Non-arc and non-interruption control scheme of phase commutation switch based on diode natural commutation

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Abstract. It is an effective way to balance three-phase loads by installing phase commutation switch (PCS) to automatically transfer single-phase load from heavy load phase to light load phase. A PCS with the circuit topology based on diode natural commutation is introduced. This PCS uses latching relay as switch element. The PCS control principle is studied under the ideal condition of three-phase voltage symmetry and pure resistance load. The influence of the load characteristics of the actual single-phase user and the three-phase voltage asymmetry on the PCS control is analyzed. Considering that the latching relay is not an ideal switch, the action parameters of the latching relay are tested. According to the actual situation of single-phase users and the batch test results of latching relays, a practical non-arc and non-interruption control scheme of the PCS is proposed. The control scheme is tested on a developed prototype of the PCS.

1. Introduction

Three-phase four-wire low-voltage distribution systems are widely used in residential and commercial areas, while the users are mostly single-phase load or single-phase and three-phase mixed load. The uneven distribution of single-phase load on three phases leads to three-phase current imbalance [1]. Single-phase loads need to be reallocated on three phases to rebalance. For the imbalance caused by the stable single-phase loads difference among the three phases, rebalancing can be realized by manually rewiring the connected phase of the single-phase load [2,3]. For those dynamic and random imbalance caused by the occasional fluctuation of single phase loads, the connected phase of the single-phase load can be automatically changed by installing the PCS [4-8].

The PCS may consist of a set of three identical switches connected to each of the three phases (figure 1 (a)). These switches can be mechanical switches, such as contactors used in [4]. It can also be an electronic switch composed of power electronic devices, such as bidirectional thyristors or two parallelized thyristors used in [1,5,6] (figure 1 (b)). It can also be a composite switch combined with a mechanical switch and an electronic switch. For example, in [7], it is formed by parallel connection of a mechanical switch and a bidirectional thyristor (figure 1 (c)). In [8], it is formed by parallel connection of a contactor and a branch of a relay series a diode (figure 1 (d)).

The mechanical switch has low conduction resistance with low dissipation power, but during the switching process arcs will be generated, mechanical contacts will be ablated, and short-term (<20ms) power interruptions will also occur. The electronic switch will not produce arcs during the switching
process and will only produce very short supply interruptions, but high conduction resistance lead to high dissipation power. Composite switch has the both merits of mechanical switch and electronic switch. It can realize non-arc switching through electronic switch and the power supply interruption time is very short or even no interruption. After the switching is completed, the mechanical switch is used with low on-resistance and low dissipation power.

![Figure 1. Circuit topology of PCS: (a) 3 mechanical switches; (b) 3 electronic switches; (c) 3 composite switches with bidirectional thyristors and mechanical switches; (d) 3 composite switches with diodes and mechanical switches](image)

The circuit topology of figure 1 (d) is adopted for the PCS in this paper. Unlike in [8], all mechanical switches use latching relays. The specific process of non-arc switching based on diode natural commutation used by the PCS is described. The influence of the single phase load characteristics of the actual single-phase user and the three-phase voltage asymmetry on the PCS control is also analyzed. Considering that the latching relay is not an ideal switch, the action parameters test of the latching relay is carried out and the results are given. According to the actual situation of single-phase users and the latching relays test results, a practical non-arc and non-interruption control scheme of the PCS is proposed. The control scheme is tested on a developed prototype of the PCS.

2. Control principle

2.1. Ideal phase commutation process

Ideally, A, B, C three-phase voltage is symmetrical, and the voltage waveform is shown in figure 2. Let the single phase user load be pure resistance. The ideal phase commutation process based on diode natural commutation is illustrated in Figure 3 with the example of switching from phase A to phase B.

1) Initial state: switch $K_{A1} K_{A2}$ closed (figure 3 (a))

The closed moment of switch $K_{A2}$ can be set at any time earlier than time $t_1$ as the initial state. There will be no arc during the switch $K_{A2}$ closing for the voltage drop of the switch $K_{A2}$ and diode $D_4$ series branch is nearly zero.

2) State: switch $K_{A1} K_{A2} K_{B2}$ closed (figure 3 (b))
The closed moment of switch $K_{B2}$ must be set later than time $t_1$ and earlier than time $t_3$ under the condition of phase A voltage higher than phase B, so that the short circuit between phase A and B will not happen. Also there will be no arc during the switch $K_{B2}$ closing for the current of the switch $K_{B2}$ and diode $D_B$ series branch is nearly zero as the diode $D_B$ is reversely cut off.

(3) State: switch $K_{A2}$ $K_{B2}$ closed (figure 3 (c))

The opened moment of switch $K_{A1}$ must be set later than the time of phase A current above zero which is also the time $t_2$ as the load is pure resistance, so that there will be no current interrupt and no arc will generate. The opened moment of switch $K_{A1}$ must also be set earlier than time $t_5$ so that the short circuit between phase A and B will not happen.

During this state, diode $D_A$ will be reversely cut off and diode $D_B$ will be conducted after time $t_3$ when the phase B voltage is higher than phase A. The connected phase of load will be switched from phase B to phase A without any control based on diode natural commutation. There will be no arc and no interruption during this process.

(4) State: switch $K_{A2}$ $K_{B2}$ $K_{B1}$ closed (figure 3 (d))

The closed moment of switch $K_{B1}$ must be set later than the time $t_3$ after the phase commutation completed, so that the short circuit between phase B and phase A will not happen. The closed moment of switch $K_{B1}$ must also be set earlier than the time of phase B current below zero which is also the time $t_4$ as the load is pure resistance. Also there will be no arc during the switch $K_{B1}$ closing for the voltage drop of the switch $K_{B2}$ and diode $D_B$ series branch is only a diode drop.

(5) State: switch $K_{B2}$ $K_{B1}$ closed (figure 3 (e))

The opened moment of switch $K_{A2}$ must be set later than the time $t_3$ after the phase commutation completed. This opened moment of switch $K_{A2}$ must also be set earlier than time $t_4$ under the condition of phase B voltage higher than phase A. So that the short circuit between phase B and phase A will not happen. Also there will be no arc during the switch $K_{A2}$ closing for the current of the switch $K_{A2}$ and diode $D_A$ series branch is nearly zero as the diode $D_A$ is reversely cut off.

(6) End state: switch $K_{B1}$ closed (figure 3 (a))

The opened moment of switch $K_{B2}$ can be set at any time after the switch $K_{B1}$ is closed and the switch $K_{A2}$ is opened. There will be no arc during the switch $K_{B2}$ opening for the voltage drop of the switch $K_{B2}$ and diode $D_B$ series branch is nearly zero.

From the above ideal phase commutation process, it can be found that there is no arc and no interruption for each switching.

It should be noted that for phase commutation of A-B, B-C, C-A there will be only one process based on diode natural commutation, but for B-A, C-B and A-C there will be two as B-C-A, C-A-B, A-B-C.

2.2. Practical situation influences

The above action moment of the PCS switch is based on the ideal situation. The actual single-phase load is not necessarily pure resistance. There may be some inductive load, or even non-linear load. The three phases of the user voltage in different positions of the low-voltage network are not necessarily symmetrical as shown in Figure 2. There may be amplitude deviation among three phase voltage. The above factors need to be taken into account for the action moment in the practical phase commutation process.

2.2.1. Load power factor influence. When the load power factor is not 1 and there exists some inductive (capacitive) load, the load current will lag behind (lead forward) the voltage. For the hybrid load composed of pure resistance and pure inductance (pure capacitance), the current lagging (leading) time can be obtained according to the power factor angle. For nonlinear loads, this lagging (leading) time is uncertain.

In order to avoid the influence of load power factor, taking A-B phase commutation as an example, the time $t_2$ $t_4$ should be delayed (advanced) with the lagging (leading) time of current behind voltage
caused by the power factor. So the opened moment of \( K_{A1} \) also should be delayed as to ensure no current interruption and no arc during the open process.

Figure 2. Waveform of symmetrical A(yellow), B(green), C(red) three-phase voltage

Figure 4. Action moment range of \( K_{B2} \), \( K_{A1} \), \( K_{B1} \), \( K_{A2} \)

2.2.2. Three phase voltage amplitude deviation influence. When there is amplitude deviation of three-phase voltage, the above time \( t_1, t_3, t_5 \) will change. When the amplitude of phase A voltage is less (greater) than phase B, the time \( t_1, t_3, t_5 \) will be advanced (delayed). So the closed moment of \( K_{B2} \) and the opened moment of \( K_{A1} \) \( K_{A2} \) will also change.

Figure 3. Ideal phase commutation example of A to B: (a) \( K_{A1} K_{A2} \) closed; (b) \( K_{A1} K_{A2} K_{B2} \) closed; (c) \( K_{A2} K_{B2} \) closed; (d) \( K_{A2} K_{B2} K_{B1} \) closed; (e) \( K_{B2} K_{B1} \) closed; (f) \( K_{B1} \) closed;

2.3. Action moment range of the PCS switches

Based on the above analysis, taking A-B commutation process as the example, for the action moment of \( K_{B2} \) and \( K_{A1} \), time \( t_1, t_2 \) needs to be postponed to \( t_1^d, t_2^d \), time \( t_3 \) needs to be advanced to \( t_3^a \); for the action moment of \( K_{B1} \) and \( K_{A2} \), time \( t_3 \) needs to be postponed to \( t_3^d \), and time \( t_4, t_5 \) needs to be advanced.
3. Practical control scheme

3.1. Action parameters of the latching relay

The above analysis gives the PCS switches action moments. However, the latching relay used in the PCS is not ideal switch. There is a time delay between the driving dc voltage applied on the magnetizing coil of a latching relay and the true closed and opened moment of the relay, noted as closed delay $t_{cd}$ and opened delay $t_{od}$. The closed delay and opened delay are not constant and have a certain variation range for the same relay. The practical control scheme of the PCS must take account of the latching relay action parameters.

We carried out a batch test of 68 latching relays, 300 times opening and closing for each relay. The minimum, maximum and variation (maximum minus minimum) of opened delay and closed delay are obtained. The statistical results are given in figure 5.

Figure 5(a) shows the cumulative probability of opened delay minimum and maximum in light blue and red. They are close to the fitted normal distribution in blue and red. The situation of figure 5(c) is nearly the same. Compared with the switch closed and opened moment range in figure 4, the range of closed delay is very large which is about 4–16 ms and the range of opened delay is also large which is about 3–9 ms. But the maximums of closed delay and opened delay variation are relative small which are 2.5 ms and 1 ms respectively as shown in figure 5(b) and (d).
3.2. Practical control scheme
To open or close the relay at a specified moment, the relay must be driven in advance according to the open delay or closed delay. To ensure that the opened and closed moment of the relay can fall within the allowable range as shown in Figure 4, the variation range of the opened delay $t_o^d$ and closed delay $t_c^d$ of the relay shall meet the following conditions:

\[
\max[t_o^d] - \min[t_o^d] < t_3^a - t_2^d \\
\max[t_c^d] - \min[t_c^d] < t_4^a - t_3^d
\] (1)

According to the previous test results in figure 5 (b) and (d), the maximum change range of relay opened and closed delay is around 2.5ms, while the minimum allowable range of relay opened and closed moment in figure 4 is around 5ms for 50Hz system. Almost all relays can meet this requirement.

According to the previous test results in figure 5 (a) and (c), the relay opened and closed delay are widely dispersed and shall be tested and recorded for each relay. The opening and closing driving advance time, $t_{o\_drv}^a$ and $t_{c\_drv}^a$, of each relay shall be set individually as:

\[
t_{o\_drv}^a = (\max[t_o^d] + \min[t_o^d]) / 2
\] (3)

\[
t_{c\_drv}^a = (\max[t_c^d] + \min[t_c^d]) / 2
\] (4)

The target opened and closed moment of relay, $t_o$ and $t_c$, shall be set to the middle value of the allowable range as shown in Figure 4, so that the relay opened moment $t_o$ and closed $t_c$ moment can have the maximum safety margin:

\[
t_o = (t_2^d + t_3^a) / 2
\] (5)

\[
t_c = (t_3^d + t_4^a) / 2
\] (6)

In order to realize the non-arc and non-interruption phase commutation for the PCS finally, the opening and closing driving moment, $t_{o\_drv}$ and $t_{c\_drv}$, of relay shall be set according to the $t_{o\_drv}^a$, $t_{c\_drv}^a$ and $t_o$, $t_c$:

\[
t_{o\_drv} = t_o - t_{o\_drv}^a
\] (7)

\[
t_{c\_drv} = t_c - t_{c\_drv}^a
\] (8)

The above control scheme is for the phase commutation from phase A to phase B. Other phase commutation mode can be derived similarly.

3.3. Prototype and test result
We developed a prototype of the PCS using the above principles as shown in figure 6. The 6 relays used in the PCS are all tested to get the action parameters. The driving moments of 6 relays are set according to the above control scheme. We carried out a lot of phase commutation tests on the prototype. The phase commutation process is non-arc and non-interruption as shown in figure 7.
4. Conclusion

A non-arc and non-interruption control scheme of the PCS adopted the circuit topology based on diode natural commutation was proposed in this paper. Considering the variable power factor and three-phase voltage asymmetry, the opened and closed moment of each latching relay in PCS was advanced or delayed based on the ideal moment. According to the opened delay and closed delay test results of each relay, the opening or closing driving delay of each relay was also calculated. The final opening or closing driving moment of each relay in the control scheme was calculated as the minus of the opened or closed moment and opening or closing driving delay. The tests carried out on the developed PCS prototype validated that the control scheme achieved the goal of non-arc and non-interruption phase commutation successfully.

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