TRANSIENT REGIMES OF THE THREE-PHASE POWER TRANSFORMERS

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Keywords: Power transformer, finite elements, transient analysis.

Abstract*: The transient regimes of a three-phase power transformer will be studied in this paper. The transient currents in the windings will be determined both analytically and by finite elements method (FEM). The no load and short circuit regimes will be considered. The current dependence of the instantaneous phase voltage and of the initial current value will be highlighted, by FEM. In order to determine analytically the transient currents, for inductances the analytical and FEM values will be used. The inductances are determined with FEM through the simulation of experimental tests. With FEM, the transient currents will be determined using transient analysis. Finally, the FEM and analytical results will be compared and discussed.*

1. INTRODUCTION

The electricity consumption in the world increases permanently. The more stringent restrictions regarding the interruption of power supply or other power quality parameters are imposed by the quality standards. The entire system of generation, transmission and distribution of electricity must work interconnected in a predictable manner and often loaded near to the maximum capacity, in order to comply with these rules. It is obvious that understanding and predicting how the entire system behaves requires thorough knowledge of the behavior of the components, separately and then interconnected. The main elements of the system are: generators, transformers and transmission lines. This paper is oriented toward power system transformers operating at power frequency level (50 Hz).

Generation of power with the synchronous machine is usually at a relatively low voltage, which is most desirable economically. Stepping up the voltage to high voltage, or extra high voltage, is done through power transformers to match the power transmission requirements: the minimization of the losses and the increase of the transmission power of the lines. The level of the transmission voltage is then stepped down (usually in many stages and of course using power transformers) for distribution and utilization purposes.

From technical-economical point of view, often more transformers must work in parallel. The connection or disconnection to or from the network depends on the electricity needs at a time. The no loaded transformer connection to the network determines a transient regime. The duration of the transient process and the manner in which the system is affected depends on the voltage, power and the circuit parameters of the transformer. The no load transient current is not dangerous for the transformer, but the transformer protection can be triggered.

When the sudden short circuit occurs, another transient regime arises. Although the duration of this regime is less than in the first case, the currents are well above the nominal value and the electrical loads are very important. The values of the transient currents, for different situations, must be accurately calculated in order to have a correct sizing of the protections. In this paper, the analytical results (of course based on simplified calculation) obtained using the value of electrical parameters analytically determined first, and then the values obtained by FEM simulations, will be discussed. Finally, the transient currents will be determined by transient finite elements analysis. In this case the variation of the inductances during the transient process is taken into account.

2. TRANSIENT REGIMES

2.1. Analytical solutions

In case of the no load connection to the network, the current variation in the primary winding of the transformer is described by equation (1). The resistive drop voltage is neglected and also the residual magnetic flux and the inductance is considered constant.

$$i_{10}(t)=-\frac{\sqrt{2}V_1}{\omega L_{10}}sin(\omega t+\alpha_{10}-\varphi_{10})-\left(\frac{\sqrt{2}V_1}{\omega L_{10}}sin(\alpha_{10}-\varphi_{10}\right)\cdot e^{-R_{10}t/L_{10}} \quad (1)$$

In (1) is noted with: V_1 – the phase voltage; R_{10}, L_{10} – the phase resistance and inductance respectively, in no load regime; ω – the angular frequency; φ_{10} - the power factor in no load regime and α_{10} - the initial voltage phase in the connection moment.

In case of the sudden short circuit, the current variation is described by equation (2), where is noted: with $i_1(0)$ the initial current.

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

The other parameters have the same meaning as in (1), but for the short circuit regime.

For the analyzed power transformer, the inductance in no load and short circuit regime respectively, analytically computed, has the values 70.14 H and 0.244 H. Also for no load regime the resistance is 9.21 Ω, and the short circuit resistance is 19.7 Ω. The rated voltages are 10000/400 V.

2.2. FEM – Analytical solutions

In this case the previous relationship has been used, but for inductances the FEM computed values were inserted. In order to compute these inductances, the corresponding numerical models were built. The models contain the magnetic core (the yokes and the column), the electrical circuits (six coils) and the air volume surrounding the transformer, fig. 1. Because this is not a reduced model (the entire transformer is included) on the all boundary of the analyzed domain, ”Flux tangential” boundary conditions were used.

In order to compute the inductance for no load regime there are several possibilities, further the one used in this paper being described. The number of turns and resistance for each primary and secondary coil were set. Next, the primary winding was supplied for a three phase voltage source and the secondary winding is no loaded, fig. 2 (the no load test is simulated). After the time-harmonic analysis, the no load current phase was obtained and the corresponding inductance was computed.

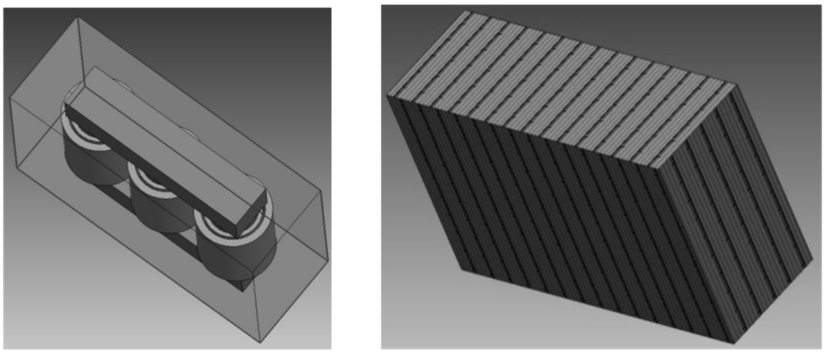


Fig. 1- The numerical model and the boundary condition

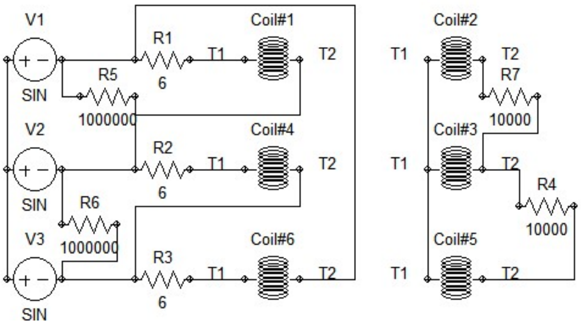


Fig. 2 – The winding feeding in no load regime

The studied transformer has delta connection in primary and wye connection in secondary. The R_1, R_2 and R_3 resistances are introduced to correct the resistance of each coil of the primary winding, so that the resistance be the same to the analytically computed one. The R_4, R_5, R_6 and R_7 resistances represent voltmeters.

The short circuit inductance can also be determined by FEM in several manners. In this paper it has been obtained simulating the short circuit test. With the secondary winding short circuited, fig. 3, the primary winding has been fed so that the current be the rated one. Time-harmonic analysis will be performed and the winding currents will be obtained. Based on the primary winding current, short circuit resistance and the phase voltage, the short circuit inductance will be computed. The R_8, R_9, and R_{10} resistances are in series with the secondary coils because in the numerical model, the insulated material is not taken into account and the model resistance is lower than the analytically computed one.

Based on FEM results, the inductance in no load regime is 69.34 H and the short circuit inductance is 0.188 H.

2.3. FEM solutions

In order to compute the transient currents by FEM, a transient analysis will be performed. The numerical model is the same with the former one, but switches are inserted in the electrical circuits, fig. 4, and they close at a preset time.

So for no load connection to the network, in primary winding three switches are used (S_1, S_2, S_3). For sudden short circuit, two switches are used (S_4 and S_5) in secondary winding.

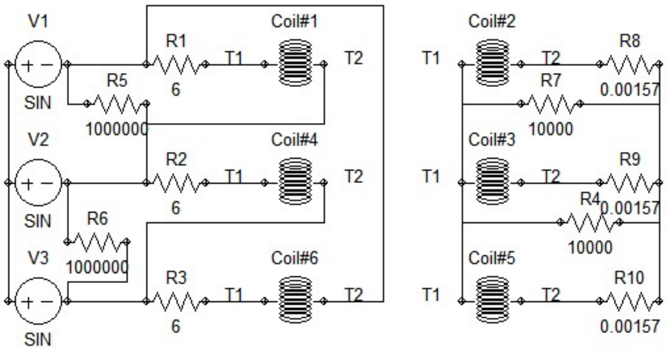


Fig. 3 – The winding feeding at short circuit test

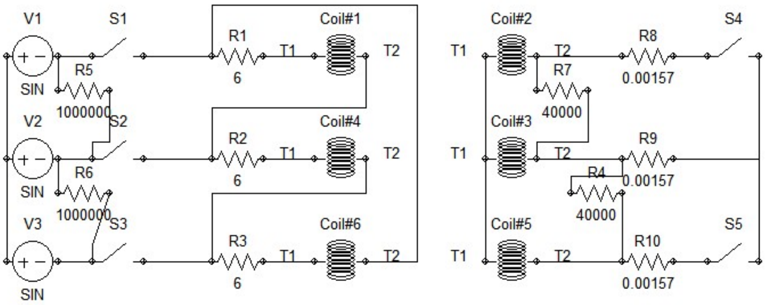
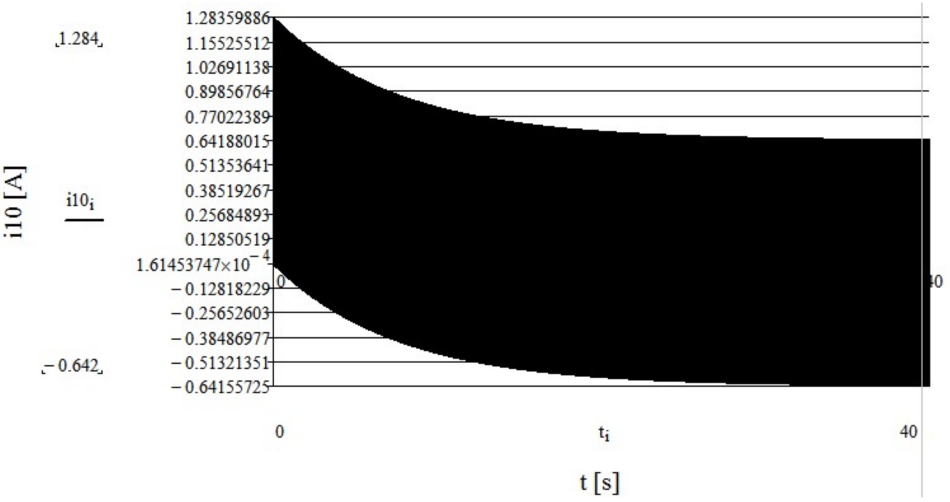


Fig. 4 – The winding of transformer in transient simulation

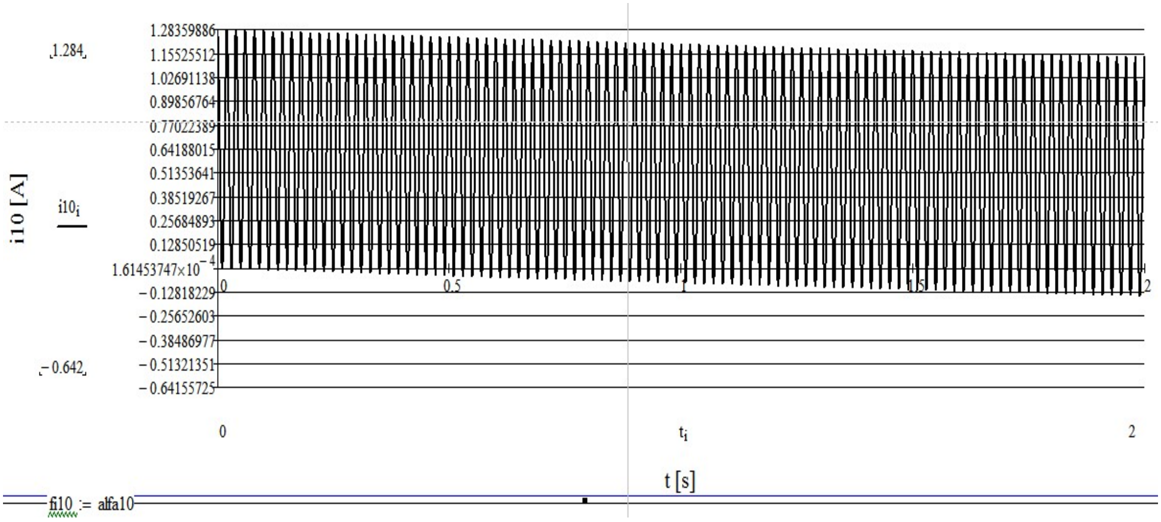
In transient analysis the used step was 1 ms. The total analysis time was 1 s for no load connection to the network and 0.4 s for sudden short circuit.

3. RESULTS

For the two transient regimes, the obtained results (analytical, FEM – Analytical and transient FEM) are showed in the following.



a)



b)

Fig. 5 – The transient current for no load connection to the network: a) (0-40s) and b) (0-2s); α_{10}=0. Analytical results

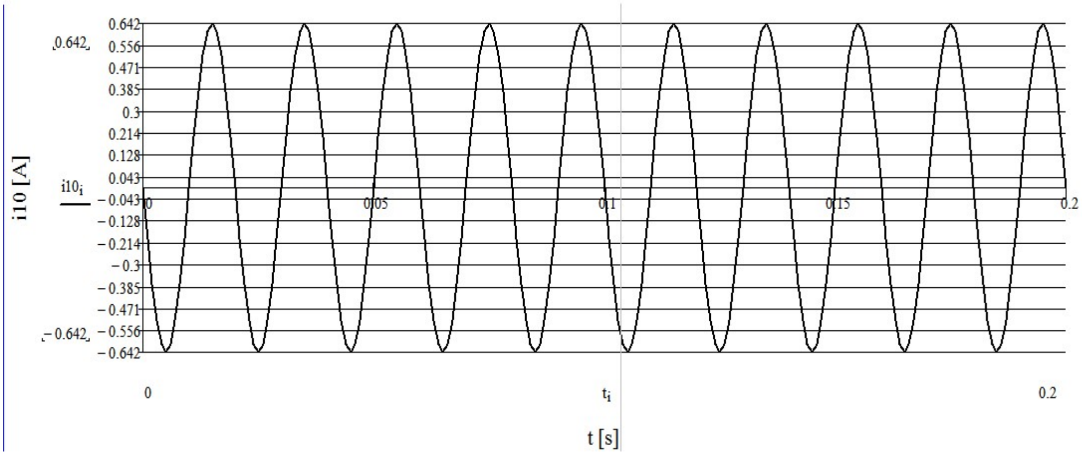
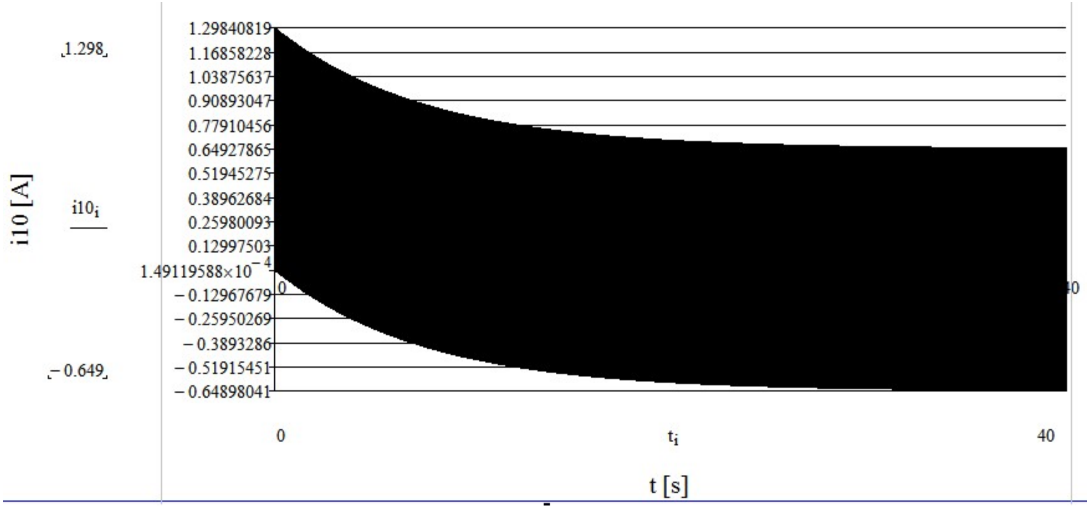


Fig. 6 – The current for no load connection to the network: (0-0.2s); $\alpha_{10}=\varphi_{10}$. Analytical result



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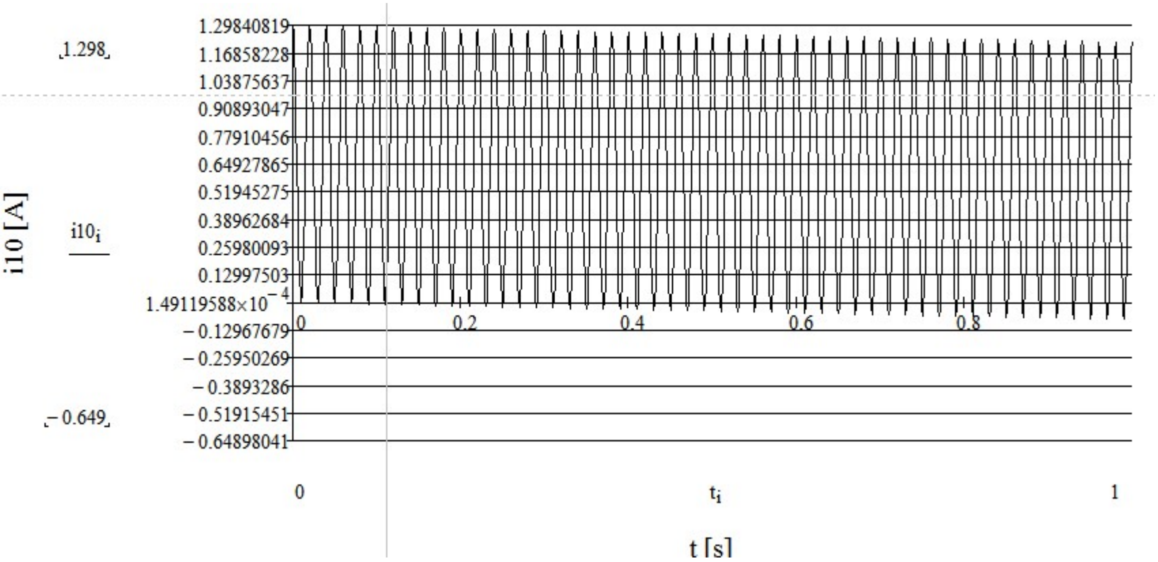


b)

Fig. 7 – The transient current for no load connection to the network: a) (0-40s) and b) (0-1s); α$_{10}$=0. FEM - Analytical results

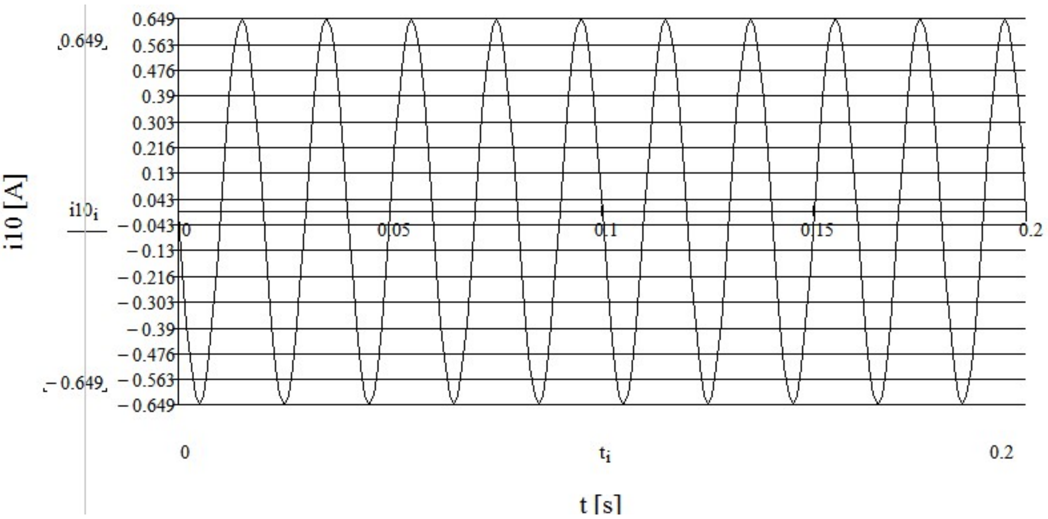
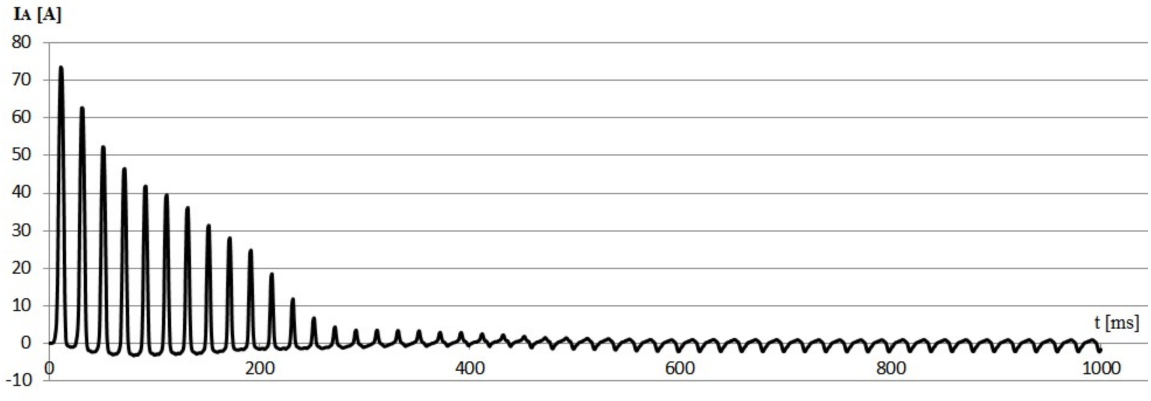
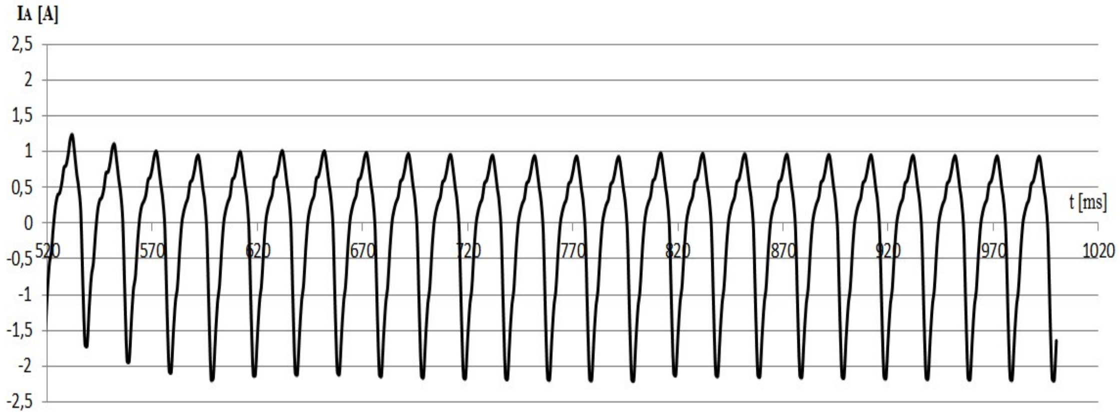


Fig. 8 – The current for no load connection to the network, (0-0.2s); α$_{10}$=φ$_{10}$. FEM - Analytical result

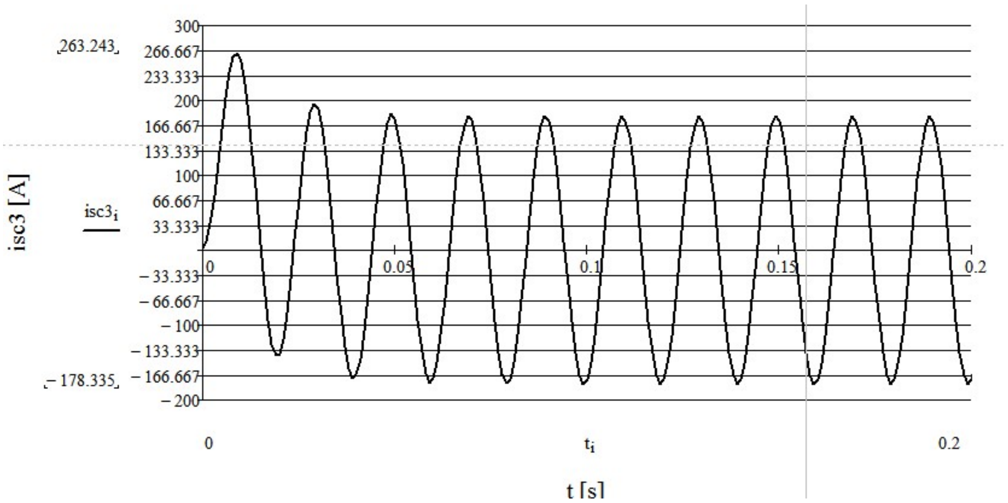


a) 0-1000 ms

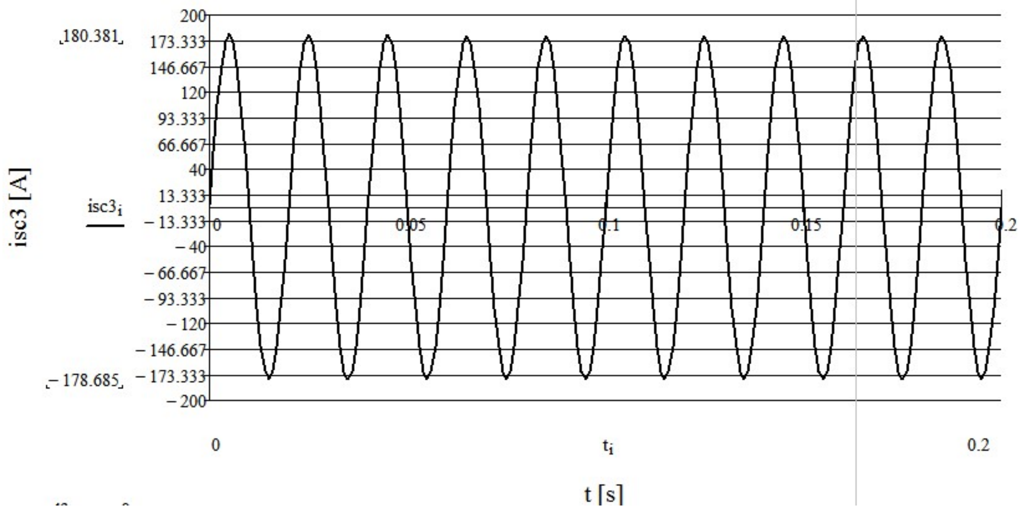


b) 520-1000 ms

Fig. 9 – The transient current for no load connection; α_{10}=0; FEM result

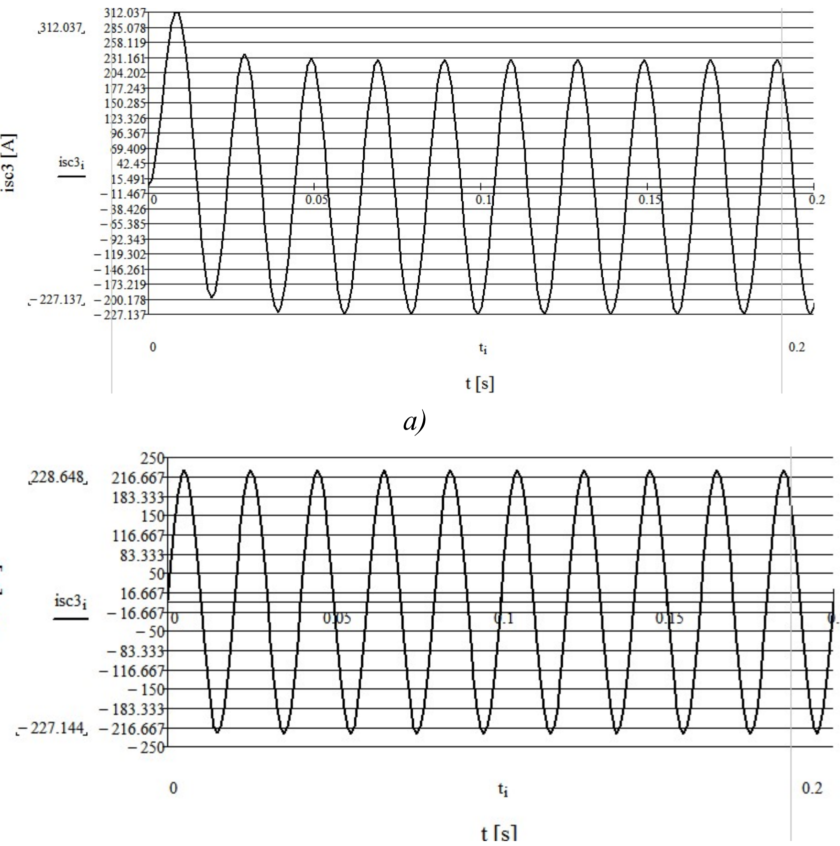


a)



b)

Fig. 10 – The current for sudden short circuit; a) α_{sc}=0; b) α_{sc}=φ_{sc}. Analytical results



a)

b)

Fig. 11- The current for sudden short circuit: a) $\alpha_{sc}=0$; b) $\alpha_{sc}=\varphi_{sc}$. FEM - Analytical results

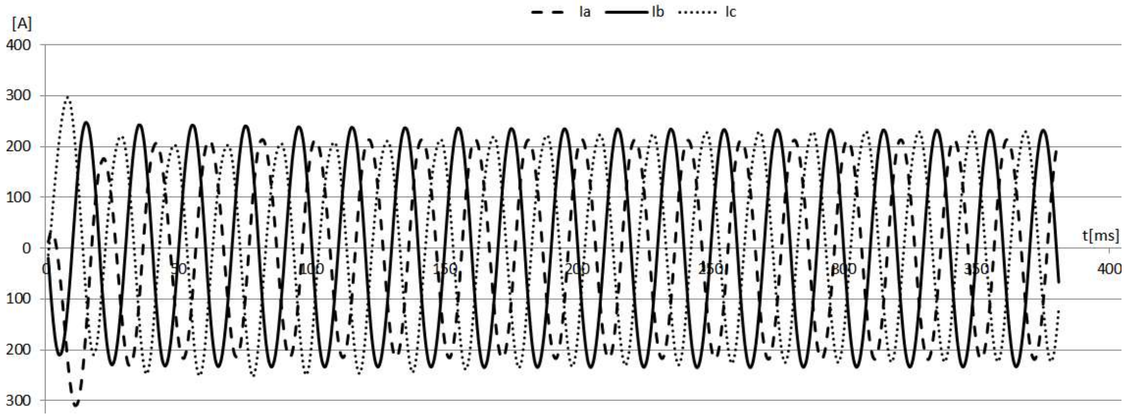


Fig. 12 – The transient currents for sudden short circuit; FEM solutions

4. CONCLUSIONS

Regarding the obtained results, it can be noticed that for the inductance in no load regime, the analytical value is very close to the FEM value. For this reason, the transient current in case of no load connection to the network, analytically computed, has the same maximum value as the FEM – Analytical one. As concerning the current obtained by transient analysis, it differs very much from the previous ones. This maximum value is approximately 73 A, that means over 100 times the value of the steady states current, being in accordance with specialty literature [3]. It can be emphasized that in case of no load connection to the network, the considered simplifying hypotheses lead to unacceptable errors, even if the used values for the transformer parameters are FEM computed. The main cause of these errors is that the inductance value has been considered constant. Actually this inductance has a low initial value and then increases up to the steady state value. For the studied transformer, it has been noticed that the initial value is only 1.23 H and the steady state value is 69.34 H, which means that the initial value is more than 50 times lower than the steady state value.

As for short circuit, the FEM inductance mainly differs from the analytical one. This is because the magnetic core material used in simulation has, in linear domain, the magnetic properties a little different from those used in analytical computation. On the other hand, the transient current FEM – Analytical determined is very close to the current obtained by transient FEM. This is due to the fact that short circuit inductance is actually constant, because the magnetic core is slightly loaded, working on the linear B-H characteristic.

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