

Transient Phenomena during the Three-Phase 300MVA Transformer Energization on the Transmission Network

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ABSTRACT

Connecting the transformer to the network may incur inrush current, which is significantly higher than the rated current of the transformer. The main cause of this phenomenon lies in the nonlinearity of the magnetic circuit. The value of the inrush current depends of the time moment of the energization and the residual magnetism in the transformer core. While connecting, the operating point of the magnetization characteristic can be found deep in the saturation region resulting in occurrence of large transformer currents that can trigger the transformer protection. Tripping of protection immediately after the transformer energization raises doubts about the transformer health. Inrush current can cause a number of other disadvantages such as the negative impact on other transformers connected on the same busbar; the increase of the transformer noise due to the large current value, the increase of the voltage drops in the network. The paper presents a simulation of the 300 MVA transformer energization using the MATLAB/Simulink software.

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1. INTRODUCTION

Immediately after connecting the transformer with no-load on the grid voltage, the magnetic flux can reach two times higher value than nominal, which due to nonlinearity of the iron core affects the transformer current [1]. The maximum value of the current in this condition is higher as the cross-section of the winding gets closer to the cross-section of the ferit plates. It is noticed that the lower current value is obtained when the remanent flux value is lower and also when the transformer dimensions are smaller. The maximum value of current at no-load is calculated with use of numeric algorithms [2]. A high value of inrush current has a negative impact on the transformer mechanical stress and decreases the quality of electric energy [3-7]. In the paper [8] numerical calculations of inrush current of power transformers are presented. The value of inrush current falls on low value in few tenths of second, while the transient phenomena takes a few seconds [9]. In papers [10-14] are shown energizations of three-phase transformer with taking into account the effect of hysteresis loop, remanent magnetic flux and the moment of transformer energization. In paper [15] authors described scenarios of energization of power transformers depending on the moment of the enegergization. The problem of inrush current is expressed in three-phase transformers and also in single-phase transformers [16]. A mathematic model description of the three-phase transformer is shown in papers [17-18]. Magnetization curves and their approximations are given in papers [19-20]. High values of inrush current for real different cases of power transformer energization are given in papers [21-23].

2. RESIDUAL FLUX

At the time moment when the transformer is connected to grid, the voltage value is [3]:

$$v(t) = V_M \sin(\omega t + \theta) \quad (1)$$

or voltage value can be written as:

$$v(t) = Ri + L \frac{di}{dt} \quad (2)$$

current i is calculated from differential equation (2):

$$i = i_s + i_p = \frac{V_m}{\sqrt{R^2 + (\omega L)^2}} \sin(\omega t + \theta - \varphi_0) + \frac{V_m}{\sqrt{R^2 + (\omega L)^2}} \sin(\theta - \varphi_0) e^{-\frac{t}{T_0}} \quad (3)$$

where is:

$$T_0 = \frac{L}{R}; \quad \text{tg} \varphi_0 = \frac{\omega L}{R} = \frac{X}{R}$$

while the flux value is [3]:

$$\phi(t) = \frac{1}{N_p} \int V_M \sin(\omega t + \theta) dt \quad (4)$$

In accordance to article [13] the residual core flux can raise up to 85% of the nominal flux but more typical magnitudes are in the range of 20 to 70% of the nominal flux value. Analytical formulation of the maximal flux given in [1] and [11] is:

$$\phi_{max} = 2\phi_n + \phi_r \quad (5)$$

3. SIMULATION AND RESULT ANALYSIS

The mathematical model was implemented in the software package Matlab / Simulink, and tested for a transformer whose parameters are shown in Table 1.

Table 1. Nominal Data and Standard Parameters of the Three-phase Transformer-400 kV Substation Peja 3 – Kosovo

Data	Value
Rated power primary / secondary	300/300 MVA
Primary voltage	400kV
Secondary voltage	115 kV
Frequency	50 Hz
Parameters of primary winding	V1 = 400 kV; R1 = 0.0018 pu; L1 = 0.076 pu
Parameters of secondary winding	V2 = 110 kV; R2 = 0.0018 pu; L2 = 0.076 pu
Short circuit voltage	12.5 %

A computer model was developed in MATLAB / Simulink program. For the transformer model is used element named "Saturable Transformer," the transformer with two windings. The model takes into account the winding resistance (R1 R2 R3), the leakage inductances (L1 L2 L3), as well as the core magnetization characteristic. The transformer is connected to the network through the switch that connects the transformer at a given time moment and thus simulates transients of all three phases. Oscillograms present voltage, current and the flux of the primary winding.

Flux-current Characteristic as shown in Figure 1. The layout of the MATLAB / Simulink modeled transformer connected to the network is given in Figure 2.

Simulations were performed for several cases of power transformer energization. Time moments of energization and remanent magnetic flux values were taken into account. The simulations were performed for three different time moments of energization: $t_1=0.02$ s; $t_2=0.0134$ s; $t_3=0.0266$ s in all three phases. The time

moment t_1 corresponds to phase L1, the time moment t_2 corresponds to phase L2 and the time moment t_3 corresponds to phase L3 of the real three phase transformer. In the real three-phase transformer energization transients in all three phases occur at the same time.

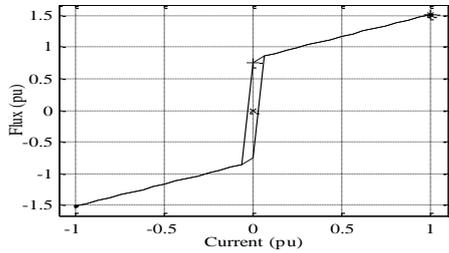


Figure 1. Flux-current Characteristic

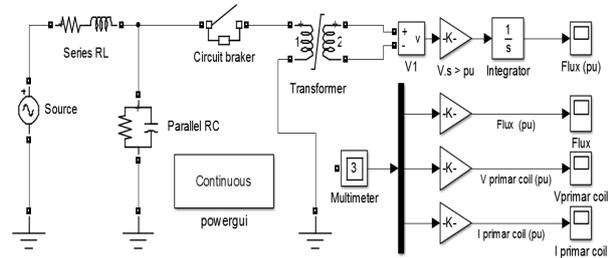


Figure 2. Transformer Model Developed in MATLAB / Simulink Software Package

3.1. Energization of Simulated Transformer Model at the Time Moment t_1

Figures 3 to 5 presents simulation results without remanent magnetism at t_1 . This is the time moment when the voltage value passes through the zero- point and the maximum magnetic flux is equal to the doubled nominal value. Energization of the simulated model represents transients of three phase transformer through the first winding of phase L1. Oscillograms in Figures 3, 4 and 5 show the change in voltage, current and flux in the time interval of a one second. The transformer energization entails an adverse effect on the network, because in this case the growth of inrush current is up to about 4 times the exploitation. The voltage on the primary winding of the transformer has a nonsinusoidal shape because of higher harmonics occurrence. The current on the primary winding reaches a value of 2.3 pu. To induce the counter vantage to the connected voltage U_1 , a sine flux Φ appears in the transformer core, which lags behind the applied voltage for 90° . Magnetizing current is not sinusoidal, as the halfperiod is symmetrical, thus it contains odd sine and cosine harmonics [1].

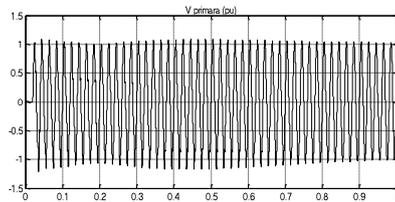


Figure 3. Voltage on Primary Winding of Simulated Transformer without Remanent Magnetism at t_1 in pu.

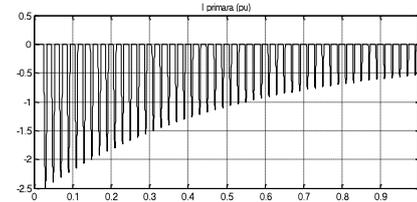


Figure 4. Current in Primary Winding of Simulated Transformer without Remanent Magnetism at t_1 in pu.

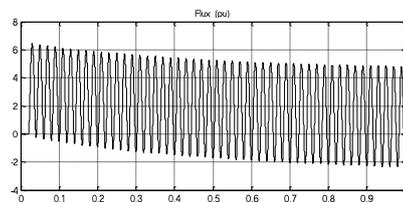


Figure 5. Flux at the Primary of Simulated Transformer without Remanent Magnetism at t_1 in pu.

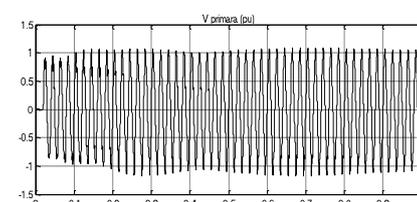


Figure 6. Voltage on Primary Winding of Simulated Transformer with Remanent Magnetism Value of 0.75 pu. at t_1 in pu.

Figures 6-8 present the results of simulations with remanent magnetism at energization at t_1 . While energizing the transformer with remanent magnetism, higher values of energization current occur in than

without remanent magnetism. In the considered model with remanent magnetism, source current has a value about 4.16 pu. According to equation 5, the maximum flux value is increased by the value of residual remanent magnetism. In this case, the magnetizing current reaches a value of about 4.61 pu.

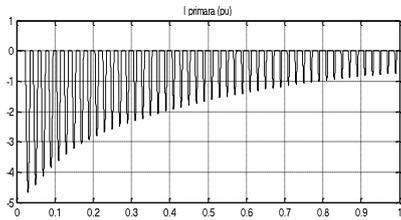


Figure 7. Current in Primary Winding of Simulated Transformer with Remanent Magnetism value of 0.75 pu at t_1 in pu.

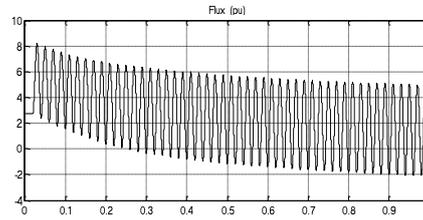


Figure 8. Flux at the Primary of Simulated Transformer with Remanent Magnetism Value of 0.75 pu at t_1 in pu.

3.2. Energizing of the Simulated Transformer at the Time Moment t_2

Figures 9 to 11 show the power transformer energization at the time moment t_2 without remanent magnetism in phase L2. Inrush current through the primary winding of simulated transformer is 0.92 pu.

Figures 12 to 14 the power transformer energization at the time moment t_2 with remanent magnetism in phase L2. An evident disorder of the current source amplitude appears while the maximum current value reaches 1.3 times nominal value. The winding current of phase L2 is 0.14 pu.

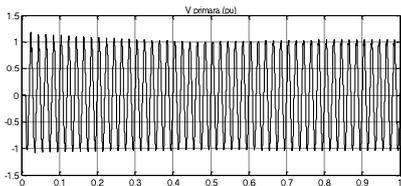


Figure 9. Voltage on Primary Winding of Simulated Transformer without Remanent Magnetism at t_2 in pu.

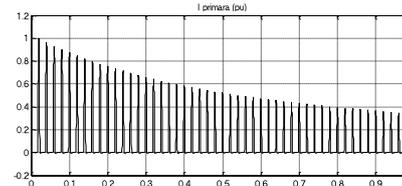


Figure 10. Current in Primary Winding of Simulated Transformer without Remanent Magnetism at t_2 in pu.

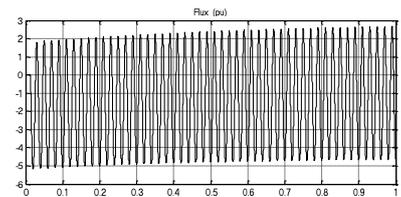


Figure 11. Flux at the Primary of Simulated Transformer without Remanent Magnetism at t_2 in pu.

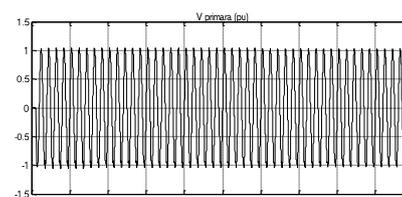


Figure 12. Voltage on Primary Winding of Simulated Transformer with Remanent Magnetism Value of 0.75 pu at t_2 in pu.

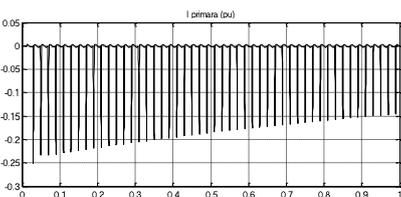


Figure 13. Current in Primary Winding of Simulated Transformer with Remanent Magnetism Value of 0.75 pu at t_2 in pu.

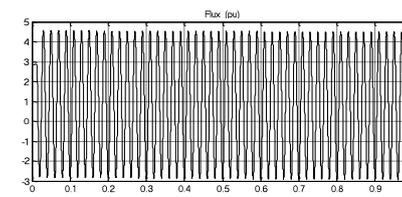


Figure 14. Flux at the Primary of Simulated Transformer with Remanent Magnetism Value of 0.75 pu at t_2 in pu.

3.3. Energizing of the Simulated Transformer at Time Moment t_3

Figures 15 to 20 show oscillograms of transformer energization at the time moment t_3 without remanent magnetism in phase L3. Energization current in this phase winding reaches 0.92 pu. Figures 21 to 23 show transformer energization at the time moment t_3 with a remanent magnetism value of 0.75 pu, phase L3. The energization current reaches 0.23 pu.

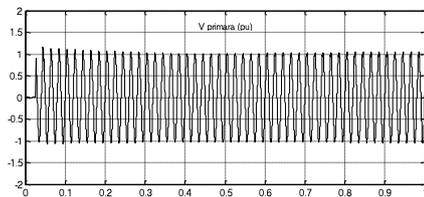


Figure 15. Voltage on Primary Winding of Simulated Transformer without Remanent Magnetism at t_3 in pu.

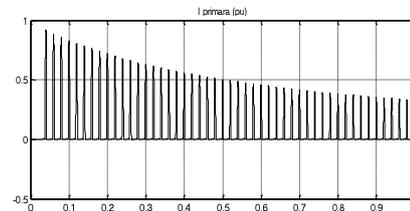


Figure 16. Current in Primary Winding of Simulated Transformer without Remanent Magnetism at t_3 in pu.

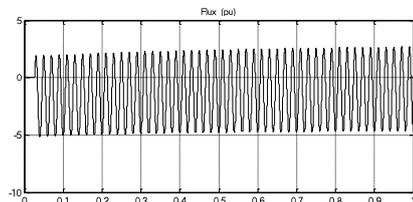


Figure 17. Flux at the Primary of Simulated Transformer without Remanent Magnetism at t_3 in pu.

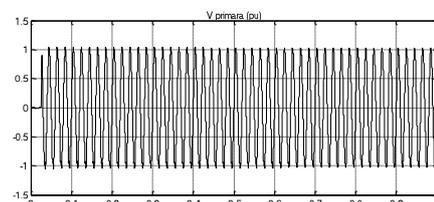


Figure 18. Voltage on Primary Winding of Simulated Transformer with Remanent Magnetism Value of 0.75 pu at t_3 in pu.

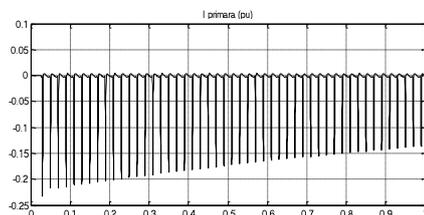


Figure 19. Current in primary winding of simulated transformer with remanent magnetism value of 0.75 pu at t_3 in pu.

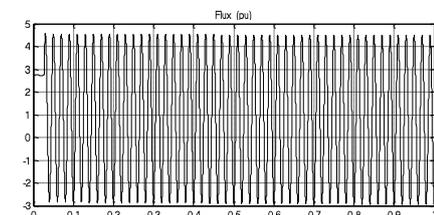


Figure 20. Flux at the primary of simulated transformer with remanent magnetism value of 0.75 pu at t_3 in pu.

3.3. Analysis Results

Simulations of transformer energization were performed at different time moments and different values of remanent flux. In the case 3.1 at the time moment of energization, the current i_s and the current i_p from equation 3 have the same value but different signs and the resulting current as the sum of those two currents is zero. This corresponds to the expected physical phenomena at the beginning of the energization, because, depending on the value of the applied voltage $v(t)$ (1), the winding current cannot be changed instantly. The role of the current i_p is to ensure preservation of the initial values of i (3) at the time moment of the energization.

Based on the current equation (3) it can be seen that the transient component of the current i_p reaches its maximal value at $\alpha_0=0^\circ$ i.e. when the transformer is connected to the grid at the time moment when the voltage value is equal to zero. On the other side, when the transformer is connected at the time moment when the voltage reaches maximal value $-u_l=U_{1m}$ i.e. $\alpha_0=90^\circ$ equation (3), the transient current is zero.

The energization current value depends on the value of the remanent magnetism at the moment of energization. The higher remanent magnetism value results in the higher energization current. The lowest value of the energization current is in the moment of the energization when the primary voltage value is the

highest and without presence of remanent magnetism. This occurs at the first power transformer energization. In a three-phase system, voltages are phase-shifted by angle of 120° . To present a real transformer energization, simulations were carried out for three different values of AC sine voltage. The energization can occur in any time moment, or applied voltage value from equation (1). For the phase L1 simulation is made when the voltage value passes through the zero point and energization current values are the highest, while in phases L2 and L3 occur increase of inrush current amplitude value, but in a smaller amount.

Authors of paper [12] simulated a transformer with similar parameters and obtained the highest inrush current value of 2.59 pu (on the phase where the voltage passes zero point at the moment of energization).

4. CONCLUSION

The major influence on the inrush current makes the value of connecting voltage and the value of the remanent magnetism in the transformer core at the moment of the energization. The inrush current value can be several times higher than the energization current. Such high current values can trip the transformer protection and thus make costs to the consumer and energy supplier.

Simulations in this paper show inrush current in three different time moments of the power transformer energization. Maximal inrush current appeared at the time moment of the energization when the applied phase voltage value was zero with residual magnetism in transformer iron core.

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