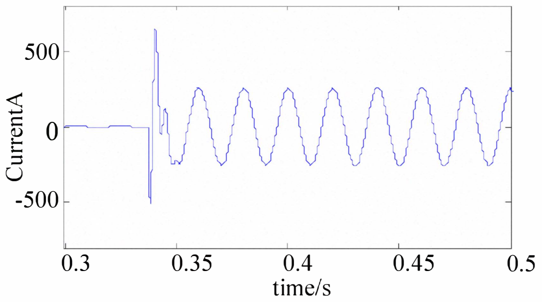

Fig 4-12. A phase capacitor current at the non-zero-crossing point

Figure 4-8 shows the system active power and reactive power detection waveform. Figure 4-9 shows the system power factor waveform. From the figure when inserting the three-phase load of 10Ω and 30mH in the 0.1s, the system reactive power instantly rise above the range of system settings, so after first group of capacitors are switched into the system the reactive power decreases, the power factor increases above the set lower limit. When inserting the three-phase load of 1.5Ω and 60mH in the 0.3s, the system reactive power instantly rise again above the range of system settings, followed by the second set of capacitor switching. Figure4-10 shows the grid side of the three-phase voltage zero-crossing detection waveform. From the waveform it can be seen that in the contactor zero-crossing switching condition three-phase pulse signals are issued in three-phase voltage's respective zero-crossing moment, with the phase angle difference between 60 . Figure 4-11 and Figure 4-12 respectively show the switching capacitor current waveforms that after 0.3s switch the contact in the voltage zero-crossing moment and at any moment. It can be seen from the figure that when the contactor closes at the voltage zero-crossing, the capacitor current has almost no impact; while closing at any moment, the impact of A-phase current is about 3 times the steady-state value. the simulation analysis verify the superiority and feasibility of passing zero control switching reactor.

C. The experiment and results analysis

For further validation of the system control performance, the system experimental platform is built, using control chip STM32F103VBT6, and the waveforms of contactor at switching instant such as a phase voltage waveform of electrified wire netting , the current through the capacitor as well as the switching signal were observed with recorder, experimental waveforms are shown in Figure 4-13 and figure 4-14.

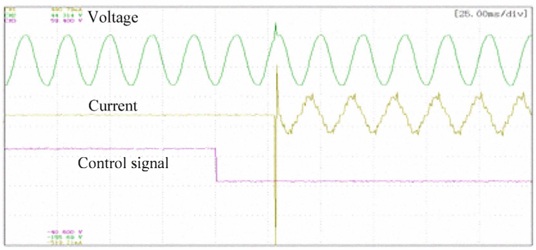

Fig 4-13.Actual waveform at the non-zero-crossing point

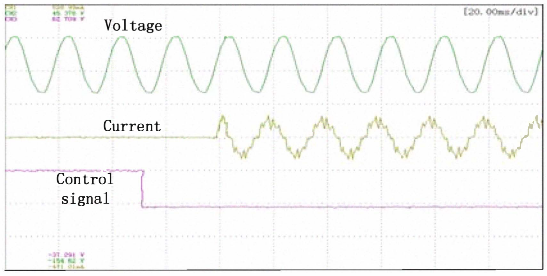

Fig 4-14.Actual waveform at the zero-crossing point

The Figure 4-13 is Actual waveform at the non-zero-crossing point, the Figure 4-14 is the waveform at the zero-crossing point, by two figure contrast it can be seen that switching at the zero-crossing point of voltage can greatly reduce surge current and the impact on the power grid in switched instant. The above two verified that, by considering the contactor actual response time, after the corresponding time delay, basically realized the capacitor zero-on-off, achieved the anticipated effect.

CONCLUSION

The simulation and experimental results show that, this research can effectively control adverse effects of surge current and voltage flicker caused by contactor switched capacitor in a switching instantaneous, to ensure reactive power compensation that meet environmental temperature perturbation condition, realizing the system safe and stable operation. According to high voltage dynamic reactive power compensation of the gently changed load conditions as the research background, the paper studied control strategy of contactor switched capacitor reactive power compensation device for suppression of negative effect, namely intelligent reactive power compensation device based on expert decision and a contactor zero-crossing control, providing solution for the large power and high voltage reactive power compensation.

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