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A Novel Strategy for Reducing Inrush Current of Three Phase Transformer Considering Residual Flux

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***Abstract*—Proper use of phase-controlled switching technology by controlling the making or breaking of the circuit breaker at predetermined phase angles of current or voltage can improve the service life of the circuit breaker (CB), avoid relay protection device from mal-operation and reduce the impact on the power grid when power equipment or load are energized or taken out. This paper proposes a novel phase-controlled switching method to address the influence of residual flux for three-phase wye winding unloaded transformers with three limbs, such as large capacitor variable frequency transformer or mine explosion-proof transformer. The optimal operation phase angle for CBs is firstly obtained via theoretical analysis. A model based on the alternative transients program/the electromagnetic transients program (ATP/EMTP) is then built to simulate the transient procedure of a power transformer during breaking and making. The simulated results confirm that the proposed switching strategy can reduce the excitation inrush current effectively when the unloaded transformers are energized. The experimental results reported in this paper are used to validate the accuracy and effectiveness of the phase-controlled switching strategy.**

***Index Terms*—Inrush current, permanent magnet actuator, phase-controlled switching strategy, residual flux, unloaded transformer.**

I. INTRODUCTION

WITH the rapid expansion of power systems, the operators are becoming increasingly concerned when energizing large transformers due to the inrush current which causes the circuit breaker (CB) to mal-operate. Currently, an idle transformer is switched on at random phase angle. Statistically, the steady-state exciting current is usually around 3%~8% of its rated current for an unloaded transformer, but for the large capacitor transformer, the steady-state exciting current is even less than 1%, however the inrush current may reach as high as eight times of its rated value when the unloaded transformer is switched on due to the saturation of its iron core. The inrush current will give rise to many adverse effects, such as shortening the lifetime of transformers [1], affecting the power quality [2] and resulting in mal-operation of over current protection devices.

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Much research was conducted to avoid the mal-operation of protection devices when an unloaded transformer is being energized. Most traditional studies focused on the identification of inrush current and fault current by extracting the feature of current [3][4]. Some algorithms were proposed to identify fault current by calculating the excitation inductance [5]. Generalized simulated annealing algorithm was used to train artificial neural network for educational purposes [6]. Some components, such as compensators, voltage compensation-type inrush current limiter and direct current (DC) reactor-type inrush current limiter, were proposed to reduce the inrush current [7]-[11]. However, the effect of those research is only limited to reduce the inrush current. Measures for inrush current mitigation using series voltage-source PWM converter, acting as a dynamic resistance, for three-phase transformer were proposed when switching the transformer on [12]. Although the method can reduce the inrush current of unloaded transformer considerably while requiring no information of the transformer, amount of residual flux, phase angle and so on, it cannot diminish the harmonic components. Though the fundamental, the second, the third and the DC components are reduced in the inrush current using PWM converters and the like, the proportion of harmonics is still large. Another scheme is to limit the inrush current by changing the distribution of coil windings to increase the transient inductance, which is sometimes known as the inrush equivalent inductance [13]. With this method it is necessary to change the design of transformer, because the transient inductance is affected by the structural parameters. If proper strategy is taken, the control of CBs can limit the inrush current effectively [14]-[16]. In fact, the research on controlling CB was firstly proposed and realized on single-phase transformers [17]-[19]. Subsequently, this technology was extended to three-phase transformers. Some useful strategies were proposed by, for instance, the incorporation of rapid closing switching strategy, delayed closing strategy and simultaneous closing switching strategy [20][21]. The aim of these strategies was to close each winding when the prospective flux is equal to dynamic core flux, which resulted in an optimal energization, without iron core saturation or inrush transient. However, these three strategies only considered the unloaded transformer with certain winding connection mode. A universal method was reported and realized by determining the operation range of making and breaking CBs via analyzing maps of inrush currents in the three phases. However, the maps have to be drawn from 400 simulations for each winding configuration of unloaded transformers, because the making and breaking time of CBs have a range of 0-20 ms with a resolution of 1 ms [22]. Such method is independent of the winding configuration but is influenced by the transformer itself. Actually, the power grid uses a large number of transformers of different design, which means one needs a large number of sophisticated simulations before this method can be implemented.

In order to reduce the impact of inrush current on power grid as far as possible, it is necessary to choose different switching strategies according to different transformer winding connections. However, from the aforementioned description, the majority of current researches are focusing on the unloaded transformer with Y connection and a grounded neutral on the primary side. This paper studies a three-limb core unloaded transformer with Y connection and ungrounded neutral point. The results of simulation via the alternative transients program/the electromagnetic transients program (ATP/EMTP) and experiment confirm that the proposed switching method can reduce the inrush current significantly when energizing the unloaded transformers.

II. Inrush Current and Phase-Controlled Switching Technology

For the unloaded single-phase transformer, the current in the primary side is equal to the exciting current while the secondary side has no current. When t=0, a voltage named u is given to the primary side of the unloaded transformer. Hence, the equation [23] of the primary side is

$$i_1 r_1 + N_1 \frac{d\Phi}{dt} = U_m \sin(\omega t + \alpha) \tag{1}$$

where i_1 and r_1 are the exciting current and equivalent resistance of the transformer primary side; Φ and N_1 are, respectively, the magnetic flux and coil number of the winding of primary edge; U_m and α are peak value and initial phase angle of the voltage, respectively. Eq. (1) is a nonlinear differential equation due to the saturation of transformer core. Since i_1 is small, the first item is much smaller than the second one. If saturation is ignored, i_1 can be expressed

$$i_1 = \frac{N_1}{L_1}\Phi \tag{2}$$

Substituting (2) into (1):

$$\frac{d\Phi}{dt} + \frac{r_1}{L_1}\Phi = \frac{U_m}{N_1}\sin(\omega t + \alpha) \tag{3}$$

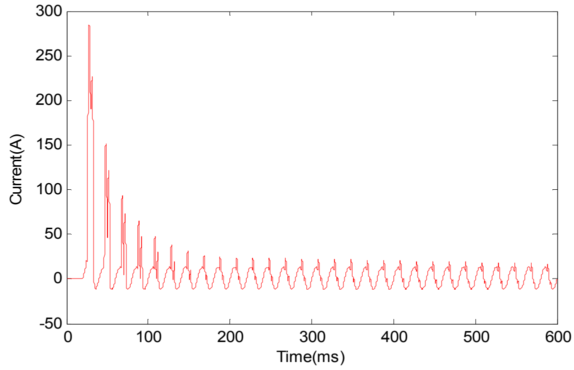
The magnetic flux can be obtained by solving (3) and assuming the initial value of magnetic flux is zero.

$$\begin{cases} \Phi = \Phi_m \sin\left(\omega t + \alpha - \arctan\dfrac{\omega L_1}{r_1}\right) - \Phi_m \sin\left(\alpha - \arctan\dfrac{\omega L_1}{r_1}\right)\cdot e^{-\frac{r_1}{L_1}t} \\ \Phi_m = \dfrac{L_1}{N_1}\dfrac{U_m}{\sqrt{r_1^2 + (\omega L_1)^2}} \end{cases} \tag{4}$$

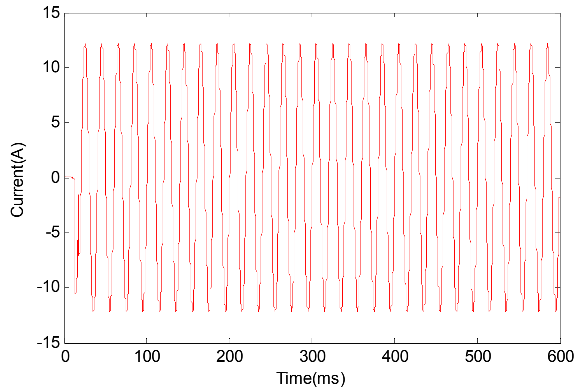
Since $r_1 << \omega L_1$ and $\arctan\frac{\omega L_1}{r_1} \approx 90^\circ$, the magnetic flux can be written as

$$\Phi = -\Phi_m \cos(\omega t + \alpha) + \Phi_m \cos\alpha \cdot e^{-\frac{r_1}{L_1}t} \tag{5}$$

From the equations above, it is easy to know that the value of inrush current is closely related to the initial phase angle of the applied voltage. If $\alpha = 0^\circ$, the magnetic flux will be expressed as $\Phi = -\Phi_m \cos(\omega t) + \Phi_m \cos\alpha \cdot e^{-\frac{r_1}{L_1}t}$. When $t = \frac{\pi}{\omega}$, the inrush current reaches the maximum value, which is nearly twice as large as Φ_m. At this time, the unloaded transformer is highly saturated and its inrush current is about 5-10 times of the rated current, and the simulation result is as shown in Fig. 1(a). If $\alpha = 90^\circ$, one can get $\Phi = \Phi_m \sin(\omega t)$. The magnetic flux in the transformer core will go straight into steady state from the beginning without transient, and the simulation result is as shown in Fig. 1(b).



(a)



(b)

Fig.1. Waveform of current when making at different phase angle, (a) $\alpha = 0^\circ$, (b) $\alpha = 90^\circ$.

Fig. 2 shows the principle of the phase-controlled switching algorithm [24]. When the control system receives the closing command, the switch angle α is firstly found, The first zero-cross point of the grid voltage before the arrival of closing command is taken as the reference point. The delay time which is necessary to close CB can be calculated according to the operation timing characteristics of the CB. The closing drive signal is then sent out when the delay time is reached. In this way the CB can be closed at the predetermined phase angle.

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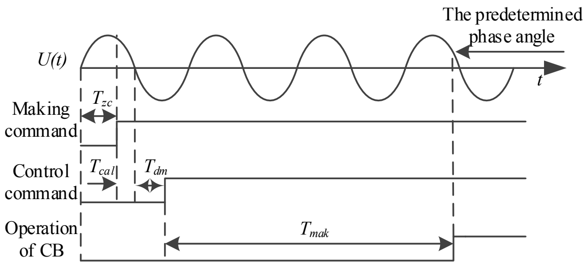

Fig. 2. the process of phase-controlled switching technology.

where T_{zc} is the period of time between the first zero-cross point of the gird voltage before the arrival of the close command; T_{cal} is the computing time needed by CPU; T_{dm} is the delay time; T_{mak} is the making time of CB's permanent magnet actuator (PMA) [25]-[29].

III. Phase-Controlled Switching Strategy of Unloaded Transformer When Considering the Influence of Residual Flux

The phase control strategy is considered when the transformer is operating under no load according to the actual case. Currently, the residual flux is not fully addressed for phase-controlled switching algorithm. In order to reduce the inrush current, the qualitative condition of the residual flux of unloaded transformer should be taken into account.

Fig. 3 shows the unloaded three-phase transformer with Y connection and the neutral point ungrounded, while in [20], the simulation model consists of three single-phase transformers unlike our three-limb core transformer. r_a, r_b, r_c are the equivalent resistances of the unloaded transformer and L_a, L_b, L_c are the equivalent inductances. The breaking process can be described in the following two steps when the impact of asymmetry of magnetic circuits is considered: 1) CB B opens when its current reaches the zero-cross point; 2) CBs A and C open simultaneously when their currents reach the zero-cross point.

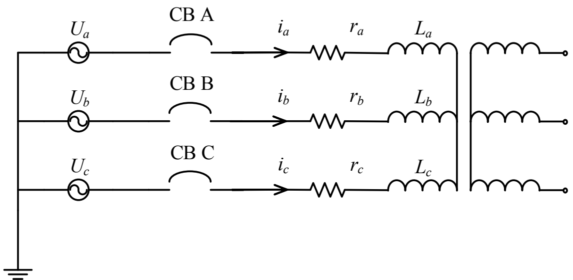

Fig. 3 Circuit model of unloaded three-phase transformer.

Supposing the phase angle of U_b is α when CB B is opened, the relationship between phases A and C satisfies:

$$\begin{cases} i_a r_a - i_c r_c + N\dfrac{d\Phi_a}{dt} - N\dfrac{d\Phi_c}{dt} \\ \qquad = U_m \sin\left(\omega t + \dfrac{2}{3}\pi + \alpha\right) - U_m \sin\left(\omega t - \dfrac{2}{3}\pi + \alpha\right) \\ i_c = -i_a \end{cases} \tag{6}$$

Since i_a and i_c are small, they can also be written as

$$\begin{cases} i_a = N\dfrac{\Phi_a}{L_a} \\ i_c = N\dfrac{\Phi_c}{L_c} \end{cases} \tag{7}$$

The magnetic flux can be obtained by solving (6) and (7).

$$\begin{cases} \Phi_a = \dfrac{L_a}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\cos\left(\omega t + \dfrac{\pi}{2} + \alpha + \beta\right) \\ \qquad + c_a e^{-\frac{r_a+r_c}{L_a+L_c}t} \\ \beta = \arctan\dfrac{r_a+r_c}{\omega(L_a+L_c)} \end{cases} \tag{8}$$

The coefficient c_a is determined by the initial value of the magnetic flux of phase A. Since $r_a << \omega L_a$ and $r_c << \omega L_c$, it can be shown that $\beta \approx 0^\circ$. Thus, the magnetic flux of phases A and C can be described as

$$\begin{cases} \Phi_a = \dfrac{L_a}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\sin(\omega t+\alpha) \\ \qquad + c_a e^{-\frac{r_a+r_c}{L_a+L_c}t} \\ \Phi_c = -\dfrac{L_c}{L_a}\Phi_a \\ \quad = -\dfrac{L_c}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\sin(\omega t+\alpha) \\ \qquad + c_c e^{-\frac{r_a+r_c}{L_a+L_c}t} \end{cases} \tag{9}$$

where the coefficients c_a and c_c, which are obtained by the magnetic flux value of phase B at the open time of CB B, determine the difference between phases A and C. It can be seen from (9) that the magnetic flux of phases A and C are equal and opposite when they are in steady state. After entering steady state, phases A and C are opened when their current reaches the zero-cross point, assuming the phase angle of U_a is γ, the value of the residual flux of three phase can be written as

$$\begin{cases} \Phi_{ar} = \dfrac{L_a}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\sin\left(\gamma - \dfrac{2}{3}\pi\right) \\ \Phi_{br} = 0 \\ \Phi_{cr} = -\dfrac{L_c}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\sin\left(\gamma - \dfrac{2}{3}\pi\right) \end{cases} \tag{10}$$

The making process includes two steps. Firstly, CBs A and C are closed at the phase angles which are equal to their open phase angles; secondly, CB B is closed when the voltage between power source and the neutral point reaches its peak. The reasons of phase-controlled strategy are described in details as follows. If the phase angle of U_a is η when CBs A and C are closed, the relationship between phases A and C can be written

$$\begin{cases} i_a r_a - i_c r_c + N\dfrac{d\Phi_a}{dt} - N\dfrac{d\Phi_c}{dt} \\ \quad = U_m \sin(\omega t + \eta) - U_m \sin\left(\omega t + \dfrac{2}{3}\pi + \eta\right) \\ i_a = -i_c \end{cases} \tag{11}$$

By solving (11), one can have

$$\begin{cases} \Phi_a = -\dfrac{L_a}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\cos\left(\omega t - \dfrac{\pi}{6} + \eta\right) \\ \quad + c_a^{'} e^{-\frac{r_a+r_c}{L_a+L_c}t} \\ \Phi_c = -\dfrac{L_c}{L_a}\Phi_a = \dfrac{L_c}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\cos\left(\omega t - \dfrac{\pi}{6} + \eta\right) \\ \quad + c_c^{'} e^{-\frac{r_a+r_c}{L_a+L_c}t} \end{cases} \tag{12}$$

When t=0, the flux values of phases A and C are equal to the values of Φ_{ar} and Φ_{cr} as written in (10). Applying this initial condition to (12), $c_a^{'}$ and $c_c^{'}$ can be expressed as

$$\begin{cases} c_a^{'} = \dfrac{L_a}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\left(\sin\left(\gamma-\dfrac{2}{3}\pi\right)+\cos\left(\eta-\dfrac{\pi}{6}\right)\right) \\ \quad = \dfrac{L_a}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\left(\sin\left(\gamma-\dfrac{2}{3}\pi\right)-\sin\left(\eta-\dfrac{2}{3}\pi\right)\right) \\ c_c^{'} = -\dfrac{L_c}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\left(\sin\left(\gamma-\dfrac{2}{3}\pi\right)+\cos\left(\eta-\dfrac{\pi}{6}\right)\right) \\ \quad = -\dfrac{L_c}{N}\dfrac{\sqrt{3}U_m}{\sqrt{(r_a+r_c)^2+\omega^2(L_a+L_c)^2}}\left(\sin\left(\gamma-\dfrac{2}{3}\pi\right)-\sin\left(\eta-\dfrac{2}{3}\pi\right)\right) \end{cases} \tag{13}$$

According to (13), $c_a^{'}$ and $c_c^{'}$ will be zero when $\eta=\gamma$. It means that if the CBs A and C are closed at the phase angle which is the same as the breaking phase angle, the flux will enter steady state from the beginning without transient, which means that the inrush current is significantly reduced. In other words, this strategy can decrease the inrush current in the making process without measuring the numerical flux values of phases A and C after the breaking process.

After the closing of CBs A and C, the voltage of the neutral point is not equal to zero with reference to the ground as shown in Fig. 4. The voltage of neutral point can be expressed

$$\dot{U}_n = \frac{1}{2}\left(\dot{U}_a - \dot{U}_c\right) + \dot{U}_c = \frac{1}{2}\left(\dot{U}_a + \dot{U}_c\right) \tag{14}$$

From the expression above, the phase angle of the neutral point is opposite to that of phase B. By using a similar strategy which is used in single-phase transformer without residual flux, CB B should be closed at the time that the voltage between the power source and the neutral point, which is equal to $3\dot{U}_b/2$, reaches the peak value [20].

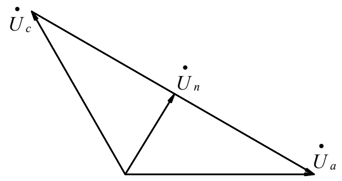

Fig. 4. Vector diagram after the making of CBs A and C.

where $\dot{U}_n$ is the voltage of the neutral point of the unloaded transformer.

Therefore, if the three-limb transformer with Y connection is at no load and the neutral point on the primary side is ungrounded, CB B is firstly opened at the time when its current reaches zero; then CBs A and C are switched off when their currents reach the zero-cross point at the same time. As similar to the breaking method, the phase-controlled switching strategy of unloaded transformer can be described as having CBs A and C being closed when their phase angles are equal to the angles of their last breaking. Then CB B is closed when the voltage between the power source and the neutral point reaches the peak value.

In reality, there can be current chopping and there is parasitic capacitance which leads to residual flux values anywhere from 0-0.85pu [20]. For the phase-controlled switching strategy proposed in this paper, the current is chopped at phase angle of zero which has nearly no effect on the determination of phase angle. Parasitic capacitance will result in harmonic current which can be divided into fundamental and harmonic sine waveform. Theoretical analysis based on fundamental sine waveform shows that the determined flux value is not needed and flux enters steady state without transient process with the proposed phase-controlled strategy. The above analysis is adapted to harmonic sine waveform. Therefore, in spite of parasitic capacitance, flux enters steady state without transient process and inrush current will be obviously reduced.

IV. Simulation and Experiment

A. Results of Simulation

An unloaded three-phase transformer model is established using ATP/EMTP software as shown in Fig. 5. This simulation model mainly has four parts: power source, two three-phase switches, unloaded transformer and detection of flux linkage. The line voltage of the power source is 6kV. The unloaded transformer has Y connection on the primary side and its neutral point is ungrounded [30]-[32]. In Fig. 5, three capacitances C_hg, C_lg and C_hl are used to simulate the distributed capacitances, and three nonlinear inductances in which the data of saturation hysteresis loop can be set are used to simulate the hysteresis effect of the iron core [33]-[35]. Flux linkage of the three phases for detection of flux linkage can be obtained by integrating the voltage of the secondary winding of the transformer, as flux linkage and voltage satisfy the expression $e_2 = -\dfrac{d\psi}{dt}$. Figs. 6-8 show the simulation results according to the proposed phase-controlled switching strategy.

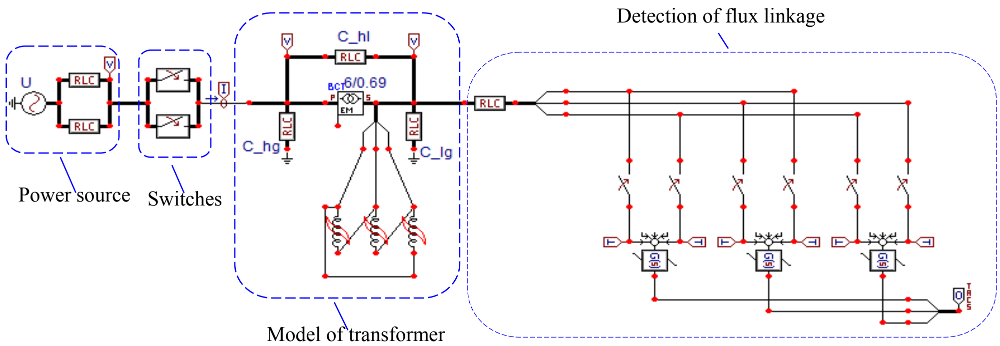

Fig. 5. ATP/EMTP model to test the phase-controlled switching strategy.

As shown in Fig. 6, when the unloaded transformer is applied with unbalanced voltage sources, such as the time after the open operation of CB B when breaking and the open operation of CBs A and C when making, the phase voltage B is equal to the voltage of the neutral point instead of zero. When the open operation of CBs is completed, U_a, U_b and U_c have the same value, which is equal to the voltage of the neutral point at the time when CBs A and C are open.

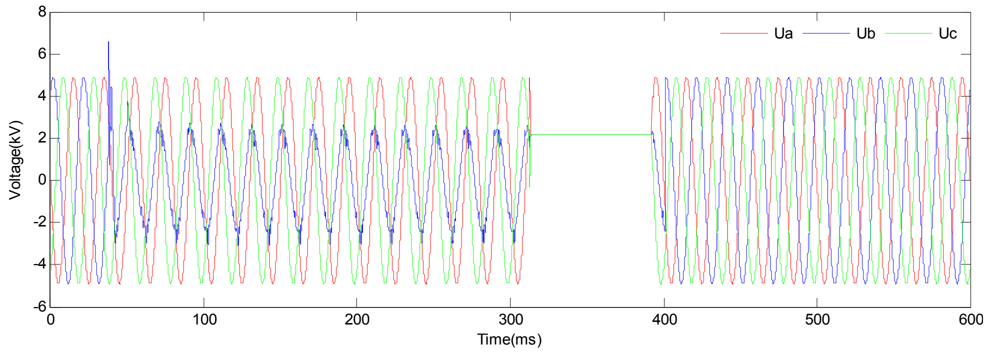

Fig. 6 Phase voltage of the primary side of transformer.

As shown in Fig. 7, after CB B is switched off, the attenuation items become small as time goes by, which is agree with (9). After a period of time, the flux linkage of phase B is near to zero, and $\Phi_a \approx -\Phi_c$. Then, when the currents of phases A and C reach zero, CBs A and C are switched off and the value of the magnetic flux flowing through them will remain constant (A is about -0.83 p.u., B is about 0.08 p.u., C is about 0.75 p.u.). Though the magnetic flux of phases A, B and C doesn't reach steady-state completely, as addressed in (10), the aforementioned strategy can still be adopted because the imbalance of residual flux between phases A and C is very small. The simulation result indicates that comparing with the steady state of magnetic fluxes before breaking, there are small differences in the magnetic fluxes of the three phases after making.

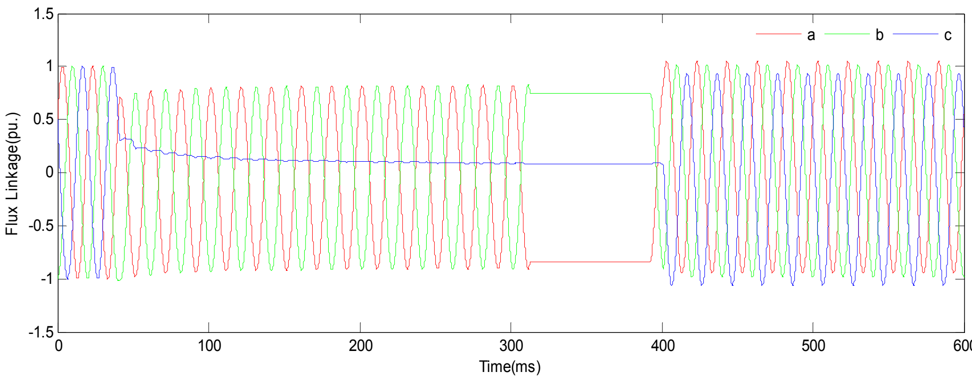

Fig. 7. The transient process of flux linkage.

Fig. 8 shows the currents of three phases which correspond to the time of Fig. 7. After the making transient has settled down, the amplitude of currents is slightly higher than that before breaking, and the inrush current has been obviously eliminated with the proposed strategy.

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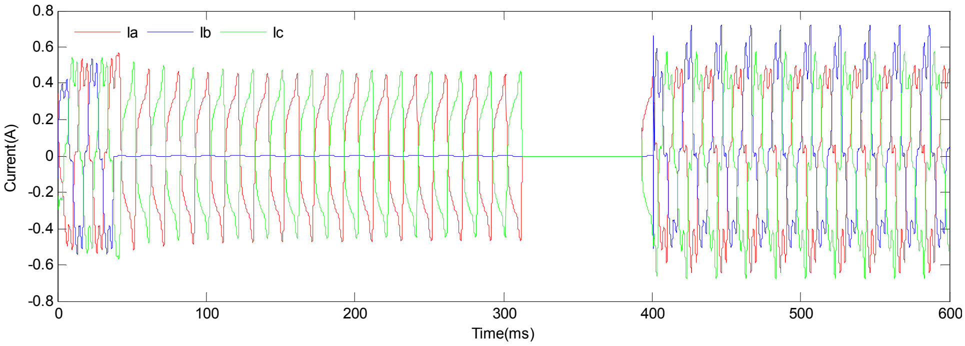
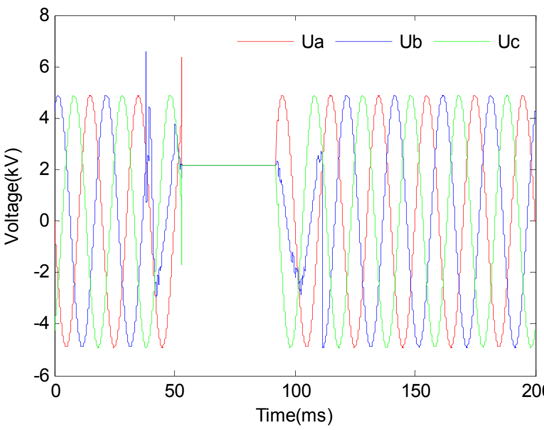


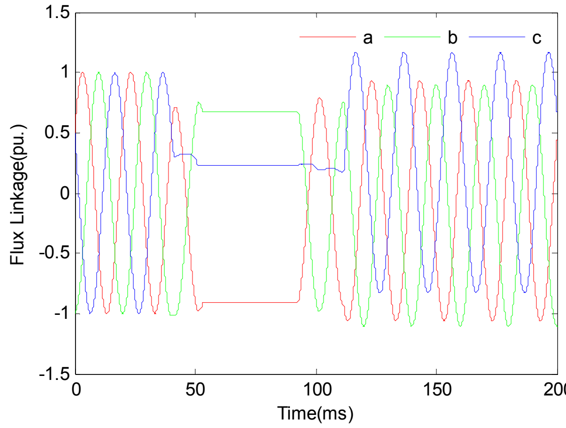
Fig. 8 Current in the primary side of the unloaded transformer.

What is worth mentioning is that it is not reasonable for CBs A and C to open after their magnetic fluxes have reached steady-state in the breaking process, because it is difficult to know whether the transient process has completely settled down without using special equipment to measure, and more importantly, it is not practical to wait a long period while the transformer is working with imbalanced voltages. The delay time between the open operation of CBs B and A, C is supposed to be shortened. This behavior will give rise to a bigger difference in the residual fluxes between phases A and C than that obtained in the simulation as reported above. However, the control strategy obtained from theory is being implemented here when shortening the delay time, since it's hard to obtain the accurate values of magnetic fluxes when adjusting the phase angle to close the CBs. In other words, it is necessary to ignore the difference in residual fluxes in order to simplify the control strategy, that is, the shortening of breaking time of phases A and C will let phase B flux value above-nominal. The adjustment of operation time of the three CBs has been made in the simulation and the results are as follows.

Fig. 9 shows that the residual flux values of the three phases are -0.9 p.u., 0.23 p.u., 0.67 p.u. respectively, and the maximum inrush current is about four times as big as the steady current before the breaking operation. Although the inrush current is higher than that in Fig. 8, the proposed phase-controlled switching strategy can obviously reduce the inrush current.



(a)



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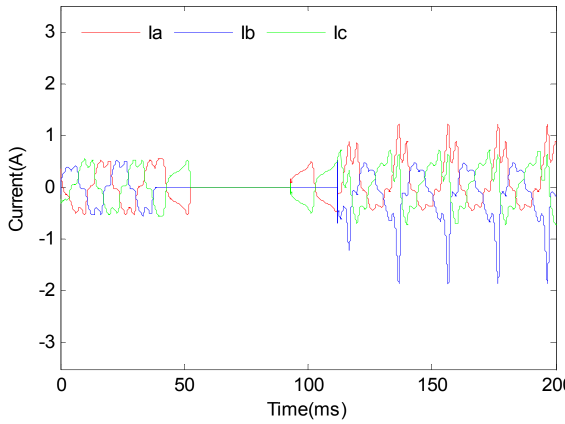


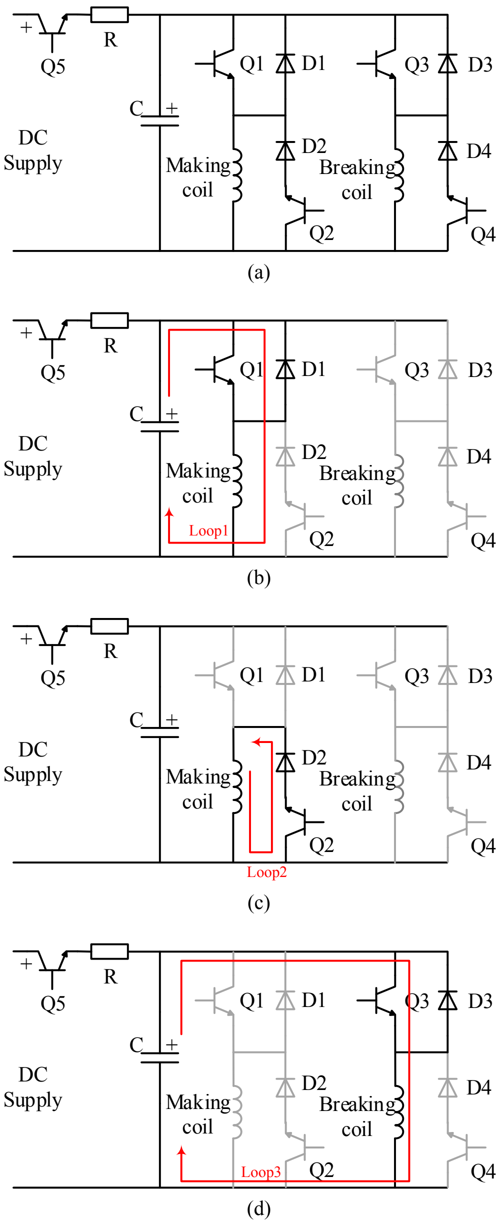
(c)

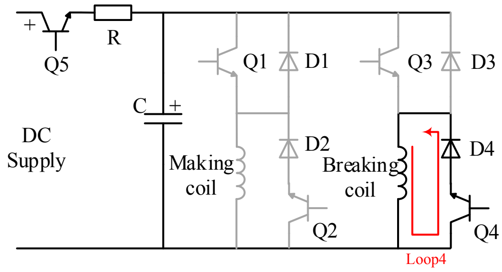
Fig. 9. Simulation results after shortening the delay time (a) Phase voltage of the primary side of transformer (b) the transient process of flux linkage (c) current in the primary side of the unloaded transformer.

B. Control System

In the control system, PMA is employed to realize the making and breaking procedures. Fig. 10(a) shows the control topology unit to excite the PMA to switch the circuit breaker on or off. Q1-Q5 are insulated gate bipolar transistors which are used to switch on or off the main circuit. Q5 and R charge the capacitor C up to its rated voltage. Q1 and Q3 are the main switches for the making circuit and breaking circuit, respectively. D1 and D3 are the corresponding protection diodes for Q1 and Q3. When making, Q1 is turned on and Q3 is turned off, current flows through loop1 which composes of capacitor C, Q1 and the making coil as shown in Fig. 10(b).

Before the making procedure, Q4 is turned off so as to stop the induced current in the breaking coil; while during the making procedure, Q2 is turned on and Q2, D2 and the making coil are forming a flywheel loop2 as shown in Fig.10(c) when Q1 is turned off at the end of the making procedure. D1-D4 are the flywheel diodes. The breaking procedure is similar to the making one. When breaking, Q3 is turned on and Q1 is turned off, current flows through loop3 which composes of capacitor C, Q3 and the breaking coil as shown in Fig. 10(d). Q2 is turned off before breaking so as not to induce current in the making coil. During the breaking procedure, Q2 is turned on and the breaking coil, Q4, and D4 can form a flywheel loop4 as shown in Fig. 10(e) when Q3 is turned off at the end of the breaking procedure.





(e)

Fig. 10. Control principle. (a) Control topology unit, (b) Making procedure and (c) flywheel loop of making coil, (d) Breaking procedure and (e) flywheel loop of breaking coil.

Fig. 11 shows the hardware platform that includes the control unit and drive unit, which is established based on DSP. The control unit is mainly composing of the processor chip TMS320F2812, power, watchdog, external memory, communication, data sampling, and remote control; the drive unit contains the charging circuit of capacitor, current transformer (CT), potential transformer (PT), detection circuit of zero-cross point, which can monitor and record the current flowing into the transformer and the voltage of the power source, and so on. As shown in Fig. 12, the software system mainly consists of two parts: one is the operation process during which the control system receives the making or breaking command; the other is the operation process when the control system is in normal service.

After the experiment platform is powered on, the software system firstly initializes the related parts, including the I/O interface, registers, external memory, etc. Subsequently, the data sampling module is triggered to process the information of voltage and current of the power grid. The next step has: 1) if there is no command of making or breaking, the data processing program comes into work according to the information from the state recognition and then the results are displayed in the master computer, 2) When receiving breaking command, the current detection circuits captures the zero point of current to trigger the breaking of circuit breakers, and the voltage detection circuits record the voltage value of three phase. In this condition, the delay time is defaulted to zero. When receiving the making command, the voltage detection circuits capture the zero point of voltage to trigger the interrupt program, and the circuit breakers are switched on after a delay time, which is calculated according to the recorded voltage value in the breaking process. The result of operation is displayed in the master computer and subsequently the program returns to the address of data sampling.

C. Experimental Setup and Results

Fig. 13 shows the experimental setup which includes three drive units, a three control unit, a CB equipped with PMA, capacitors, an unloaded transformer with a rated voltage of 6kV/0.69kV and a capacity of 630kVA, three CTs and a three-phase PT. Three clip-on ammeters are used to measure the CT current and an oscilloscope is used to display the current waveform. The PT measures the voltage waveform to be used to identify the phase angle. As highlighted in Fig. 13, the test

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place includes two areas: the high voltage area and the low voltage area due to safety consideration.

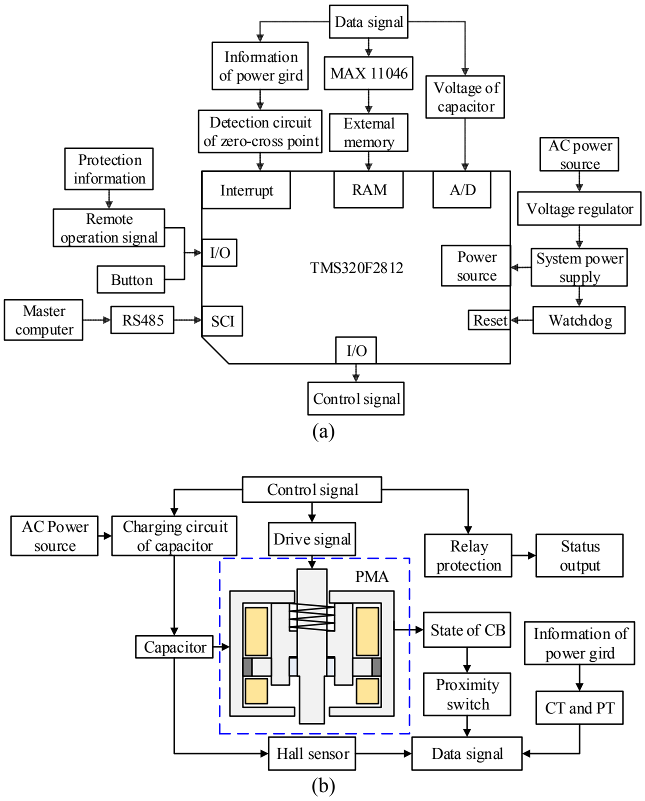


Fig. 11. Platform of hardware circuit. (a) Control unit, (b) drive unit.

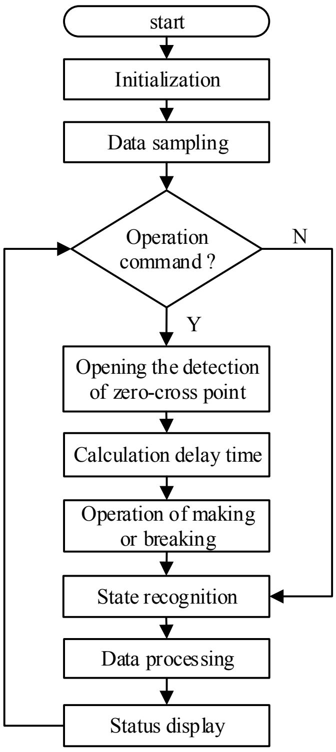


Fig. 12. The main program flow chart of software system.

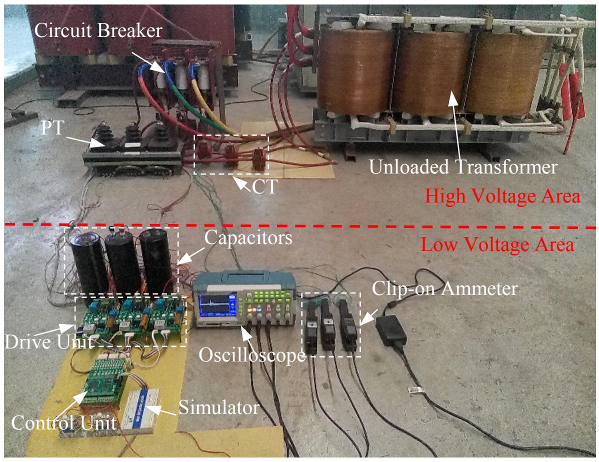


Fig. 13. Experimental setup.

Fig. 14 shows the experimental results without phase-controlled strategy. The maximum of the inrush currents of the three phases is about 60A when the three phases CBs are closed randomly and simultaneously. In the worst case, the inrush currents will be higher than the value displayed in Fig. 14, which may result in mal-operation of the over current protection device.

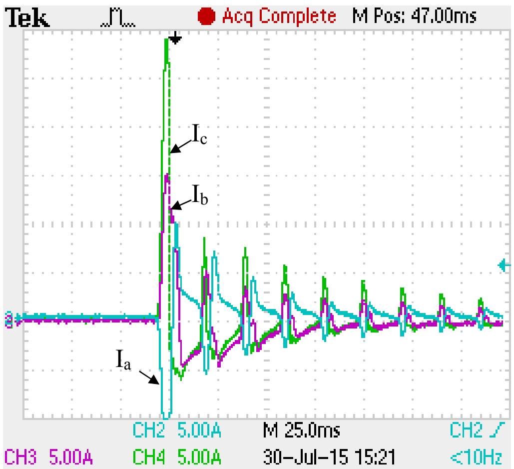
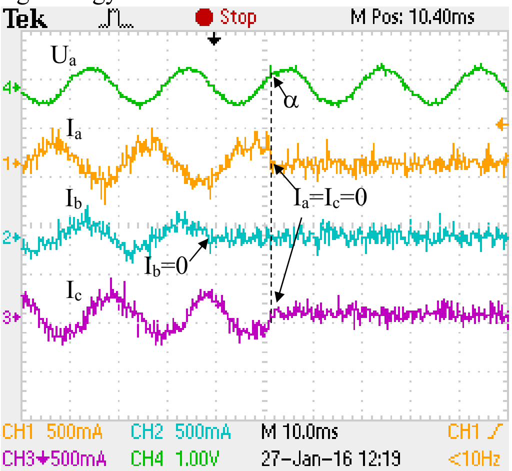
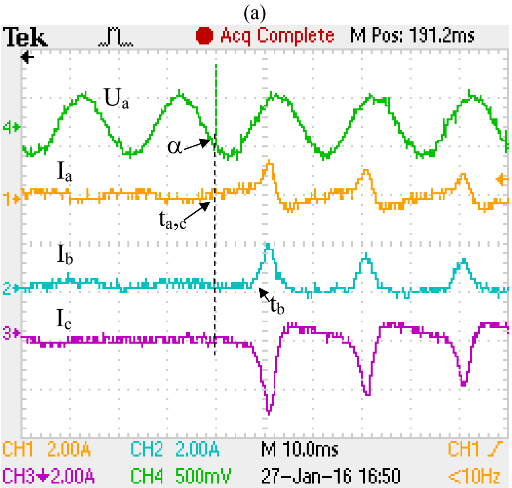


Fig. 14. The measured currents of three phases when closing three CBs randomly at the same time. (The ratio of the primary current and the secondary current is 20:1, and the clamp takes ten turns winding as sampling signal. The ratio of the actual current and sampling current is 2:1)

Fig. 15 shows the experimental results with phase-controlled strategy, which is determined at voltage angle α. The voltage angle α that the transformer is de-energized at and then re-energized can be determined as follows: 1) In the breaking process as shown in Fig. 15(a), CB B is switched off when the current of phase B is zero. Then, CBs A and C are switched off when the current of phases A and C is zero. According to the recorded voltage value $U=U_m\sin\alpha$ (where U_m is amplitude of the voltage), the voltage angle α of phase A can be determined by $\alpha=\arcsin(U/U_m)$. 2) In the making process, CBs A and C are switched on at $t_{a,c}$ when the voltage angle of phase A reaches $\alpha=\arcsin(U/U_m)$. Then, CB B is switched on at t_b when the voltage U of phase B reaches the peak value U_m. Fig. 15(b) shows that the maximum value of the inrush currents is about 6A, which is much less than that as shown in Fig.14. The experimental results verify that the inrush currents can be reduced effectively by using the proposed phase-controlled switching strategy.



(a)



(b)

Fig. 15. Experimental results. (a) breaking procedure and (b) making procedure with phase-controlled switching strategy. (The ratio of the primary current and the secondary current is 20:1, and the clamp takes ten turns winding as sampling signal. The ratio of the actual current and sampling current is 2:1)

V. CONCLUSIONS

This paper presents a novel method to reduce inrush current when considering the effect of residual flux. According to theoretical analysis, if the unloaded three-limb transformer is connected in Y and the neutral point in the primary side is ungrounded, when it is switched off, the opening order of CBs is that CB B should be opened at the time when its current is equal to zero; then CBs A and C are opened when their currents reach the zero-cross point at the same time. Based on the proposed breaking method, the residual flux in the iron core of an unloaded transformer can be controlled. Then, the phase-controlled switching strategy of the making process of an unloaded transformer is such that the CBs A and C should be closed when their phase angles are the same as the angles of their last opening period, and CB B is then closed when the voltage of phase B reaches the peak value. Both simulated results based on ATP/EMTP software and experimental ones are reported to showcase that the proposed phase-controlled switching strategy can significantly reduce the inrush current.

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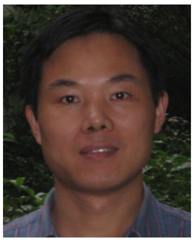

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