Study of a low voltage reactive power dynamic compensation device with continuously adjustable capacity

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Abstract. A dynamic reactive power compensation device with continuously adjustable capacity is designed for low voltage power grid. According to the time requirement of reactive power dynamic compensation for capacitor switching, a signal generating circuit of voltage/current zero-crossing triggering switching is designed. A capacitor combination method to improve the compensation accuracy and the control strategy to change the compensation power of capacitor by adjusting voltage are put forward. The hardware structure of compensation device, reactive power compensation control mode, capacitor switching control method and capacitor output power regulation method are designed. Using Matlab/Simulink, the simulation results show that the proposed method can realize continuous reactive power adjustment according to the set power factor.

1. Introduction
The inductive loads in power grid leads to the increase of line loss and voltage drop, the power factor also decreases [1]. Therefore, reactive power compensation must be used to improve the above situation. There are many options for reactive power compensation technologies, such as FC fixed capacitor [2], TCR thyristor switching reactor [3], TSC thyristor switching capacitor [4], SVG static var generator [5], etc. There are two problems in the low-voltage network with capacitor as the main reactive power supply. One is the timing of capacitor switching. When the capacitor is put into operation, if the voltage at both ends of the switch is not equal, inrush current will be generated; if the current is not equal to zero at the moment of capacitor removal, flashover will be generated. The other one is over or under compensation. Although the access state of the capacitor bank is determined by the reactive power of the load, it will still lead to under or over compensation due to the difference of capacitance magnitude of the capacitor bank, and even produce switching oscillation [6]. The first problem can be solved by controlling the thyristor and other electronic switching elements, putting the capacitor into work when the grid voltage crossing zero, and cutting off the capacitor when the capacitor current crossing zero. However, the above method needs to consider the discharge of capacitors, so the switching interval is long. The second problem can be solved by adjusting the voltage of the capacitor so as to continuously adjust the reactive power. Reference [7, 8] used auto-transformer or inductive voltage regulator to change capacitor voltage, but they failed to achieve continuous and step less regulation of reactive power. In reference [9], SVC is used in low-voltage power grid to realize accurate and continuous compensation of reactive power, but it is too expensive. In reference [10], capacitor is connected in parallel with reactor, and then connected between the output end of inverter and compensation node, and the nature and size of
compensation reactive power are changed by switching and adjusting the output voltage of inverter, but the method is only applicable to three-phase balance load.

In this paper, a kind of reactive power dynamic compensation device with continuously adjustable compensation power and low cost is developed. A capacitor configuration scheme with high compensation precision is presented, a capacitor voltage/current zero-crossing switching device is designed, a circuit topology and control strategy for continuously adjusting capacitor power are designed to realize continuous adjustment of reactive power.

2. Function of dynamic reactive power compensation device
The reactive power compensation device includes two parts: the mutual compensation part and the split-phase compensation part, the schematic diagram is shown in figure 1. The mutual compensation part is composed of three capacitors with equal reactive capacity connected by Δ, each phase of the split-phase compensation part is composed of three capacitors with proportional distribution capacity in parallel, and at the end of each phase of the split-phase compensation part is connected with an inverter for voltage regulation. Each capacitor of the split-phase compensation part is equipped with a switch, which can independently turn on/off the capacitor; the inverter device is equipped with a bypass switch to control whether the voltage regulation is carried out.

![Figure 1. Wiring diagram of reactive power compensation device.](image-url)

2.1. Response speed
The capacitor switching circuit as shown in figure 2.
Voltage detection and capacitor switching circuits work as follows. Start MSP430 and two voltage transmitters. The main program of capacitor switching is executed after the self-check of single-chip microcomputer (SCM). LV25-p module is adopted for the voltage sensor, and the output ports of the sensor are respectively converted into voltage values through resistors R1 and R2. The SCM samples the voltage values of resistors R1 and R2 in real time and makes a subtraction to the two sampling values. When the difference value is 0, the P4.4 pin of SCM sends the switch-on signal, and the capacitor is put into operation. As the phase difference between the current flowing through the capacitor and its terminal voltage is 90°, when the terminal voltage reaches the maximum value, the current is 0A. At this time, the capacitor can be cut off to avoid flashover. Using Proteus Software to analyze the above capacitor switching circuit, the switching signal is as shown in figure 3.

![Schematic diagram of voltage detection and capacitor switching](image)

**Figure 2.** Schematic diagram of voltage detection and capacitor switching

When the instantaneous value of AC voltage is equal to the instantaneous value of capacitor voltage, the signal of connecting capacitor will be generated, when the instantaneous value of AC voltage reaches
the peak value, the signal of cutting-off capacitor will be generated. According to the national standard, the time requirement for dynamic compensation is that the time interval of repeated switching capacitor should not be more than 1 second, this circuit can capture the switching time of capacitor within 100ms, which meets the requirement.

2.2. Compensation accuracy

2.2.1. Capacitor capacity combination. The capacitor combination of the device is as follows:

1) The capacitors of mutual compensation part is triangle connection, three phase capacitor switching at the same time, to provide basic reactive power demand for the load, the capacitors of split-phase compensation part operates separately according to the reactive load of each phase. Because the capacitance of mutual compensation part is connected to the line voltage, its compensation power is 3 times to which is applied phase voltage.

2) In split-phase compensation part, each phase has 3 capacitors, they are called \( C_k \) (k=1, 2, 4), their capacity ratio is 1:2:4, so they can realize the capacity combination of 1~7 levels, the capacitors of mutual compensation are called \( C_{\text{com}} \), which is divided into n parts, Each part has a capacity ratio of 1.

The capacity of each capacitor can be determined according to the combination proportion of the capacitors:

1) Suppose the total compensation capacity to be configured for each phase is \( Q_x \), and the weight sum of capacitor capacity is \((1 + 2 + 4 + 1n)\), the compensation capacity of the minimum capacitor can be calculated as

\[
Q_1 = \frac{Q_x}{1+2+4+1n+3}
\]

2) The capacity of the minimum capacitor is

\[
C_1 = \frac{Q_1}{2\pi f U_2}
\]

3) The capacity of split-phase compensation part and the capacity of the mutual compensation part can be determined according to the weight proportion.

According to the above capacity combination method, the compensation deviation can be controlled within \([\pm Q_{\text{min}}/2, Q_{\text{min}}/2]\). Suppose n=1, the minimum compensation capacity \( Q_{\text{min}} \) is 1 / 10 of \( Q_x \), and the compensation deviation is about ±5%. If the reactive load of each phase is large, the number of capacitor groups of the mutual compensation part can be increased.

2.2.2. Switching strategy. The switching strategy is:

1) During operation, if the reactive power of each phase is larger than the capacity of the mutual compensation part, the mutual compensation part shall be put into operation, and then the appropriate capacitance of the split-phase compensation part shall be put into each phase, and the power factor shall meet the requirements through voltage regulation.

2) During operation, if the reactive power of single-phase load is less than the capacity of the mutual compensation part, the capacitors of mutual compensation part shall be cut off, and then appropriate capacitance of the split-phase compensation part shall be put into each phase, and the power factor shall meet the requirements through voltage regulation.

3) In case of over/under compensation of reactive power due to load change, the voltage can be directly adjusted to make the power factor meet the requirements, or it can be resolved by cutting/switching the capacitor and adjust the voltage.
2.2.3. The method of continuous adjustment of compensation capacity. It can be seen from formula (2) that the capacitance power $Q$ is proportional to $U^2$, so the capacitor voltage can be changed to adjust the output of reactive power.

The continuous regulation device of split-phase compensation capacitors is composed of inverter and capacitor in series. Its single-phase topology is shown in Fig. 4, and the control block diagram is shown in Fig. 5.

Calculation formula of reactive power of capacitor is:

$$Q = 2\pi f C (|\dot{U}_s - \dot{U}_{VSD}|)^2$$  \hspace{1cm} (3)

Where $f$ is the frequency, $U_s$ is the phase voltage, $\dot{U}_{VSD}$ is the output voltage of the inverter, and the reactive power value can be adjusted by adjusting the voltage $\dot{U}_{VSD}$.

According to the difference of power factor, PWM duty cycle is calculated and the output voltage $\dot{U}_{VSD}$ is controlled. The reactive power can be changed by continuously adjusting $\dot{U}_{VSD}$, so as to change...
the potential difference between the two ends of the capacitor. When the phases both \( \dot{U}_S \) and \( \dot{U}_{VSD} \) are the same, the voltage difference between both ends of capacitor decreases and the reactive power generated decreases; when the phases both \( \dot{U}_S \) and \( \dot{U}_{VSD} \) are opposite, the voltage difference increases and the reactive power generated increases.

3. Controller of compensation device

The compensation device controller is shown in figure 6. The device includes a reactive power compensation controller, a switching control unit and a power regulating unit.

LPC1768 32-bit SCM is selected as the central processor of the reactive power compensation controller, the MSP430F149 microcontroller is selected as the switching control unit, and the adopts TMS320F2802 digital processor is selected as the inverter controller chip.

Figure 6. Schematic diagram of controller of reactive power compensation device

4. Control software design

4.1. Main process of reactive compensation control mode

When the compensation device is started, the lower limit value \( \cos \phi_A \) and the upper limit value \( \cos \phi_B \) of the power factor shall be set first, and the mark D of the capacitor shall be initialized (if the capacitor is not put into operation, D is 0, put into operation is 1). The controller shall collect the voltage and current data of the access point in real time, and calculate the active, reactive and power factor \( \cos \phi \). When the \( \cos \phi \) is lower than \( \cos \phi_A \), the capacitor connected sub process shall be executed, and appropriate amount of capacitance shall be connected according to the difference between \( \cos \phi_A \) and \( \cos \phi \), or (and) raise the capacitor voltage to make the power factor meet the requirements. When the reactive power is inverted \( (Q_s<0) \) after the capacitor is put into operation, the capacitor cut-off subprocess is started to reduce the compensation power; if the reactive power direction is positive \( (Q_s>0) \) and the power factor exceeds the upper limit \( \cos \phi_B \), the capacitor voltage is reduced to stabilize the power factor between \( \cos \phi_A \) and \( \cos \phi_B \). Reactive compensation control flow is shown in figure 7.
4.2. Capacitor switching control sub process

As shown in figure 8 (a), when power factor \( \cos \phi < \cos \phi_A \) and \( Q_s > 0 \), the compensation power needs to be increased to make \( \cos \phi \) rises to \( \cos \phi_A \). The capacitor connected sub process judge whether the mutual compensation part has been put into operation, and then judge either to put in split-phase compensation part or (and) raise the capacitor voltage to make the power factor meet the requirement.

As shown in figure 8 (b), when reactive power is inverted (\( Q_s < 0 \)), the compensation power needs to be reduced. The capacitor cut-off sub process judge whether to exit the mutual compensation part, and then judge either to exit capacitor of split-phase compensation part; or (and) reduce the capacitor voltage to make the power factor meet the requirement.
4.3. Dynamic regulation sub process of capacitor power

The device calculates the power and power factor \( \cos \phi \) by sampling the bus voltage and current value, calculates \( \cos \phi_A \cdot \cos \phi \) and \( \cos \phi - \cos \phi_B \), and decides to increase or decrease the output power of the capacitor according to the calculation result, and drives the inverter to change the output voltage, thus changes the capacitor compensation power, so that the power factor meets the set range. The regulation flow of capacitor output power is shown in figure 9.

(a) Capacitor sub process

(b) Capacitor cutting sub process

Figure 8. Capacitor switching control flow chart.
Initialize system
clock
Start
increase the voltage
and output power of
capacitor
Calculated power
and $\cos \phi$
$\cos \phi_A - \cos \phi^B > 0$ or not?
Yes
No
increase the voltage
and output power of
capacitor
$\cos \phi - \cos \phi^B > 0$ or not?
Yes
No
Reduce the voltage and
output power of
capacitor
End

Figure 9. Flow chart of capacitor output power regulation

5. Simulation verification
Matlab / Simulink platform is used to build the system model based on figure 1 and the control system model based on figure 4, and the examples of putting capacitor into operation, increasing the capacitor voltage and reducing the capacitor voltage are simulated respectively. The parameters involved in the examples are shown in Table 1.

Table 1. Simulation model parameters.

| The parameter                  | Parameter selection | The parameter                  | Parameter selection |
|--------------------------------|---------------------|--------------------------------|---------------------|
| Rated voltage of power supply  | 400                 | Filter capacitor              | 10μF                |
| Rated voltage of three-phase load | 380               | $\cos \phi_A, \cos \phi^B$    | 260                 |
| DC supply voltage              | 100V                | $k_p, k_i$                    | 0.737, 32.2349      |
| switching frequency            | 50 kHz              | Single phase minimum          | 5kVar               |
| Filter inductance              | 2mH                 | compensation capacity         |                     |

1) In the case of absence of reactive power, the device automatically connects the compensation capacitor and adjusts the capacitor voltage to increase the reactive power. The simulation scenario 1 is set: the initial active power of load is 50kW and the reactive power is 33kVar. The load power remains unchanged, and the device automatically adjusts the compensation power. Among them, the mutual compensation part is put into operation at 1.5s, and the compensation capacity is 15kVar. The simulation results are shown in figure 10:
From the simulation results in figure 10, it can be seen that:

The compensation device is not started before 1.5s, and the reactive power required by the load is completely provided by the power supply, resulting in a lower power factor. At 1.5s, the 15kVar compensation power is provided by the mutual compensation part, so that the power factor rises to 0.94. At 1.7s, split-phase compensation part put 10kVar capacitance in, and the power factor rises to 0.988. At 2s, the device automatically adjusts the capacitvoltage of split-phase compensation part, so that its peak voltage rises from 311V to 353V, the output power of the capacitor increases to 13kVar, and the power factor reaches 0.99.

2) The reduction of load power causes the power factor to cross the upper limit, and the device adjusts the capacitor voltage to reduce the reactive output. The simulation scenario 2 is set: At 3s, active power reduction to 43kW and reactive power reduction to 30kVar. At 4s, the active power is reduced to 36kW and the reactive power to 26kVar. The simulation results are shown in figure 11:
Variation curve of capacitor voltage of split-phase compensation part

Figure 11. Simulation results of scenario 2

It can be seen from figure 11 that after the reactive power of the load is reduced to 30kVar, the compensation device remains in the previous working state, and the power factor rises to 0.9965; because the power factor exceeds the upper limit value of 0.996, voltage regulating device is out of operation at 3.2s, and the power factor drops to 0.994. At 4s, reactive power of the load reduce to 26kVar, as can be seen from figure 11 (b), the power factor is larger than 0.996, therefore, the capacitor voltage of split-phase compensation part is reduced by the inverter, and the compensation power is reduced from 10.8kVar to 6.7kVar, and the power factor is reduced to 0.9957.

3) The change of load causes reactive power to be reversed. The device removes the capacitor and adjusts the voltage to make the power factor meet the requirements. The simulation scenario 3 is set: The active power of the load is 77kW, and the reactive power is 35kVar, and the capacitors of mutual compensation part and $C_1$, $C_2$ which belong to split-phase compensation part are put into operation. At 7.5s, active power and reactive power are reduced to 67kw and 27kVar respectively. The simulation results are shown in figure 12:

Figure 12. Simulation results of scenario 3

It can be seen from figure 12 that the load power is reduced at 7.5s, and the compensation power is larger than the reactive power of the load, resulting in a 2.8kVar reverse power, device automatically
cuts off the capacitor $C_1$, and no reverse power is generated, at this time, the power factor is 0.9995. At 7.9s, the device reduces the capacitor voltage, and the power factor is reduced to 0.9959.

6. Conclusion
The reactive power dynamic compensation device designed for low-voltage power grid can quickly and effectively reduce the energy loss and improve the quality of power supply.

1) By using the zero-crossing switching circuit and strategy, the switching response time of the capacitor is less than 100ms, and the inrush current and flashover arc are avoided.

2) The compensation capacity of reactive power can be adjusted continuously by voltage regulation, which can effectively stabilize the power factor, avoid switching oscillation of capacitor and expand the compensation range.

3) By changing the output of reactive power through voltage regulation, the switching times can be reduced and the service life of the switch can be improved.

4) The reactive power that changed by voltage regulation is less, the cost of voltage regulation device can be controlled.

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