Inrush Current Investigation for Single Phase Power Transformers by Means of Magnetic Material Core Characteristics

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***Abstract*— The paper propose a quantitatively study of the inrush current that occurs when a no loaded single phase power transformers is energized. An analytical approached is suggested, that along with various switching parameters, the main magnetic core material characteristics are considered. Thus a comparison between the parameters of the inrush current for different core magnetic materials of a 6 kVA general purpose single-phase transformer is carried out.**

Keywords*— *inrush current, single phase transformer, magnetization curves

I. Introduction

An extreme high value of the current is surged when a no loaded power transformer is initially connected [1, 2]. The amplitude of these inrush currents can reach up to 20 times the rated current of a transformer. These currents generate significant undesirable effects for both transformer and network functionality [3, 4]. The main factors that influence the inrush current features are [5, 6]: peak supply voltage and its phase at the instant of switching, the geometry of the transformer core, the total resistance of the primary winding circuits and *H-B* characteristic of the core magnetic material along with the magnitude and polarity of the remnant flux density in the transformer core at the energizing moment. This paper is going to quantitatively investigate the magnetic core characteristic effect on the inrush current amplitude and its wave form.

II. Transformer Model – Semianalytic Solution

In order to obtain a deterministic characterization of the single phase transformer at the instant of switching, a simple circuit model was adopted. This considers the winding resistance R_1 and its nonlinear inductivity mainly described by the magnetic core *H-B* characteristic. Thus, one can analytically describe the inrush current $i(t)$ and magnetic flux $\Phi(t)$ time dependence:

$$\begin{cases} \dfrac{d\Phi(t)}{dt} = \dfrac{R_1 i(t) - u(t)}{w_1} \\ i(t) = \dfrac{H\left(\Phi(t)/A_c\right) l_m}{w_1} \end{cases}, \quad u(t) = \hat{U}\sin(\omega t + \varphi), \quad (1)$$

where $u(t)$ the supply voltage of amplitude U and initial phase φ, H is the core magnetic strength, A_c is the effective cross section of the core, lm mean magnetic path length and w1 is the primary turns numbers.

The above expressions require (along with the detailed core geometrical description) the magnetic core characteristic in terms of its *H-B* representation. That can be accomplished using different approaches [7, 8]. For our investigations we select Brauer [9] analytical function that describes the *B-H* dependency and used Rosenbrock method [10] for solving the non linear differential equations systems (1). The initial value parameter is imposed by the remanent magnetization of the magnetic B_{ro} core before the energizing process and is being expressed in terms of initial magnetic flux $\Phi_0 = B_{ro}A_c$.

Aiming to investigate the harmonic content of the IC waveform a Fourier analysis is carried out. Thus, the corresponding terms of the Fourier series are numerically evaluated:

$$\begin{aligned} a_0 &= \frac{1}{T}\int_0^T i(t)\,\mathrm{d}t; \quad a_k = \frac{1}{T}\int_0^T i(t)\cos(k\omega t)\,\mathrm{d}t, \\ b_k &= \frac{1}{T}\int_0^T i(t)\sin(k\omega t)\,\mathrm{d}t, \qquad k = 1, 2, 3... \end{aligned} \quad (2)$$

Additionally, using (2), each harmonic level of the IC waveform is quantitatively evaluated in order to later estimate their contribution to the spectrum relative to the fundamental:

$$\begin{aligned} i(t) &= \sum_{k=0}^{n}\left[a_k\cos(k\omega t) + b_k\sin(k\omega t)\right], \\ c_k &= \sqrt{a_k^2 + b_k^2}, \quad h_k[\%] = \frac{c_k}{c_1}\cdot 100 \end{aligned} \quad (3)$$

III. Simulation Results

A general purpose UI core 6 kVA power transformer was chosen for our investigation. Different magnetic core materials were selected in order to examine the wave form and amplitude of the inrush current. The worst switching condition were selected: zero phase angle of the applied voltage and maximal positive remnant flux density for the examined magnetic core material. Thus, for instance, Fig. 1 and Fig. 2 present the inrush current variation over a half period after the energizing using for two different core materials: silicon steel M 27 and Low Carbon Steel 1020.

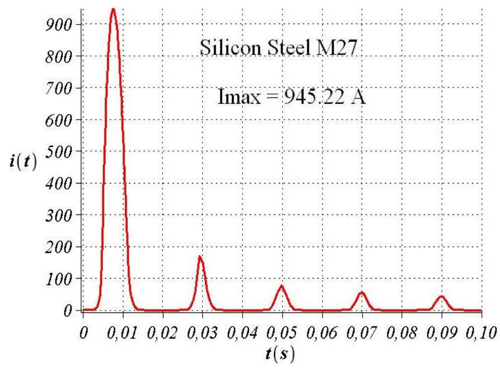

Fig.1 Inrush current variation for a 6 kVA transformer with a magnetic core made of silicon steel M 27.

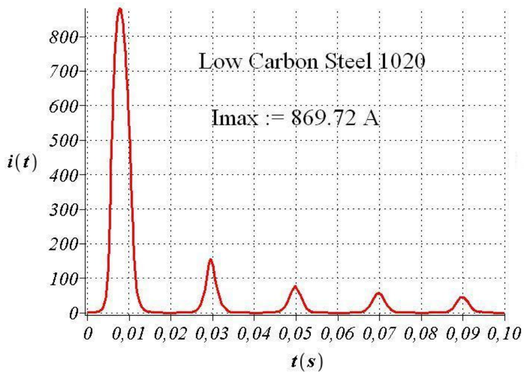

Fig.2 Inrush current variation for a 6 kVA transformer with a magnetic core made Low Carbon Steel 1020.

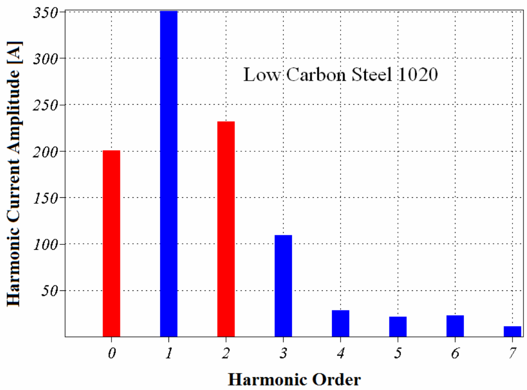

Fig.3. Histogram of the inrush current spectrum For Low Carbon Steel 1020

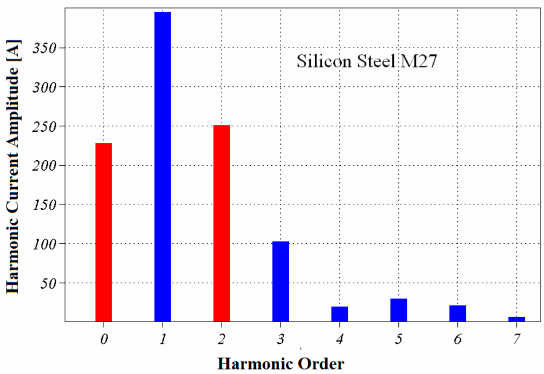

Fig.4. Histogram of the inrush current spectrum Silicon Steel M27

According to (3) for the investigated materials, was obtained:

$$\begin{cases} h_0[\%] = \dfrac{c_0}{c_1} \cdot 100 = 57.2\ \% / 57.7\%, \\ h_2[\%] = \dfrac{c_2}{c_1} \cdot 100 = 65.9\ \%. / 63.6\% \end{cases} \quad - \text{first} \quad / \quad \text{second}$$

investigated material

IV. CONCLUCSIONS

Using a simple circuit model for the energizing process of a single phase transformer, a quantitative study over the inrush current was accomplished. Thus, solving the nonlinear equations system, which derived from the proposed model, a quite accurate predetermination of the inrush current amplitude and weave form was predicted. The influence of the magnetic core characteristic was systematically analyzed for a very large class of materials used as magnetic core of the single phase transformer of powers class around 6 kVA. Along materials *B-H* description our computation took into account also the indicated stacking factors. The study reveals the importance of material characterization for the accuracy of inrush current amplitude estimation.

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REFERENCES

[1] P. C. Y. Ling and A. Basak, “Investigation on magnetizing inrush current in single-phase transformer,” *IEEE Trans. Magn.*, vol. 24, no. 6, pp. 3217–3222, Nov. 1988.

[2] J. Faiz and S. Saffari, “Inrush Current Modeling in a Single-Phase Transformer,” *IEEE Trans. on Magn.*, vol. 46, no. 2, pp. 578 - 581, Feb. 2010.

[3] A. A. Adly, “Computation of Inrush Current Forces on Transformer windings,” *IEEE Trans. Magn.*, vol. 37, no. 4, pp. 2855–2857, July 2001.

[4] M. Nagpal, T.G. Martinich, A. Moshref, K. Morison, and P. Kundur “Assessing and limiting impact of transformer inrush current on power quality,” *IEEE Trans. Power Del.*, vol. 21, no. 2, pp. 890-896, Apr. 2006.

[5] M. G. Vanti, S. L. Bertoli, S. H. L. Cabra, A. G. Geren, Jr., and P. Kuo-Peng, “Semianalytic Solution for a Simple Model of Inrush Currents in Transformers,” *IEEE Trans. Magn.*, vol. 44, no. 6, pp. 1270–1273, June 2008.

[6] Y. Wang, S.G. Abdulsalam, and W. Xu, “Analytical formula to estimate the maximum inrush current,” *IEEE Trans. Power Del.*, vol. 23, no. 2, pp. 1266-1268, Nov. 2008.

[7] A. Waindok, “A Method for Calculation of the Inrush Current in Single Phase Transformer including the Residual Flux,” *Przegląd Elektrotechniczny (Electrical Review)*, vol. 88, no 5b, pp. 194-201, 2012.

[8] X. Wang, D. W. P. Thomas, M. Sumner, J. Paul, and S. H. L. Cabral, “Characteristics of Jiles–Atherton Model Parameters and Their Application to Transformer Inrush Current Simulation,” *IEEE Trans. on Magn.*, vol. 44, no. 3, pp. 340 - 345, March 2008.

[9] J. R. Brauer "Simple equations for the magnetization and reluctivity curves of steel", IEEE Trans. Magn., vol. MAG-11, pp.81, 1975.

[10] Shampine, L.F. and Corless, R.M. "Initial Value Problems for ODEs in Problem Solving Environments". J. Comp. Appl. Math. Vol. 125(1-2). (2000): 31-40.