The Study of Transient Regimes for a Shell-Type Transformer

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***Abstract*—The transient no-load regime and transient sudden short-circuit regime, of a small power shell-type transformer, will be studied in this paper. Will be determined the current variation in the primary circuit both analytically and by numerical analysis based on finite elements method (FEM). The software used for study is MagNet, developed by the Infolytica Company**.

I. INTRODUCTION

A. *Main geometrical dimensions of the transformer*

The transformer has the main geometrical dimensions shown in Fig. 1. The primary and secondary nominal voltages are, V1n/V2n=220/16 V and the numbers of turns, N1=1320, N2=106. The transformer apparent power is S=100 VA. The magnetic core of the transformer will be made of cold rolled steel sheet with non-oriented crystals for which the maximum value of the magnetic flux density is imposed to about 1T.

B. *The parameters of the windings*

The phase resistance and leakage reactance have been calculated analytically with relations:

$$R = \rho \frac{N l_{av}}{S_1}, \quad L_\sigma = \mu_0 N^2 \frac{l_{av}}{l_s}\left(\frac{a}{3}+\frac{\delta}{2}\right) \qquad (1)$$

where l_{av} - the average length of the turn, ρ - conductor (copper) resistivity, μ_0 - air permeability, and $\delta = 0.5\text{mm}$ - air-gap between the windings, and $l_s = \left(1-\frac{a_1+a_2+\delta}{\pi h_b}\right)h_b$, a1=8mm, a2=6mm (Fig.1).

The values of the data calculated analytically are: $R_1 = 20\Omega$, $R_2 = 0.213\Omega$, $I_{10} = 0.097\text{A}$, $L_{10} = 7.22\text{H}$, $L_{1\sigma} = 13.79\text{mH}$, $L_{2\sigma} = 0.09382\text{mH}$ and $L'_{2\sigma} = 14.55\text{mH}$, the value reflected to the primary.

Considering an efficiency, $\eta = 0.85$, the transformer nominal currents are, $I_{1n} = \frac{S}{\eta V_{1n}} = 0.534\text{A}$, $I_{2n} = \frac{S}{V_{2n}} = 6.25\text{A}$.

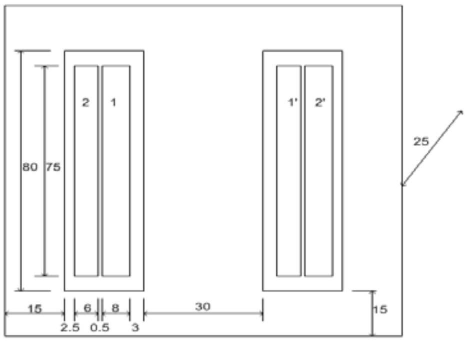


Figure 1. Main dimensions of the transformer

C. *The no-load connection to the network*

The transient regime of no-load connection to the network is described by the equation,

$$v_1 = R_{10} i_{10} + \frac{d\lambda_{10}}{dt} \qquad (2)$$

where the voltage is, $v_1 = \sqrt{2} V_1 \sin(\omega i + \alpha_c)$ and the no-load magnetic flux can be expressed in terms of the periodic and transient component, $\lambda_{10}(t) = \lambda_1(t) + \lambda_2(t)$, with *C* – a constant depending on α_c, ω – the angular frequency and α_c - the initial voltage phase in the connection moment.

The previous equation can be solved analytically only under the simplifying assumptions as: the no-load resistance causes a negligible voltage drop, and for no-load inductance, a constant value is considered, which assumes a linear magnetic circuit.

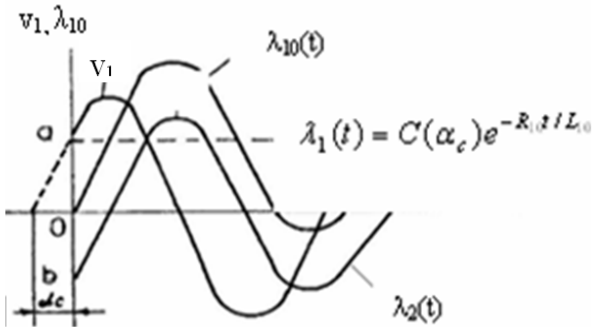


Figure 2. The voltage and flux time variation

If the residual magnetic flux in transformer is zero, the previous equation solution is

$$i_{10}(t) = -\frac{\sqrt{2}V_1}{\omega L_{10}}\cos\left(\omega t + \alpha_c\right) + \left(\frac{\sqrt{2}V_1}{\omega L_{10}}\cos\alpha_c\right)e^{-R_{10}t/L_{10}} \tag{3}$$

This solution is the sum of two components: stationary and transient. The time in which transient component is amortized is directly proportional with L_{10}/R_{10} ratio.

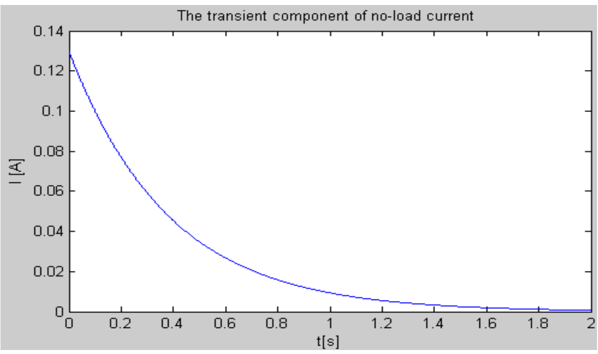
The solution obtained in the considered simplifying assumptions is sufficiently accurate for large transformers and which operate at low magnetic flux density.

But in case of small transformers, or for large transformers which operate at common flux density, the previous solution is no longer accurate.

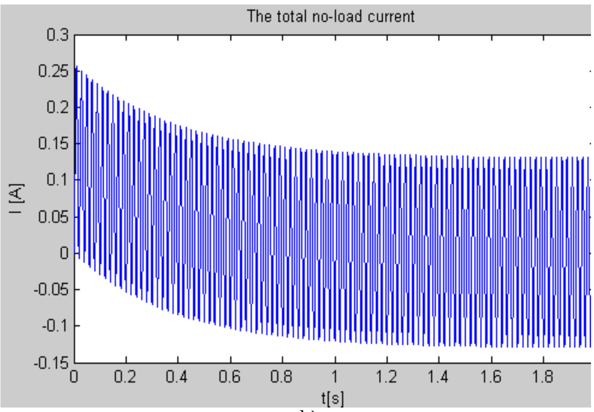
Fig. 3 shows the analytic solution of the current variation in transient regime. Magnetic circuit material is CR10, and the transformer is connected to the network at the moment when the voltage crosses zero ($\alpha_c = 0$).

D. The sudden short-circuit transient regime

Because in case of a short-circuit, the currents flowing in windings are much higher than the magnetizing current, the magnetizing inductance can be neglected, and transient regime is described by equation



a)



b)

Figure 3. The no-load connection to the network - Analytical solutions

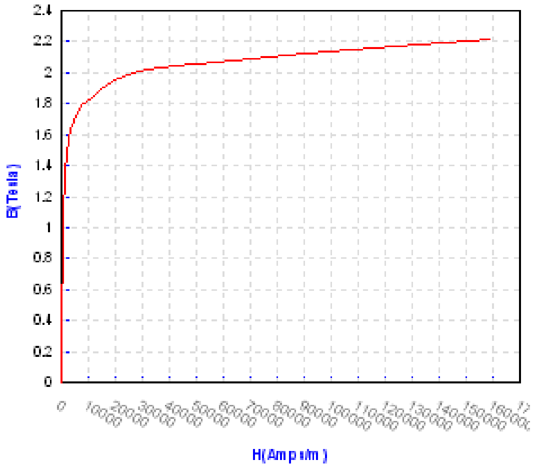


Figure 4. Magnetization curve of CR10

$$v_1 = \left(R_1 + R_2^{'}\right)i_{1sc} + \left(L_{1\sigma} + L_{2\sigma}^{'}\right)\frac{di_{1sc}}{dt} \tag{4}$$

Unlike the no-load regime, in the short-circuit regime the total leakage inductance may be considered constant, with sufficient accuracy, throughout the transitional process.

The equation solution is

$$i_{1sc}(t) = \frac{\sqrt{2}V_1}{\sqrt{R_{sc}^2 + (\omega L_{sc})^2}}\sin(\omega i + \alpha_{sc} - \varphi_{sc}) + \left(i_1(0) - \frac{\sqrt{2}V_1}{\sqrt{R_{sc}^2 + (\omega L_{sc})^2}}\sin(\alpha_{sc} - \varphi_{sc})\right) \cdot e^{-t\frac{R_{sc}}{L_{sc}}} \tag{5}$$

where $R_{sc} = R_1 + R_2^{'}$, $L_{sc} = L_{1\sigma} + L_{2\sigma}^{'}$, φ_{sc} - the voltage-current phase angle at short-circuit, and $i_1(0)$ - the primary winding current at the moment when short-circuit is produced.

This solution is presented in Fig. 5 for the case when the magnetic circuit is CR10, and the voltage phase at the moment when short-circuit is produced is $\alpha_{sc} = 270 + \varphi_{sc}$.

II. THE FINITE ELEMENTS ANALYSIS

A. The parameters of the windings

Numerical analysis will be realized so as to simulate experimental tests of the transformer.

The 3D model (Fig. 6) was done only to determine that part of the leakage and no-load inductances that are not in the 2D model, but will be introduced in the electrical circuits of this model.

The model corresponds to a portion of 1/8 of the full transformer, thus using the advantage of existing symmetries.

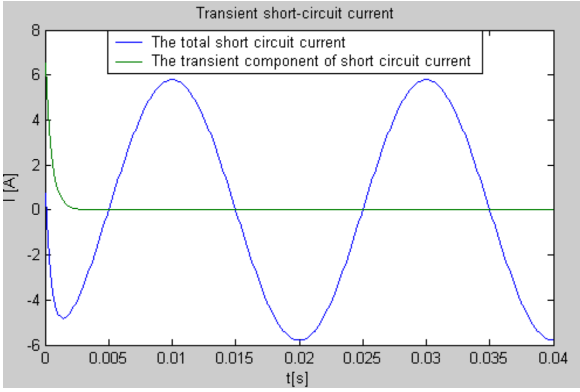


Figure 5. The sudden short-circuit – Analytical solutions

For this reason, the results will be multiplied by 8. This model is enclosed in a prism with dimensions 200x200x170mm (the calculus domain).

Boundary conditions used were the flux tangential, only on the underside using the field normal.

For the magnetic core was chosen a non-linear material, in MagNet called CR10.

The number of turns for the primary and secondary winding was set at $N_1/2=660$, and $N_2/2=53$ respectively.

The model used to study transient regimes is 2D and it corresponds to 1 / 4 of transformer.

The part of the no-load inductance which is missing in 2D model is $\frac{L_{10}(3D) - L_{10}(2D)}{4} = 0.0218H$, the leakage inductance of the primary winding which is missing, $\frac{L_{1\sigma}(3D) - L_{1\sigma}(2D)}{4} = 0.00226H$, and the leakage inductance of the secondary which is missing in 2D model, $\frac{L_{2\sigma}(3D) - L_{2\sigma}(2D)}{4} = 1.8 \cdot 10^{-5} H$.

In the electrical circuits of the 2D model have been also introduced resistances, so that the total resistances of the windings, to become equal with those analytically calculated ($R_1/4$ or $R_2/4$ for 2D model).

The electrical circuits of the transformer with additional circuit elements introduced, for transient regimes simulation, are shown in Fig. 7.

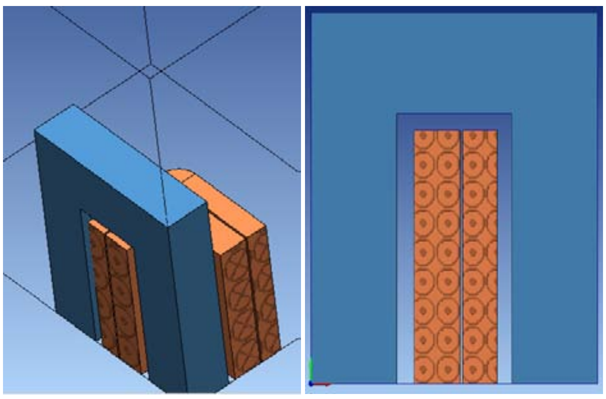
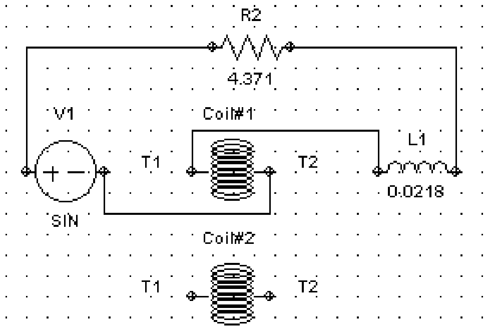
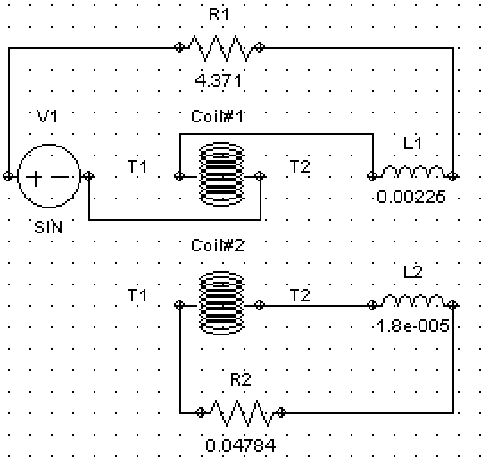


Figure 6. 3D and 2D numerical models (corresponding to 1/8 of transformer and 1/4 respectively)



a) The no-load connection



b) The sudden short circuit

Figure 7. The electrical circuits for transients regimes

Transient numerical analyses were carried out, the primary winding being fed with a voltage described by the relation, $v_1 = \frac{\sqrt{2} \cdot 220}{4} \sin(\omega t + \alpha_c)$.

Fig. 8 shows the transients no-load currents variation for different values of α_c. Note that for this small transformer, the transient component becomes insignificant in less than 1s (Fig. 8b). This time is less than that obtained analytically (Fig. 3a), which is about $4 \cdot L_{10}/R_{10} = 1.5s$. That is due to the decrease of the no-load inductance when the current increases. But the transient process can reach 20s in case of a large transformer with high voltages.

The transient current is null if the connection is made at the moment when the voltage is maximum ($\alpha_C = 90$). In this case, the steady-state regime is established directly. The worst case is when $\alpha_C = 0$, the transient current reaches maximum value.

It can be noted that the decrease of the no-load inductance in the first moments of the transient process has also the effect of increasing the maximum value of the no-load current (Fig.8 and Fig.3b).

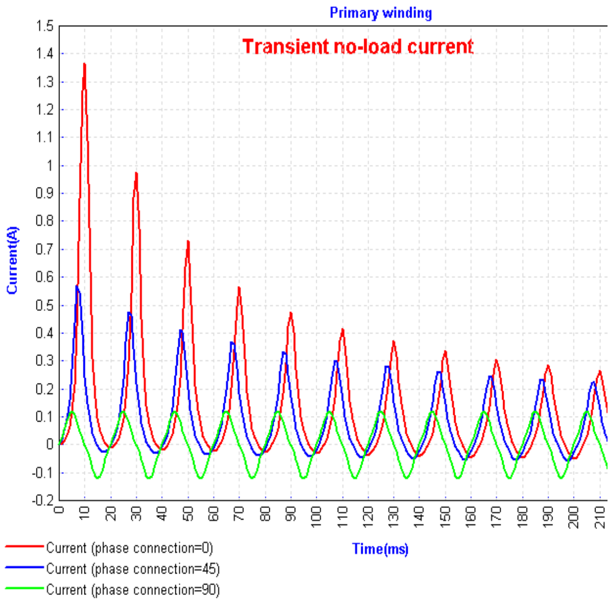
As regards the transient short-circuit regime of the studied transformer, it can be noticed that is almost negligible, Fig. 9. This is due to the very small ratio $L_{SC}/R_{SC} = 5.14 \cdot 10^{-4}$ s, which means that the transient current becomes negligible in about 2 ms.

For this reason, the transient component could only have a positive effect (in this case), causing a decrease in the initial current. Thus, the total transient current does not exceed the steady-state current, regardless when short-circuit occurs.

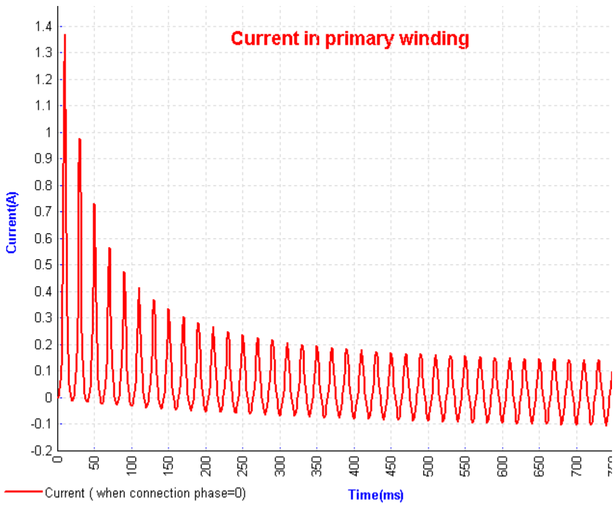
III. CONCLUSIONS

In conclusion, it is specified that the transient numerical analysis based on FEM takes into consideration permanent variation of the no-load inductance. The value of no-load inductance determines, in each moment the maximum value of the transient no-load current.

On the other hand, can emphasize that the transient short-circuit current, is determined analytically with sufficient accuracy, since the total short-circuit inductance does not change during the transient regime.



a) The transient current for different phase connection



b) The depreceation of transient component

Figure 8. The no-load currents

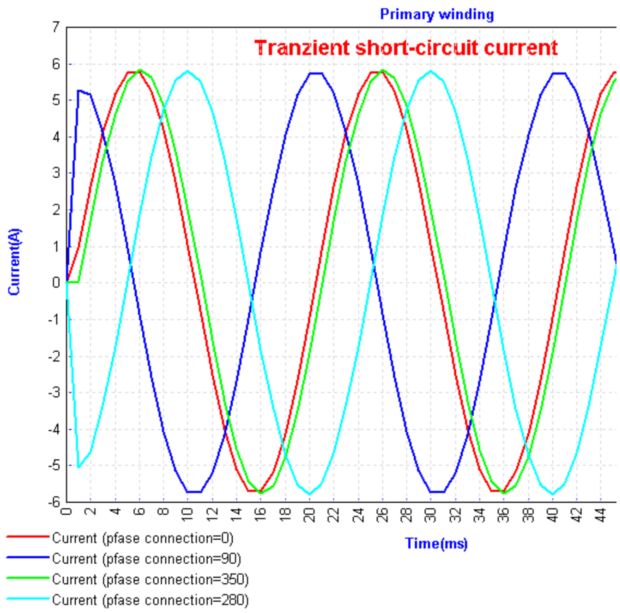


Figure 9. The sudden short circuit currents

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