

# A NOVEL METHOD FOR ENERGIZING TRANSFORMERS FOR REDUCING INRUSH CURRENTS

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**Abstract:** Control and reduction of inrush currents of energizing transformers and reactors is an important problem in electric power systems where different methods are utilized for this purpose. In this paper, reviewing the most common methods, a novel method has been proposed and utilized for inrush current reduction in energizing transformers. In the proposed method, non simultaneous three phase switching is done within 10 cycles of time difference and a more little neutral point resistance has been utilized. Through the simulation results done with PSCAD/EMTDC, the efficiency of the proposed method in reducing the inrush current of energizing transformers as fast as possible is proved.

**Keywords:** Inrush current, Transformer energizing, Non-simultaneous switching

## I. INTRODUCTION

One of the most important facts about energizing the transformers and reactors in power systems is related to the inrush currents generated and distributed in the system. Several methods are utilized for controlling and reducing the amount of the inrush currents of energizing transformers. The conventional methods suffer from the high values of the resistances and the great amount of the loss, therefore, the studies on proposing and applying newer methods with less problems and loss are under investigation. Meanwhile, power quality standards and reconstruction of the power systems enforce the electric utilities to decrease the amount of the inrush current generated by energizing the transformers.

The other significant disadvantages of the inrush currents are as follows:

- Incorrect operation and failures of electrical machines and relay systems
- Electrical and mechanical vibrations among the windings of the transformer
- Irregular voltage distribution along the transformer windings
- High amount of voltage drop at the power system at energization times
- Possibility of resonances in the power system due to the various frequencies of the inrush current
- Current disturbances and harmonics increase in the system and lower power quality characteristics

Therefore, it is of great importance to propose and apply new methods for energizing the transformers in the power systems to prevent the mentioned problems while improving the power quality standards in the power system which will result in the satisfaction of the costumers.

In this paper, reviewing the most common methods, a novel method has been proposed and utilized for inrush current reduction when energizing transformers. In the proposed method, non simultaneous three phase switching is done within 10 cycles of time difference and a more little neutral point resistance has been utilized. The proposed method is capable of reducing the inrush current faster than the other conventional methods with less generated loss in the system. Through the simulation results done with PSCAD/EMTDC, the efficiency of the proposed method in reducing the inrush current of energizing transformers as fast as possible is proved.

## II. A NOVEL PROPOSED METHOD

Inrush currents are due to the flux variations in the transformer core which is dependent to network voltage. Therefore, considering the network voltage as:

$$U_1 = U_{1m} \sin(\omega t + \varphi_0) \quad (1)$$

where  $U_{1m}$ ,  $\omega$  and  $\varphi_0$  are the voltage amplitude, angular frequency and phase difference of the transformer fed voltage. Therefore, the transformer core flux equation is:

$$\varphi_t = \varphi_p + \varphi_L = -\varphi_m [\cos(\omega t + \varphi_0) - \cos\varphi_0] e^{-\frac{r_l}{L_l} t} \pm \varphi_{rem} e^{-\frac{r_l}{L_l} t} \quad (2)$$

where  $L_l$  and  $r_l$  are the inductance and resistance of the primary winding,  $\varphi_{rem}$  as the hysteresis flux and  $\varphi_m$  as the maximum flux at the steady-state,  $\varphi_p$  as the steady-state component and  $\varphi_L$  as the transient component of the core flux. Therefore, the parameters in Eq. 2 can be utilized for reducing the transient flux of the transformer which would result in decreasing the transformer inrush current.

Some of the common solutions for this purpose are:

- Reducing the hysteresis flux of the transformer
- Switching on the transformer at voltage peak
- Increasing the frequency at switching time
- Reducing the voltage at switching time

- Utilizing starting resistances

Since the inrush currents of the transformer are unbalanced, this will result in the inrush current flow through the transformer neutral point. Utilizing a series resistance in the neutral point of the transformer will behave as a starting series resistance and can improve the inrush current reduction. The schematic diagram of the proposed method is shown in Fig. 1 where a low rating switch is also needed.

There would not be great decrease in the inrush current when the three phases of the transformer are switched on simultaneously but it decreases greatly when they are switched on non-simultaneously and respectively.

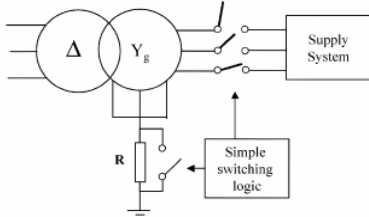


Fig. 1. Proposed method of energizing transformer utilizing neutral point resistance.

### III. ANALYSIS AND SIMULATION OF THE PROPOSED METHOD

A 100 MVA, 230/66 kV Y $\Delta$  three phase transformer has been simulated with PSCAD/EMTDC software for studying the inrush current characteristics of energizing the transformer with different methods. Later on, the proposed method has also been applied to study the reduction of the inrush currents, too.

#### Simultaneous switching without neutral resistance (custom method)

In this transformer energizing method, simultaneous switching of three phases occurs at any time except peak voltage of the phases (for example when voltage of phase A is zero) where the related inrush current of the transformer is as shown in Fig. 2.

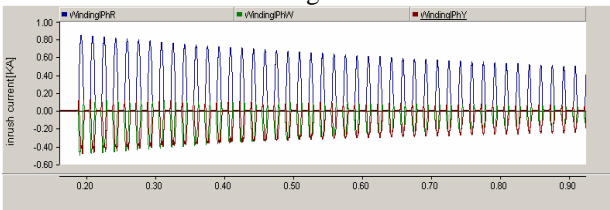


Fig. 2. Inrush current waveform in three-phase simultaneous switching method (custom method).

In this method, the maximum current of phases A, B and C is respectively equal to 831, 575 and 556 amperes.

#### Simultaneous switching at peak voltage without neutral resistance (custom method)

In this transformer energizing method, simultaneous switching of three phases occurs at peak voltage of one phase (for example phase A) where the related inrush current of the transformer is as shown in Fig. 3.

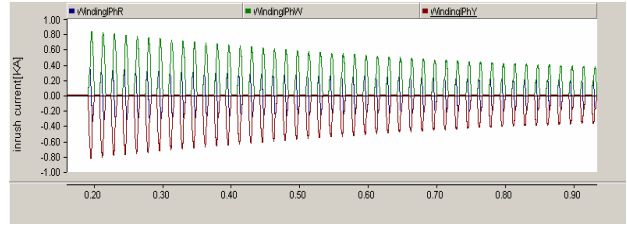


Fig. 3. Inrush current waveform in three-phase simultaneous switching method at peak voltage of one phase (custom method).

In this method, the maximum current of phases A, B and C (without considering the initial peak magnitude) is respectively equal to 267, 810 and 827 amperes.

#### Non-simultaneous switching at peak voltage without neutral resistance (custom method)

In this transformer energizing method, non-simultaneous switching of three phases occurs at peak voltage of each phase where the related inrush current of the transformer is as shown in Fig. 4.

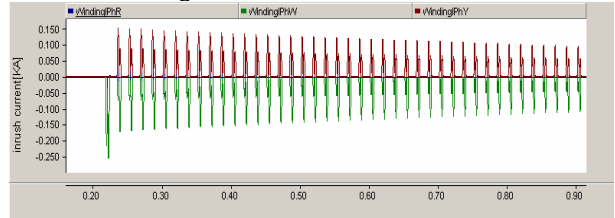


Fig. 4. Inrush current waveform in three-phase non simultaneous switching method at peak voltage of each phase (custom method).

In this method, the maximum current of phases A, B and C (without considering the initial peak magnitude) is respectively equal to 74, 148 and 150 amperes.

Studying these simulation results, it is proved that non-simultaneous switching at peak voltage of each phase is more capable of reducing transformer inrush current when energizing, in comparison with other conventional methods.

#### Non-simultaneous switching at peak voltage (proposed method)

The most significant parameter of the proposed method is the neutral point resistance. Through the simulation results, it is proved that the higher the resistance value, the more reduction in the inrush current of the first phase since the resistance is in series with the first phase. But this leads to an increase in the first phase when switching the second phase. This characteristic has been shown in Fig. 5.

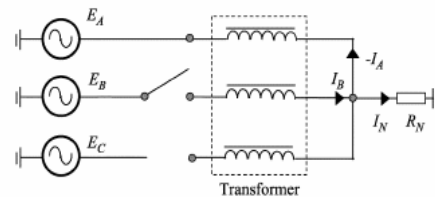


Fig. 5. Current flow characteristics for energizing second phase.

Increasing the resistance value ( $R_N = \infty$ ), the three-phase transformer circuit is equal to two line voltage fed single-phase transformers in series with each other which results

in an increase of the inrush current. The inrush current also increases when switching the third phase while the resistance is connected to the circuit. Therefore, it is preferred to disconnect the resistance when switching the third phase. This can show the poor performance of the described non-simultaneous energizing method where the problem is about energizing the second and third phases. For example, the energizing method for switching the second phase of the transformer is shown in Fig. 6.

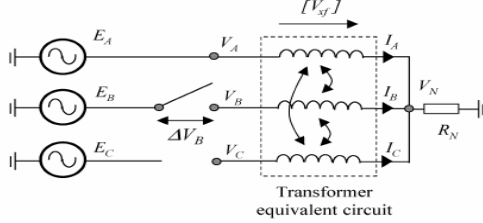


Fig. 6. Schematic diagram of proposed transformer energizing method.

Since, a no-load transformer is equal to three coupled windings, the electrical equations of the transformer at the steady state can be written as:

$$V_{xf} = \begin{bmatrix} V_{Axf} \\ V_{Bxf} \\ V_{Cxf} \end{bmatrix} = j \begin{bmatrix} X_s & X_m & X_m \\ X_m & X_s & X_m \\ X_m & X_m & X_s \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} \quad (3)$$

Where  $X_s$  and  $X_m$  are mutual and self inductances of each equal branch of the transformer (without considering the resistances) and  $V_{xf}$  as shown in Fig. 6. The most important parameter is the voltage on the switch of phase B which is shown as  $\Delta V_B$  in Fig. 6. According to the characteristics of the circuit, we have:

I. If  $|\Delta V_B| = 0$ , the second phase switching would not cause any transients in the current waveforms.

II. If the saturation effect of the transformer is neglected, the second phase switching would cause current transients with the amplitude equal to  $|\Delta V_B|$ .

III. If the saturation effect of the transformer is considered, the current transients due to the second phase switching would increase in according with the increase in  $|\Delta V_B|$  where the relation of the inrush current and  $|\Delta V_B|$  is nonlinear. Since, the inrush current amplitude can be controlled by  $|\Delta V_B|$  indirectly, the relation between  $|\Delta V_B|$  and  $R_N$  should be studied. Therefore, according to Fig. 6,  $|\Delta V_B|$  can be written as:

$$V_N = R_N I_N \quad \Delta V_B = E_B - V_B$$

$$\begin{bmatrix} E_A \\ V_B \\ V_C \end{bmatrix} = j \begin{bmatrix} X_s & X_m & X_m \\ X_m & X_s & X_m \\ X_m & X_m & X_s \end{bmatrix} \begin{bmatrix} I_A \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} V_N \\ V_N \\ V_N \end{bmatrix} \quad (4)$$

Solving the equations for  $|\Delta V_B|$ , we have:

$$|\Delta V_B| = E \sqrt{3 + (X_m - X_s) \frac{X_m + 2X_s + \sqrt{3}R_N}{R_N^2 + X_s^2}} \quad (5)$$

Similarly, the same equations can be written for the steady state condition of the circuit before the third phase switching as:

$$V_N = R_N (I_A + I_B) \quad \Delta V_C = E_C - V_C$$

$$\begin{bmatrix} E_A \\ V_B \\ V_C \end{bmatrix} = j \begin{bmatrix} X_s & X_m & X_m \\ X_m & X_s & X_m \\ X_m & X_m & X_s \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ 0 \end{bmatrix} + \begin{bmatrix} V_N \\ V_N \\ V_N \end{bmatrix} \quad (6)$$

Solving the equations for  $|\Delta V_C|$ , we have:

$$|\Delta V_C| = E \sqrt{\frac{9R_N^2 + (X_s + 2X_m)^2}{4R_N^2 + (X_s + X_m)^2}} \quad (7)$$

The best point for selection of neutral point resistance is when  $|\Delta V_B| = |\Delta V_C|$ , therefore, we have:

$$\frac{9R_N^2 + (X_s + 2X_m)^2}{4R_N^2 + (X_s + X_m)^2} = 3 + (X_m - X_s) \frac{X_m + 2X_s + \sqrt{3}R_N}{R_N^2 + X_s^2} \quad (8)$$

Since, Eq. 8 can not be solved through analytical methods, numerical methods can be applied. This equation shows  $R_N$  variations in accordance with  $X_s$  and  $X_m$  parameters.

$X_s$  and  $X_m$  parameters of the transformer can be calculated through short-circuit and no-load tests of the transformer. Since the short-circuit impedance of the transformer is littler in comparison with no-load impedance, we have:

$$X_s = \frac{2}{3} X_{open} \quad X_m = -\frac{1}{3} X_{open} \quad (9)$$

Inserting Eq. 9 in Eq. 8, the optimized value of the neutral pointy resistance of the transformer is calculated as:

$$1 - \frac{3\sqrt{3}R_N X_{open} + 3X_{open}^2}{9R_N^2 + 4X_{open}^2} = \frac{27R_N^2}{36R_N^2 + X_{open}^2} \quad (10)$$

Therefore, we have:

$$R_{N-Optimal} \approx 0.085 X_{open} \quad (11)$$

$$\Delta V_{Optimal} \approx 0.68E \quad (12)$$

The neutral point resistance, varies the steady-state voltage of the third phase switch, therefore, if the resistance voltage is equal to zero, the third phase switch would be zero, as shown in Fig. 7. Finally, it should be noticed that utilizing non-simultaneous three phase switching and disconnecting the neutral point resistance, the inrush current due to the third phase switching will disappear.

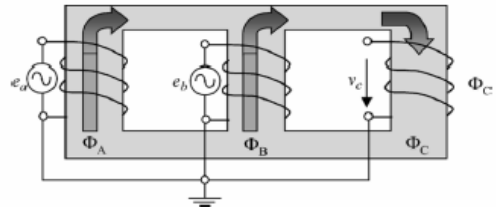


Fig. 7. Magnetic flux flow characteristics for energizing the third phase.

As shown in Fig. 7, the first and second phases are energized, so the core flux of the third phase is equal to:

$$\Phi_C = -(\Phi_A + \Phi_B) \quad (13)$$

And the induced voltage in the third phase is equal to:

$$v_c = \frac{d\phi_c}{dt} = -\frac{d(\phi_a + \phi_b)}{dt} = -\frac{d\phi_a}{dt} - \frac{d\phi_b}{dt} = -e_a - e_b = e_c \quad (14)$$

Eq. 14 proves that the induced voltage is equal to the source voltage therefore no inrush current would happen at the third phase switching. In addition, if  $R_N$  is great enough, the energizing conditions would be the same as energizing the second phase; therefore, the neutral point resistance selection is of great importance in inrush current reduction.

In the simulations done with PSCAD/EMTDC, a non-simultaneous switching within 10 cycles has been applied for energizing the transformer. The neutral point resistance has 0.1, 1 and 1000 kilo ohms values which are disconnected at third phase switching time.

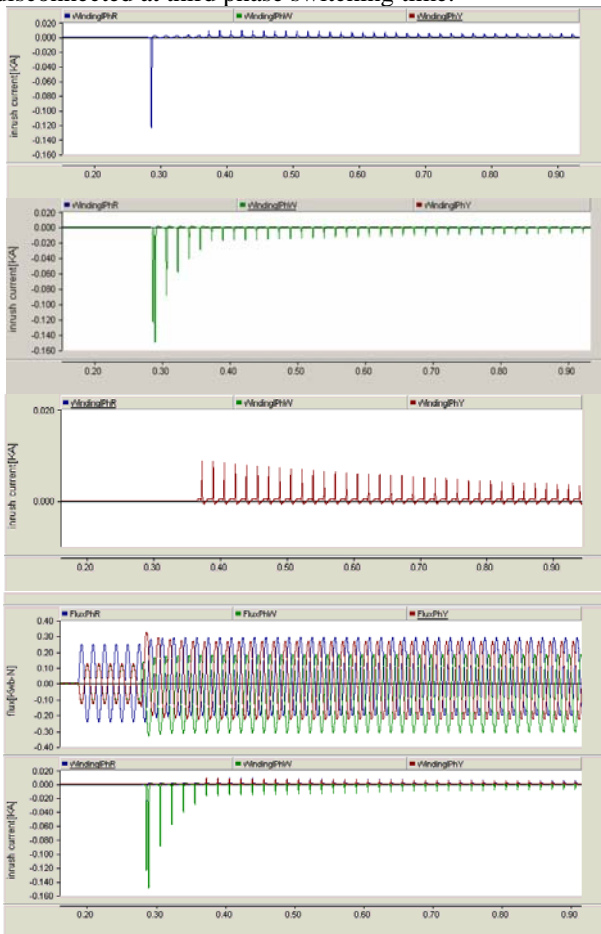


Fig. 8. Inrush current waveform in non simultaneous switching method in peak voltages with a 100 ohms resistance at neutral point (proposed method) for Phases A, B, C, three windings fluxes and the current of three phases (from top to bottom respectively).

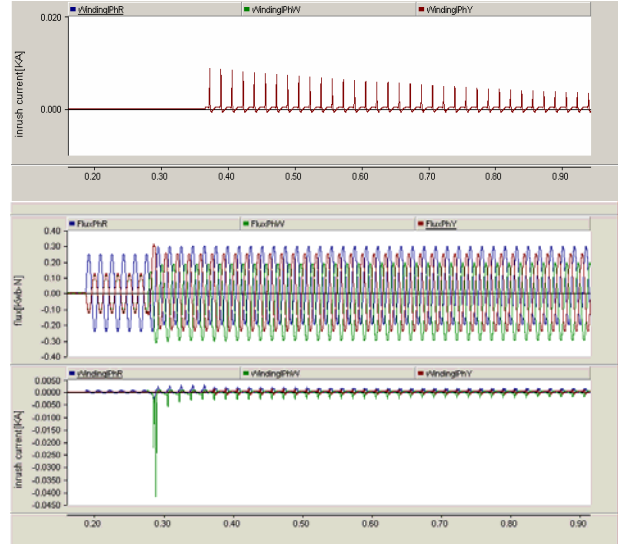
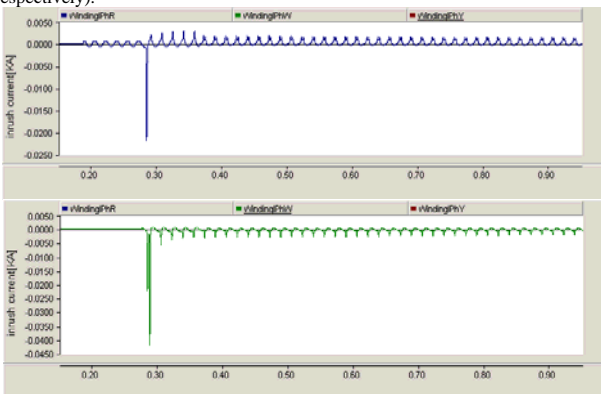


Fig. 9. Inrush current waveform in non simultaneous switching method in peak voltages with a 1 kilo ohms resistance at neutral point (proposed method) for Phases A, B, C, three windings fluxes and the current of three phases (from top to bottom respectively).

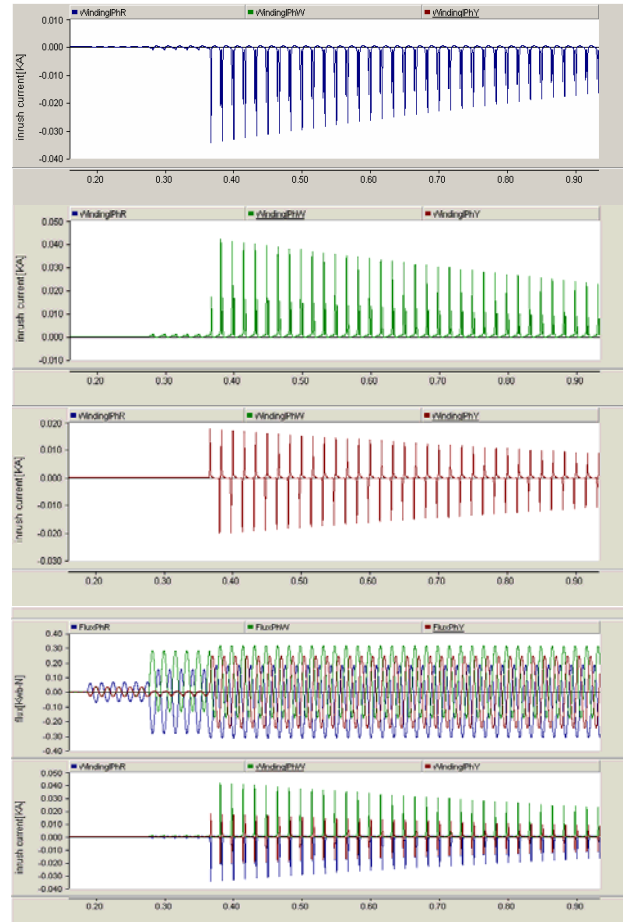


Fig. 10. Inrush current waveform in non simultaneous switching method in peak voltages with a 1 Mega ohms resistance at neutral point (proposed method) for Phases A, B, C, three windings fluxes and the current of three phases (from top to bottom respectively).

### DC current injection through three adjustable current sources

In this method, utilizing three adjustable DC current sources, some DC current is injected to the transformer prior to energizing which results in decreasing the inrush

current through varying the transformer hysteresis flux. The schematic diagram of this method is also shown in Fig. 11.

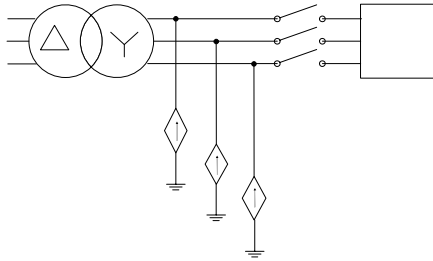


Fig. 11. Transformer energizing method utilizing DC current injection method.

Utilizing this method for the simultaneous switching of the transformer at the peak voltage of phase A, when energizing, the required DC current to be injected to the transformer equals 0.02, 0 and 0.2 amperes for phases A, B and C, respectively. Studying the waveforms of the windings fluxes and inrush currents in this method as shown in Fig. 12, it is proved that the inrush current of the transformer has been reduced greatly.

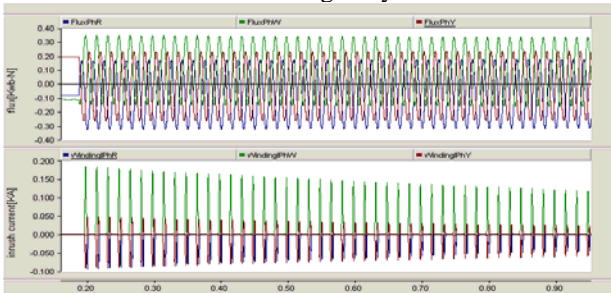


Fig. 12. Waveforms of fluxes of windings (top) and inrush currents of phases (bottom) in simultaneous switching method utilizing DC current injection method.

Applying this method for the proposed non-simultaneous switching of the transformer within 10 cycles and injecting -0.0576, -0.0339 and -0.166 amperes, the inrush current of the transformer has been reduced greatly as shown in Fig. 13. Studying this figure, it is shown that the inrush current exists in the first 10 cycles and before the third phase switching which disappears by switching the third phase of the transformer.

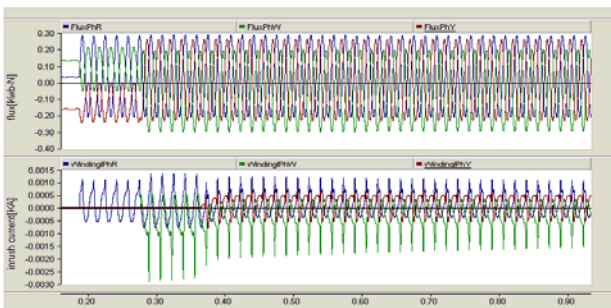


Fig. 13. Waveforms of fluxes of windings (top) and inrush currents of phases (bottom) in non-simultaneous switching method utilizing DC current injection method.

#### IV. CONCLUSION

In this paper, different methods for control and reduction of inrush currents of energizing transformers in electric power systems were studied and a novel method was proposed. The proposed method is based on non-simulations three phase switching within 10 cycles where a little neutral point resistance has also been utilized. Through the simulation results done in PSCAD/EMTDC, the efficiency of the proposed method in reduction of inrush currents as fast as possible was proved.

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