Calculation and Analysis of Transformer Inrush Current Based on Parameters of Transformer and Operating Conditions

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Introduction

Magnetizing inrush current in transformers results from any abrupt changes of the magnetizing voltage. This current in transformer may be caused by energizing an unloaded transformer, occurrence of an external fault, voltage recovery after clearing an external fault and out-of-phase synchronizing of connected generator [1-2]. Because the amplitude of inrush current can be as high as a short-circuit current, a detailed analysis of the magnetizing inrush current under various conditions is necessary for the concerns of a protective system for the transformers. In this regard, some numerical and analytical methods have been proposed in the literature. In [3], analytical expressions for the magnetic fluxes of no-load three-phase transformer is presented that can be used for inrush current calculation. In [4], by analytical solution of two differential equations that governs the behavior of a transformer, the magnetic flux and inrush current are determined. For modeling transformer core including hysteresis, [5] used Jiles-Atherton theory and presented a new algorithm on a sample transformer. In [6], an analytic formula is presented to calculate the peak inrush current of a nonlinear inductor with a series resistor. In [7], a simple model for the transient period of inrush current is presented. This model is developed from the structural parameters of transformer. To avoid malfunctiom of protection system under magnetizing inrush current, many researches are conducted for the discrimination of inrush current from internal fault currents. For example, in [8-10], inrush current are discriminated from internal fault current by second harmonic criterion. For discrimination of these currents, [11] used the sum of active power flowing into the transformer from each terminal. In [12], a criterion function in terms of difference of amplitude of wavelet coefficients is defined. Then by using this criterion function for three phases, the internal faults are discriminated from the inrush current.

In this paper, first, the fundamentals of inrush current and the formulas that are used for calculation it, are presented. Then a one-phase transformer is simulated in MATLAB and the effects of switching angle variation, energizing circuit impedance and remanent flux on the characteristics of inrush current are investigated in detail.

Fundamentals of Inrush Current

It is very well known that a transformer will experience magnetizing inrush current during energization. Inrush current occurs in a transformer whenever the residual flux does not match the instantaneous value of the steady-state flux which would normally be required for the particular point on the voltage waveform at which the circuit is closed [13].

For the explanation of the mechanism causing inrush current in a transformer's primary winding when connected to an AC voltage source, we consider (1), where λ and v are the instantaneous flux in a transformer core and voltage drop across the primary winding, respectively

$$v = \frac{d\lambda}{dt}. \tag{1}$$

As we see from (1), the rate of change of instantaneous flux in a transformer core is proportional to the instantaneous voltage drop in the primary winding or on the other hand, the flux waveform is the integral of the voltage waveform. In continuously-operating transformer, these two waveforms are shifted by 90°. But a significant difference exists between continuous-mode operation and energization of a transformer. During continuous operation, the flux level is at its negative peak when voltage is at its zero point, but during energization the flux has to start at zero. So, for a rising voltage just started from zero, the magnetic flux will reach approximately twice its normal peak as it integrates the area under the voltage waveform's first half-cycle. This amount of flux, because of the nonlinear characteristic of the magnetization curve, causes saturation of the transformer. During saturation, disproportionate amounts of mmf are needed to generate magnetic flux. This means the winding current, which creates the mmf to cause flux in the core, will disproportionately rise to a value easily exceeding twice its normal peak. Fig. 1 shows the generation of inrush current in a transformer. As seen from the figure, exceeding flux

from the knee point, results in large magnetizing current that in some circumstances can be ten times of the rated current in a transformer.
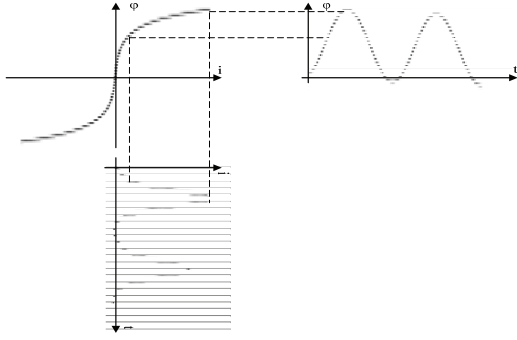

Fig. 1. Generation of inrush current in a transformer

The general equation that gives the amplitude of inrush current as a function of time can be expressed as (2):

$$i(t) = \frac{\sqrt{2} V_m}{Z_t} * K_w * K_s * \left(sin(\omega t - \varphi) - e^{\frac{-(t-t_0)}{\tau}} . sin\alpha \right), \quad (2)$$

where V_m – maximum applied voltage; Z_t – total impedance under inrush, including system; φ – energization angle; t – time; t_0 – point at which core saturates; τ – time constant of transformer winding under inrush conditions; α – function of t_0; K_w – accounts for 3 phase winding connection; K_s – accounts for short-circuit power of network.

For the purpose of designing a protective system for transformer, the peak value of inrush current is an important factor. In these cases, a simplified equation can be used to calculate the peak value of the first cycle of the inrush current. This equation is as follow

$$i_{peak} = \frac{\sqrt{2} V_m}{\sqrt{(\omega.L)^2 + R^2}} \left(\frac{2.B_N + B_R - B_S}{B_N} \right), \quad (3)$$

where V_m – maximum applied voltage; L – air core inductance of the transformer; R – total dc resistance of the transformer; B_N – normal rated flux density of the transformer core; B_R – remanent flux density of the transformer core; B_S – saturation flux density of the core material.

As seen from the equations (2) and (3), the value of inrush current is dependent to the parameters of transformer and operating conditions. So a detailed analysis for finding the relations between the inrush current characteristics and these factors are needed.

Simulation results

When a transformer is energized under no load or lightly loaded conditions, inrush current may flow in the primary circuit. In this situation, the equivalent circuit of transformer can be shown as Fig. 2 where R_s, L_s, R_p, L_m and R_t are series resistance, series inductance, core losses resistance, magnetizing inductance and source resistance respectively.

In order to investigate the effects of some parameters of transformer or network on the inrush current of a typical transformer, a 120 VA, 60 Hz, (220/120) V transformer

with those parameters are presented in [4], is selected. The parameters of the equivalent circuit of this transformer referred to the 220V winding are shown in Table 1.
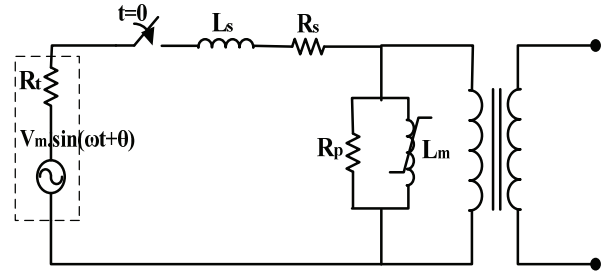

Fig. 2. Equivalent circuit of the transformer under no load

Table 1. Parameters of the simulated transformer

Parameter	R_s (Ω)	L_s (mH)	R_p (Ω)
Value	15.476	12	7260

Also, the magnetization curve of the transformer is given in (4) where i and λ are magnetizing current and flux respectively

$$i(\lambda) = (63.084 \times 10^{-3}) \sinh(2.43\lambda). \quad (4)$$

It should be noted that equations (5)-(8) are used to calculate the fundamental and second harmonic components of inrush current, where N, T and f are number of samples in each cycle, period and frequency of the power system, respectively. Also, m indicates fundamental and second components with the numbers 1 and 2, respectively. The sampling rate of 30 kHz has been used in this paper:

$$a_m = \sum_{n=1}^{N} \frac{2}{T} (\int_{t_n}^{t_{n+1}} i_n . \cos(m. 2\pi f. x) \, dx, \quad (5)$$

$$b_m = \sum_{n=1}^{N} \frac{2}{T} (\int_{t_n}^{t_{n+1}} i_n . \sin(m. 2\pi f. x) \, dx, \quad (6)$$

$$c_m = \sqrt{a_m^2 + b_m^2}, \quad (7)$$

$$\%2ndHarmonic = \frac{c_2}{c_1} \times 100. \quad (8)$$

Effects of switching angle

In this section, the effect of switching angle variation on the characteristics of inrush current has been investigated. The remanent flux (B_r) for all switching angles is 0.826 Wb-coil. Also the source resistance has been considered to zero. Fig. 3 shows the effect of different switching angles (θ) on the amplitude of inrush current. As seen from the figure, the highest amplitude of inrush current is at 0° that is 5.52A. Also, it can be seen, increasing of the switching angle will decrease the amplitude of inrush current.
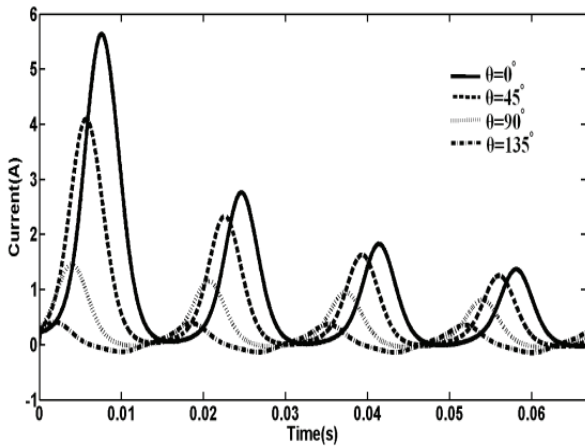
Fig. 3. Effect of switching angle variation on the amplitude of inrush current

The second harmonic content of inrush current is shown in Fig. 4. As seen from this figure, increasing of the switching angle causes to a decrease in the percentage second harmonic.
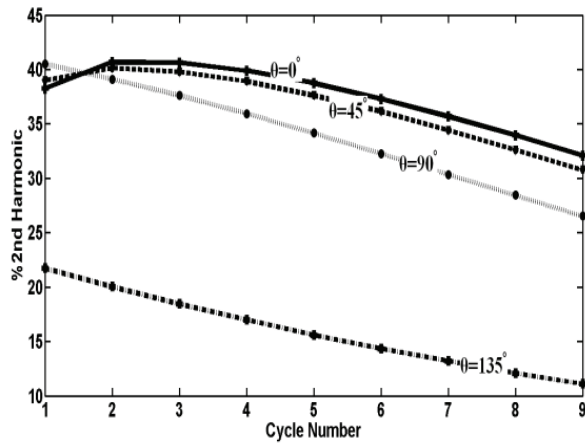

Fig. 4. Effect of switching angles in the percentage second harmonic

It should be noted that, although, the highest amplitude of the inrush current appears in the first cycle and then decays, but the highest percentage second harmonic does not necessarily appear in the first cycle. For instance as seen from Fig. 3 and Fig. 4, at θ=90˚, both amplitude and percentage second harmonic have been decreased with increasing cycle, but at θ=0˚, although the amplitude of inrush current have been decreased, but second harmonic firstly increased and then decreased. This is important when using second harmonic content to restrain the relay operation during magnetizing inrush conditions.

Effects of source resistance

In this case, the switching angle (θ) is 0˚. Also, the remanent flux (B_r) is the same as the previous section. The effects of source resistance have been considered by increasing R_t. Fig. 5 shows the effect of source resistance on the amplitude of inrush current. As seen from figure, increasing source resistance will decrease the amplitude of

inrush current. Also, it causes faster decay in the amplitude of inrush current. Therefore, it can be said that transformers located closer to the generating plants display higher amount of inrush currents lasting much longer than transformer installed electrically away from generator.
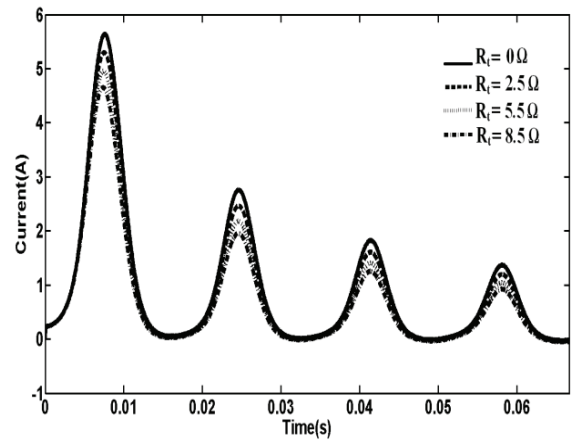

Fig. 5. Effect of source resistance on the amplitude of inrush current

The effect of source resistance in the percentage of second harmonic has been shown in Fig. 6. The results show that the amount of percentage of second harmonic will be decreased by increasing the source resistance.
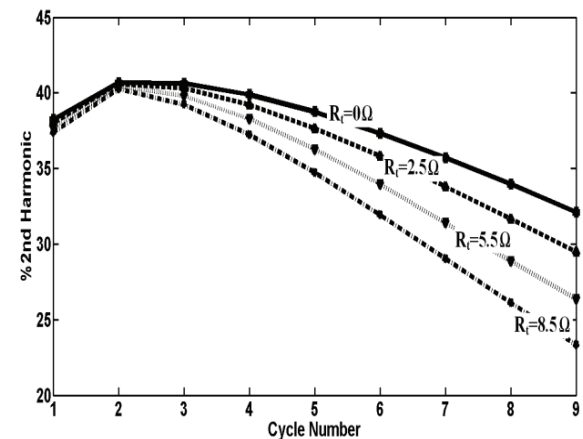

Fig. 6. Effect of source resistance in the percentage second harmonic

Effects of the remanent flux

The effect of remanent flux on the first cycle peak current at different switching angles is shown in Fig. 7. As seen from figure, the first cycle peak current has large change when the remanent flux varies. Also the results indicate that switching at θ=90˚ or B_r=0 may not necessarily reduce the magnitude of inrush current. So, for reducing inrush current, an appropriate switching angle by considering remanent flux must be selected.

Conclusions

In this paper, the effects of some parameters on the characteristics of inrush current are investigated in MATLAB Simulink.
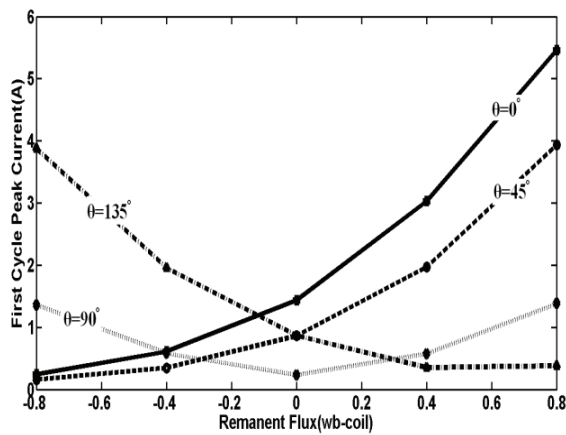
Fig. 7. Effect of remanent flux on first cycle peak current

Results show that increasing switching angle at a positive remanent flux or source resistance will decrease the amplitude of inrush current. It has been shown that largest second harmonic content may not necessarily appear at the first cycle. The effect of remanent flux on the first cycle peak current shows that it has large changes when the remanent flux varies. Also, it has been concluded that for reducing inrush current, an appropriate switching angle by considering remanent flux, must be selected.

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An inrush current is a transient current with high amplitude that may occur when a transformer is energized under no load or lightly loaded conditions. The magnitude of inrush current may be as high as ten times or more times of transformer rated current. This could result in huge mechanical and thermal stresses on transformer in addition to inadvertent operation of the protective relay systems. This paper represents the effects of some factors on the inrush current of transformers. For this purpose, a one-phase transformer is simulated in MATLAB and the effects of switching angle variation, the energizing circuit impedance and the remanent flux on the characteristics of inrush current are investigated. The results show that increasing circuit resistance or switching angle will decrease inrush current amplitude. Also, it is concluded that for reducing inrush current, appropriate switching angle with respect to the remanent flux must be selected. The results can be used for a better understanding of the inrush current characteristics and proper actions of the protective system. Ill. 7, bibl. 13, tabl. 1 (in English; abstracts in English and Lithuanian).

M. Jamali, M. Mirzaie, S. Asghar Gholamian. Transformatoriaus parametrų ir darbo sąlygų įtakos transformatoriaus įmagnetinimo srovei apskaičiavimas ir tyrimas // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2011. – Nr. 3(109). – P. 17–20.

Įmagnetinimo srovė yra didelės amplitudės momentinė srovė, kuri gali atsirasti, kai transformatorius susižadina, kai nėra jokios apkrovos arba kai ji maža. Įmagnetinimo srovė gali būti daugiau nei dešimt kartų didesnė už nominalią vertę. Toks poveikis, atsiradęs dėl mechaninių ir terminių procesų, neigiamai veikia reles. Aprašomi veiksniai, turintys įtakos įmagnetinimo srovei. Atliktas vienfazio transformatoriaus modeliavimas programų paketu Matlab, įvertinti pagrindiniai parametrai. Il. 7, bibl. 13, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).