

Mitigation of Magnetizing Inrush Current using Sequential Phase Energization Technique

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Introduction

Inrush current is a well-known transient current that may occur when an unloaded or lightly loaded transformer is energized. The amplitude and shape of the inrush current depend on several factors such as switching time, remanent flux, impedance of the system from which the transformer is energized and etc. [1]. Because the magnitude of this current can be as high as short circuit currents, many researches have been conducted to assess and limit the amplitude and impact of these currents. In [2], transformer nonlinearities during transient and unbalanced conditions like inrush current is simulated using separate magnetic and electric equivalent circuits and then nonlinear mathematical model is carried out using Newton-Raphson iterative method. For the simulation of the magnetizing currents, [3] is developed a model from the structural parameters of the transformer. In [4], a new model using wavelet filter bank is presented and transient phenomena like inrush current are simulated. For modeling transformer core including hysteresis, [5] used Jiles-Atherton theory with variable parameters. In [6], a computational technique is used to calculate inrush current at various switching conditions and the effects of some parameters like switching angle, energizing circuit impedance and remanent flux on the inrush current characteristics are discussed. Also, limiting and canceling inrush currents have been investigated in the literature. In [7], a virtual air gap which equivalent thickness varies in function of controllable parameters is used to reduce inrush current in a single phase transformer. In [8] an altered winding coil distribution is proposed to restrain inrush current with appropriate voltage regulation and short circuit current. Sequential phase energization technique is documented in [9–11]. In this technique, each phase of a three-phase transformer is energized in sequence with some delays between them, while a suitable neutral resistor is placed at the neutral point. In [12–13], a controlled switching with considering core flux transients has been used to eliminate inrush current.

In this paper, the sequential phase energization technique has been used to mitigate magnetizing inrush current. Because, the size of the resistor which is connected to the neutral point of the transformer, has an important role, analytical formulas have been derived to calculate inrush current amplitude with a neutral resistor. To verify the validity of the analytical formulas, a MATLAB program has been written and the sizes of the neutral resistor for different inrush current reduction ratios in a typical transformer have been obtained and then implemented in MATLAB SIMULINK.

Sequential Phase Energization Technique

It is well-known that the inrush currents are highly unbalanced among three phases. If a transformer is Y grounded at the energization side, its neutral will also contain the inrush current. So, it can be expected that the insertion a resistor into the transformer neutral, may reduce the magnitude of the magnetizing inrush current. The basic idea of the sequential phase energization is shown in Fig. 1 where, V_a , V_b and V_c are phase voltages and R_N is grounding resistor. Also, t_a , t_b and t_c are the closing times of the breakers where, $t_c > t_b > t_a$.

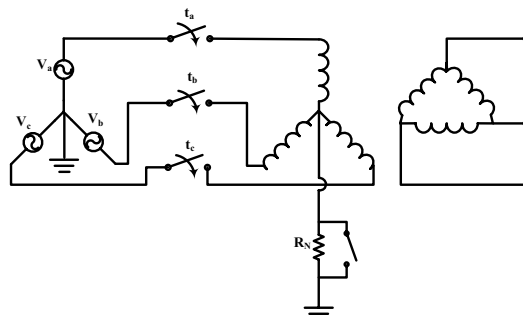


Fig. 1. Sequential phase energization scheme with a grounding resistor

As stated in [9], a simultaneous closing of all three-phase breakers does not produce considerable reduction on

the inrush currents. So, for improving the results, closing each phase of the breaker in sequence with some delays between them was proposed. With this way, the neutral resistance can behave as a series resistor and this method can effectively reduce the magnitude of inrush current. Also, it should be noted that because the neutral current in normal system operation is close to zero, the bypass breaker may not be needed or can have a low rating.

Calculation of inrush current with a neutral resistor

It has been found that the peak of inrush current in the first phase energization is the highest among the three phases [11]. So, the size of the neutral resistor for a specific inrush current reduction ratio can be calculated upon the first phase energization. In the first phase energization, the equivalent circuit of the unloaded transformer with a neutral resistor can be shown as Fig. 2 where, R_S , L_S , R_P , R_N and $V(t)$ are series resistance, series inductance, core loss resistance, neutral resistance and input source, respectively. Also, the magnetizing branch in the equivalent circuit of the transformer has been presented with $i_m(\lambda)$ where, λ is the linkage flux.

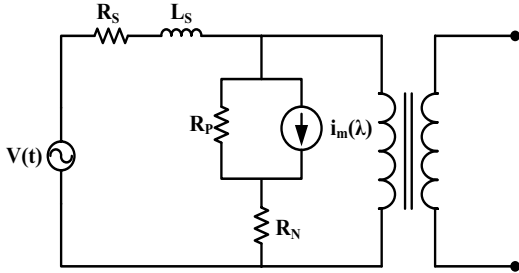


Fig. 2. Equivalent circuit of the transformer with neutral resistor

For the circuit shown in Fig. 2, the following equations can be written in the primary side of the transformer:

$$V(t) = R_S i(t) + L_S \frac{di(t)}{dt} + \frac{d\lambda(t)}{dt} + R_N i(t), \quad (1)$$

$$i(t) = \frac{1}{R_P} \frac{d\lambda(t)}{dt} + i_m(\lambda). \quad (2)$$

Because in the actual transformer, $i_m(\lambda)$ is nonlinear, the equations (1) and (2) result into a system of nonlinear ordinary differential equations. For solving these equations, we can discrete time t into j intervals. These equations can be successively integrated from $t=0$ until $t=j\Delta t$ with considering $i_m(\lambda)$ is constant in every Δt interval. So, integrating equations (1) and (2) in the intervals t_{j-1} and t ($t_{j-1} < t < t_j$) results into equations (3) and (4), where, $\alpha \equiv (R_P + R_S + R_N)/L_S$ and $\beta \equiv R_P/L_S$:

$$i(t) = i(t_{j-1})e^{-\alpha(t-t_{j-1})} + e^{-\alpha t} \int_{t_{j-1}}^t e^{\alpha\tau} \left(\frac{v(\tau)}{L_S} + \beta i_m(\tau) \right) d\tau, \quad (3)$$

$$\lambda(t) = \lambda(t_{j-1}) + \int_{t_{j-1}}^t v(\tau) d\tau -$$

$$-(R_S + R_N) \int_{t_{j-1}}^t i(\tau) d\tau - L_S [i(t) - i(t_{j-1})]. \quad (4)$$

Also, with considering $V(t) = V_m \sin(\omega t + \theta)$, the following recursive equations for the calculation of the current and flux in a transformer can be achieved:

$$i(t_j) = i(t_{j-1})e^{-\alpha\Delta t} + \frac{V_m}{L_S \sqrt{\alpha^2 + \omega^2}} \times [\sin(\omega t_j + \theta - \varphi) - \sin(\omega t_{j-1} + \theta - \varphi) e^{-\alpha\Delta t}] + \frac{\beta}{\alpha} (1 - e^{-\alpha\Delta t}) i_m(t_{j-1}), \quad (5)$$

$$\lambda(t_j) = \lambda(t_{j-1}) - \frac{V_m}{\omega} [\cos(\omega t_j + \theta) - \cos(\omega t_{j-1} + \theta)] + \frac{(R_S + R_N)}{\alpha} i(t_{j-1}) (e^{-\alpha\Delta t} - 1) + \frac{(R_S + R_N)V_m}{L_S \sqrt{\alpha^2 + \omega^2}} \times \left[\frac{\cos(\omega t_j + \theta - \varphi)}{\omega} - \frac{\cos(\omega t_{j-1} + \theta - \varphi)}{\omega} - \sin(\omega t_{j-1} + \theta - \varphi) \times \frac{(e^{-\alpha\Delta t} - 1)}{\alpha} \right] - \frac{(R_S + R_N)\beta i_m(t_{j-1})}{\alpha} \times \left[\Delta t + \frac{(e^{-\alpha\Delta t} - 1)}{\alpha} \right] - L_S [i(t) - i(t_{j-1})], \quad (6)$$

where $\Delta t = t_j - t_{j-1}$ and $\varphi = \arctg(\omega/\alpha)$.

(5) and (6) have been used to calculate the size of the neutral resistor to achieve a specific inrush current reduction ratio. The procedure for calculation a specific inrush current reduction ratio is described in Fig. 3. It should be noted that inrush current reduction ratio has been calculated with (7)

$$\text{inrush current reduction ratio} = \frac{i_{\text{peak}, R_N \text{ calculated}}}{i_{\text{peak}, R_N = 0}}. \quad (7)$$

Simulation results

In this section, for investigation of inrush current reduction ratio, a three-phase transformer consisted of single-phase transformers is considered. These transformers are connected in Yg- Δ . The parameters of single-phase (220/120) V, 50Hz, 120VA transformers are $R_S = 15.476\Omega$, $L_S = 12\text{mH}$, $R_P = 7260\Omega$. Also, the magnetizing current versus linkage flux is as follow

$$i_m(\lambda) = 63.084 \times 10^{-3} \sinh(2.43\lambda). \quad (8)$$

Fig. 4 shows the inrush current waveforms for different phases when no mitigation method is used. As seen from the figure, the highest amplitude of inrush current among three phases has been appeared in the phase A that is 1.437A.

For calculation the neutral resistor size for a specific inrush current reduction ratio a program based on the analytical formulas has been written in MATLAB M-File. Fig. 5 shows the inrush current waveforms when sequential

phase energization technique with $R_N=345.6\Omega$ has been used. The size of the neutral resistor has been obtained for a 30% inrush current reduction ratio. As seen from the figure, with selection a suitable R_N , the peak of the inrush current in phase A has been decreased to 30% (0.431A). Also, it should be noted that a 1 second delay between each switching stage has been used to allow phase fluxes to lose most of the dc component.

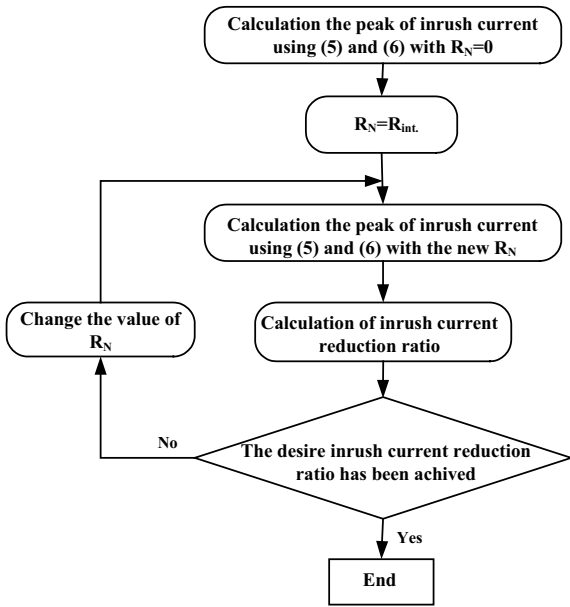


Fig. 3. Procedure for calculation a specific inrush current reduction ratio

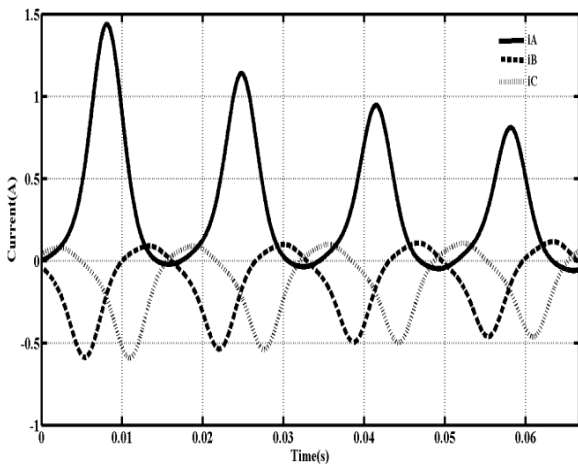


Fig. 4. Inrush current waveforms when no mitigation method has been used

For showing the usefulness of the sequential phase energization, a simultaneous energization of all phases with $R_N=345.6\Omega$ has been simulated. The waveforms of the inrush currents of all phases have shown in Fig. 6. As seen from the figure, simultaneous energization is not effective as sequential energization (Fig. 5) that has a delay between energization of each phase.

Fig. 7 shows change of the neutral resistor as a function of inrush current reduction ratio. As seen from the figure, for more reduction in inrush current amplitude

(lower amount of inrush current reduction ratio) a larger neutral resistor is needed.

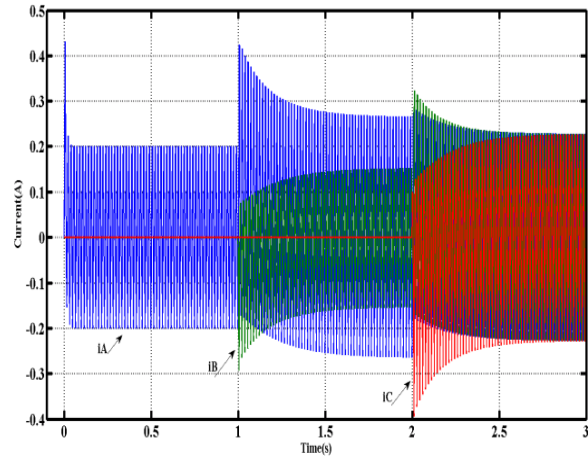


Fig. 5. Mitigation of inrush current with sequential phase energization technique

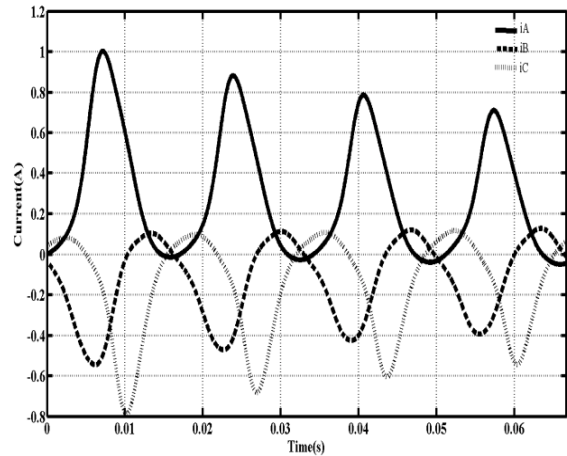


Fig. 6. Inrush current waveforms with simultaneous energization of all phases and $R_N=345.6 \Omega$

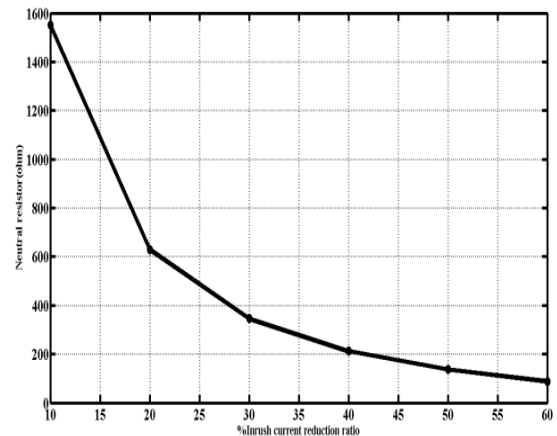


Fig. 7. Change of the neutral resistor as a function of inrush current reduction ratio

Conclusions

The peak of inrush current in the first phase energization is the highest among the three phases when sequential phase energization technique is used. Because, the neutral resistor that is used in this technique has an

important role, analytical formulas with considering neutral resistance have been derived to calculate inrush current amplitude in the first energization. For investigation of the validity of the analytical formulas, a typical three-phase transformer constructed of single-phase transformers selected. Then, using the analytical formulas, a neutral resistor for 30% inrush current reduction ratio was obtained and applied to the neutral point of the transformer. Simulation results show the usefulness of the analytical formulas.

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Received 2010 08 15

M. Jamali, M. Mirzaie, S. Asghar-Gholamian. Mitigation of Magnetizing Inrush Current using Sequential Phase Energization Technique // Electronics and Electrical Engineering. – Kaunas: Technologija, 2011. – No. 2(108). – P. 67–70.

Energization of a transformer under no load or lightly loaded conditions may result in inrush current with high amplitude that can be comparable with the fault currents. These currents have undesirable effects, including malfunction of the differential relay, mechanical and thermal stresses on transformer and reduced power quality of the system. In this paper, a sequential phase energization technique has been used to mitigate magnetizing inrush current in a grounded system. Because in this technique, the size of the resistor, which is connected to the neutral point of the transformer, has an important role, analytical formulas have been derived to calculate inrush current amplitude with a neutral resistor. These analytical formulas have been implemented in the M-File of the MATLAB software for calculation of different inrush current reduction ratio. Then for the verification of the results, the obtained neutral resistor has been applied to the equivalent circuit of a typical three-phase transformer and inrush current reduction has been determined by MATLAB SIMULINK. III. 7, bibl. 13 (in English; abstracts in English and Lithuanian).

M. Jamali, M. Mirzaie, S. Asghar-Gholamian. Įmagnetinimo srovės sumažėjimo tyrimas taikant nuoseklų fazinį sužadinimo metodą // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 2(108). – P. 67–70.

Transformatoriaus susižadinimas, kai nėra prijungta jokios apkrovos arba kai ji maža, gali sukelti didelės amplitudės įmagnetinimo srovės šuolį. Tokiu atveju ši srovė gali būti traktuojama kaip parazitinė ar gedimo srovė. Tokie reiškiniai mažina transformatorių ilgaamžiškumą, blogina tiekiamos elektros energijos kokybę, neigiamai veikia reles. Atliktas modeliavimas programų paketu MATLAB, pateiktos formulių matematinės išraiškos, apskaičiuoti rezistorių matmenys, turintys įtakos pašalinėms srovėms. II. 7, bibl. 13 (anglų kalba; santraukos anglų ir lietuvių k.).