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Analysis of a three-phase three-legged power transformer fundamental ferroresonance

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Abstract. The paper analyses the ferroresonance phenomenon using measurements, modeling and simulations. The measurements are performed on a ferroresonant system in a laboratory set-up as an equivalent to an existing power-network subsystem in which a three-phase three-legged power transformer is brought to a ferroresonance state by applying irregular switching of a circuit breaker. An equivalent model of a three-phase three-legged power transformer is used taking into account both the magnetic coupling of the three legs over a zero-sequence inductance and the magnetic asymmetry of the transformer legs. The experimentally obtained nonlinear magnetization curve is well approximated using the proposed double exponential function. The numerical results with the presented mathematical model are verified by comparing them with the results of the corresponding measurements.

Keywords: ferroresonance, measurement, modeling, three-phase three-legged power transformer

Analiza osnovne feroresonance trifaznega trikrakega močnostnega transformatorja

V članku je predstavljena analiza pojava feroresonance, vključno z modeliranjem meritev in simulacijami. Meritve so bile izvedene na feroresonančnem sistemu v laboratorijskih pogojih, ki so bili prilagojeni tako, da posnemajo enakovreden obstoječi podsistem elektroenergetskega omrežja, v katerem je trifazni trikraki močnostni transformator zaradi nepravilnega preklopa odklopnika priveden v feroresonančno stanje. Uporabljen je bil enakovreden model trifaznega močnostnega transformatorja s tremi kraki, pri čemer sta bili upoštevani tako magnetna sklopitev treh krakov prek induktivnosti ničelnega zaporedja kot tudi magnetna asimetrija krakov transformatorja. Eksperimentalno pridobljena krivulja nelinearne magnetizacije je zelo natančno aproksimirana s predlagano dvojno eksponentno funkcijo. Dobljeni matematični model in njegove numerične rezultate smo preverili s primerjavo z ustreznimi meritvami.

1 INTRODUCTION

Ferroresonance is a nonlinear dynamic phenomenon that appears due to energy oscillations between a nonlinear magnetic inductance and a linear electric capacitance. The harmonic power sources and low losses of power systems considerably contribute to this undesired phenomenon [1]-[2].

Components with nonlinear inductances, such as iron cores of voltage and power transformers are present everywhere in the network. Electric capacitances are also numerous in the network. They are installed in circuit breakers for uniform voltage distribution, used for the compensation of reactive power, and they exist as mutual and ground electric capacitances between overhead lines, underground cables, etc. [3]-[4]. The power system voltage waveform can be considerably distorted due to polyharmonic currents and voltages produced by the ferroresonance effect. Considering its negative impact on the system stability, it is almost impossible to conduct experiments and investigations of the ferroresonance effect directly in the network. Consequently, to analyse ferroresonance, mathematical models, numerical simulations and laboratory measurements are usually used.

Development of an accurate mathematical model capable of predicting ferroresonance is a complex task. Due to their complexity, nonlinearity and non-deterministic nature, the parameters of a real system inevitably deviate from the corresponding parameters of the mathematical model, thus affecting the model accuracy. In modeling ferroresonance, a considerable attention should therefore be paid to transformer modeling. The current attempts to investigate the ferroresonance phenomenon are usually based on modeling and measurement a single-phase transformer [5]-[13]. Modeling a three-phase power transformer in the context of ferroresonance, with a special focus on modeling nonlinear magnetizing curves, is a considerable modeling challenge. This is probably the main reason why scientific publications dealing with ferroresonance of three-phase transformers are rather scarce [14]-[20].

The main goal of the paper is to present a comprehensive ferroresonance study that includes: assembly of a ferroresonance system in a laboratory set-up; development of a suggested model of a three-phase three-legged power transformer by taking into account both the magnetic coupling between the transformer legs

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over a zero-sequence magnetizing inductance and the magnetic asymmetry of the transformer legs; approximation of the nonlinear magnetizing curves of the transformer by employing an original double-exponential function; validation of the proposed mathematic model of the studied ferroresonance system by comparing the simulation and measurement results.

The rest of the paper is organized as follows. Section 2 reviews measurement results of a ferroresonant system assembled in a lab and describes in detail the used modeling procedure. Section 3 shows compares the simulated and measured ferroresonant voltage waveforms. Section 4 draws conclusions of the study.

2 Ferroresonance measurement and modeling

To anable an extensive experimental study and measurement of the ferroresonance phenomenon, a nonlinear system closely resembling actual ferroresonance states in the network is set up. The system consists of a three-phase three-legged power transformer in a no-load regime, a capacitor group and a three-phase circuit breaker. The ferroresonance oscillations of the system are excited by irregular switching operations of the circuit breaker.

Two different configurations of the system are analyzed in terms of their dependence on the switching operations and capacitors connection.

- Variant 1 (Case Study 1):

The ferroresonance oscillations are excited by switching-on only one phase of the transformer while the switching-on the remaining two phases fails (Figure 1). The ferroresonant circuit is formed over two capacitors of the open phases (phases 2 and 3) and the nonlinear inductance of the transformer. The capacitors are provided for electric capacitances of the overhead transmission lines, underground cables and capacitor banks for the network reactive power compensation.

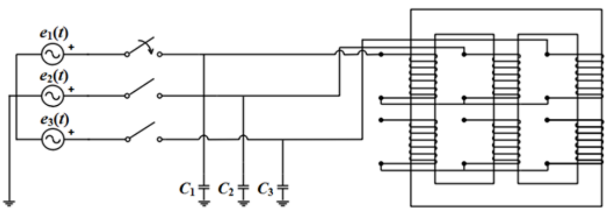

Figure 1. Ferroresonance of a three-phase three-legged power transformer – switching-on phase 1.

- Variant 2 (Case Study 2):

The transformer is turned into a ferroresonance state by a three-phase switching-on, when a simultaneous three-phase switching operation is performed over three series capacitors (Figure 2). Such ferroresonant state closely resembles an actual situation of a series compensation of the network reactive power.

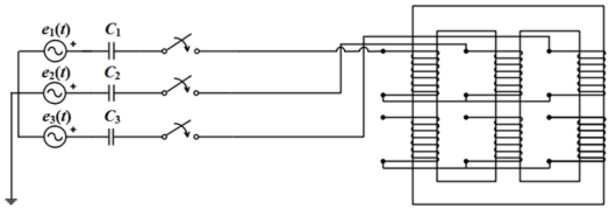

Figure 2. Ferroresonance of a three-phase three-legged power transformer – simultaneous switching-on the phases.

2.1 Measurement system

The measurements are performed on a three-phase three-legged power transformer with the voltage ratio 500/380 V, nominal power 2.4 kVA, and Y-connection of the primary and secondary side with the insulated neutral point. The capacitors used for Variant 1 and 2 are different:

- Variant 1: $C_1 = 2{,}05\,\mu F$, $C_2 = 2{,}09\,\mu F$, $C_3 = 2{,}04\,\mu F$,
- Variant 2: $C_1 = 5{,}59\,\mu F$, $C_2 = 5{,}54\,\mu F$, $C_3 = 5{,}57\,\mu F$.

To achieve an independent asynchronous switching operation in Variant 1, three single-phase circuit breakers are used.

The waveforms of the phase voltages and the neutral point voltage are measured. In Variant 1, the voltage terminals of the measuring device are connected before the circuit breaker in order to measure the voltage form before the ferroresonance occurrence. The remaining voltages are measured at the transformer contacts. In Variant 2, the voltage terminals of the measurement device are connected before the circuit breaker in all three phases.

To record the waveform of the ferroresonant voltages, an electric power quality analyzer is used (FLUKE 434). The recorded waveforms and those obtained with numerical simulations are presented in Section 3.

2.2 Mathematical model of a three–phase three–legged power transformer

A very important component of the ferroresonance study is mathematical modeling of the components of a considered real system. Due to its nonlinear character, frequently dependent parameters and a large variety of magnetic-core constructions, the considered power transformer poses a considerable problem for mathematical modeling.

The ferroresonance phenomenon belongs to the group of the low-frequency electromagnetic transients [4]. The frequency range affects several aspects of transformer modeling. The existing modeling approaches [14-20], [21], [23] pay a special attention to the following transformer characteristics: iron-core configuration, magnetizing curve, self and mutual winding inductances, and leakage inductances. The most of the transformer models are developed and implemented with the well-known EMTP-ATP simulation software enabling simulation circuit analysis of electromagnetic transients.

The available transformer models for the circuit-based simulations of electromagnetic transients can be divided into the following three groups [14]-[20], [21],[22]:

- transformer with a magnetic saturation effect,
- transformer represented in a matrix form, and
- transformer based on the duality principle.

Each group has its specific advantages and drawbacks when used for circuit-based modeling of low-frequency electromagnetic transients.

Drawbacks of the transformer model with a magnetic saturation effect are its limited usage, inaccuracy of the topological structure and numerical instability. The model transformer, represented in a matrix form takes no account of different winding and core topologies. This limits its accuracy to the frequency range below 1 *kHZ*. The duality-principle based transformer model is usually very complex and requires the use of numerous ideal transformers.

The paper presents a simplified three-phase three-legged transformer model for ferroresonance simulations. It is capable of representing asymmetric magnetic legs and their mutual coupling over a zero-sequence magnetizing inductance. It is shown that such simplified model well performs ferroresonance simulations capable of producing highly accurate results that have an excellent agreement with measurements.

The proposed model is based on an equivalent circuit (Figure 3) of three-phase three-legged transformer used for the measurements described in Section 2. The linear parameters of the equivalent circuit given in Figure 10 are: R_p resistance of the primary winding, L_p leakage inductance of the primary winding, L_0 zero-sequence magnetizing inductance, and R_m resistance representing the core losses. The nonlinear element of the circuit is the core magnetizing inductance of transformer L_m.

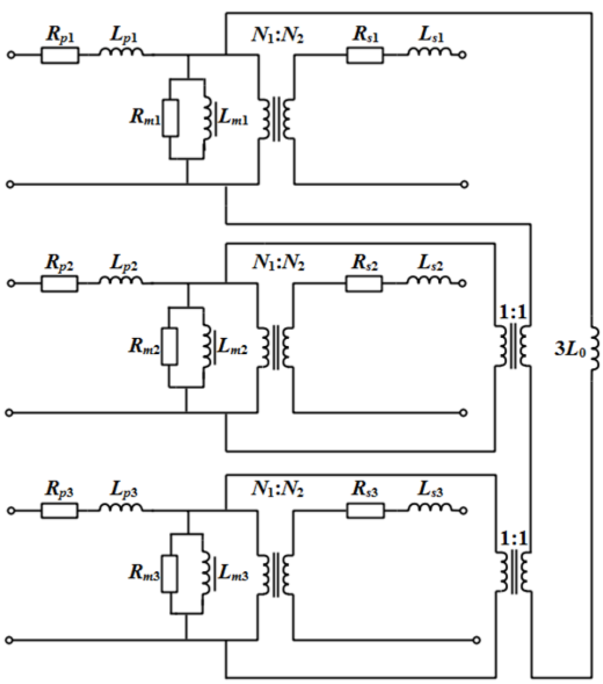

Figure 3. Equivalent circuit of a three-phase three-legged transformer.

Measured values of the transformer parameters (j = 1, 2, 3) are:

- Resistance of the primary winding: $R_p = R_{pj} = 1.5\ \Omega$;
- Leakage inductance of the primary winding: $L_p = L_{pj} = 1.0\ mH$;
- Zero-sequence magnetizing inductance: $L_0 = 15.0\ mH$;
- Resistance indicating the core losses: $R_m = R_{mj} = 4626\ \Omega$.

2.3 Mathematical model of a three–phase three–legged power transformer

Modeling transformer iron core is very important when analysing the electromagnetic transients. To study ferroresonance, there are three different iron-core modeling approaches available: 1) a model with a nonlinear inductance and a constant value of the magnetizing resistance; 2) a model with a nonlinear inductance and a nonlinear magnetizing resistance; 3) a model with a hysteresis inductance and nonlinear magnetizing resistance.

In our study, an iron-core model with a nonlinear inductance and linear magnetizing resistance is used. In the first step, the RMS *I-U* curves of each transformer leg are measured and then numerically converted into the corresponding peak-value-based *i*-φ curves [23]. In the second step, the obtained *i*-φ magnetizing curves are approximated by a double exponential function:

$$i_m(\phi) = a_j\left(e^{b_j\phi} - e^{-b_j\phi}\right), \quad j = 1,2,3 \qquad (1)$$

The reasons to use the approximation function (1) are:

- the function is continuous and infinitely differentiable,
- the function is odd, i.e. it is symmetric with respect to the coordinate-system origin.

Unknown parameters a and b of the function are determined by using the least-squares method which minimizes the deviation of the function (1) from the measured magnetizing curve. The values of the parameters, obtained with the least-squares method are:

- the first outer leg 1: $a_1 = 0.00396, b_1 = 4.417$,
- the inner (middle) leg 2: $a_2 = 0.00121, b_2 = 4.917$, and
- the second outer leg 3: $a_3 = 0.002307, b_3 = 4.743$.

Figure 4 shows the nonlinear magnetizing curves of the transformer legs, being approximated.

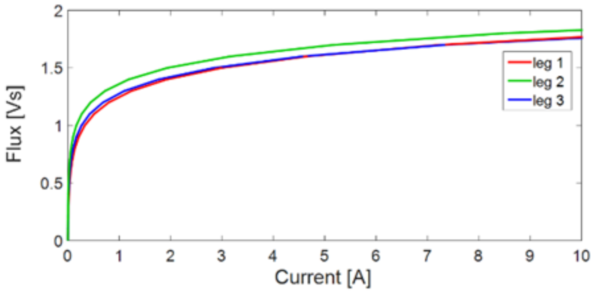

Figure 4. Nonlinear magnetizing curves of the three transformer legs.

2.4 Contribution of the power network

The power network is modeled by using three-phase voltage source $e_j(t), j = 1,2,3$ accompanied by the adjacent series $R_n - L_n$ impedance of each phase. The voltage sources are defined as harmonic time functions:

$$e_j(t) = E_{mj} sin(\omega t + \theta_j) \tag{2}$$

where E_{mj} are the voltage amplitudes and θ_j are the voltage phase shifts.

Using the value of the three-phase short-circuit power at the connection point with network S_{ks} and nominal voltage of network U_n, the parameters of the network series impedance are: $R_n = 1.117\ m\Omega, L_n = 0.0356\ mH$.

3 Numerical simulations

Our numerical simulations of the ferroresonant system are performed by using the EMTP-ATP software. The failed switching of the two phases during the connection of the transformer at a no-load state to the network (Variant 1) is actually a premature switching-on of the circuit breaker of phase 1. Figure 5 shows the equivalent circuit of the ferroresonant system (Variant 1) and Figures 6-9 show a comparison of the obtained numerical simulation and measurement results.

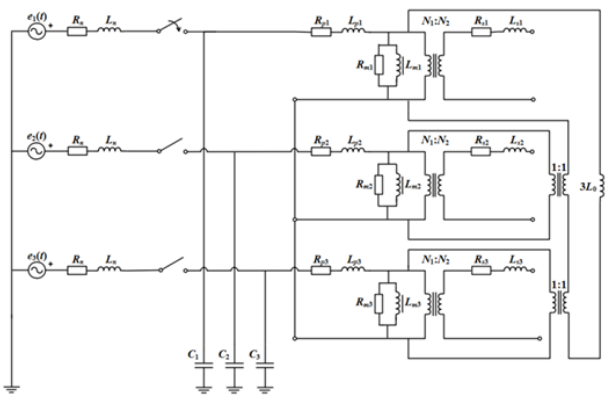

Figure 5. Equivalent circuit of the ferroresonant system – Variant 1.

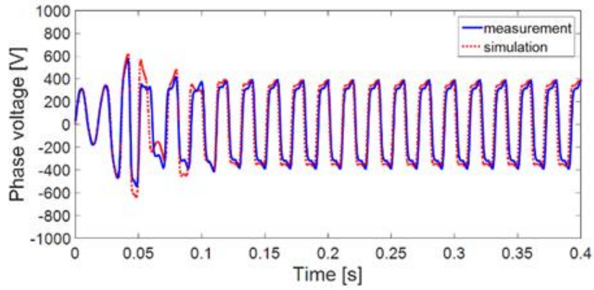

Figure 6. Phase 1 voltage: simulation vs. measurement (Variant 1).

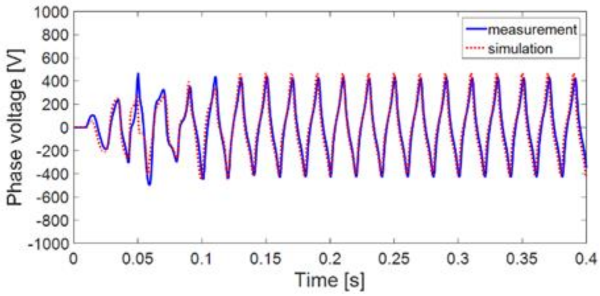

Figure 7. Phase 2 voltage: simulation vs. measurement (Variant 1).

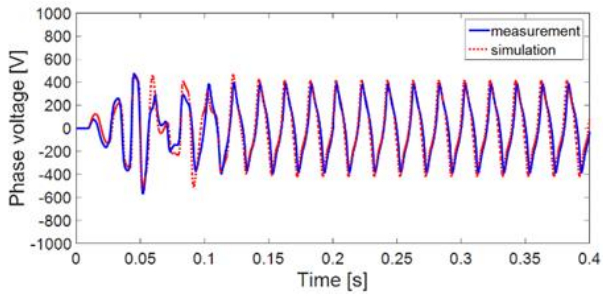

Figure 8. Phase 3 voltage: simulation vs. measurement (Variant 1).

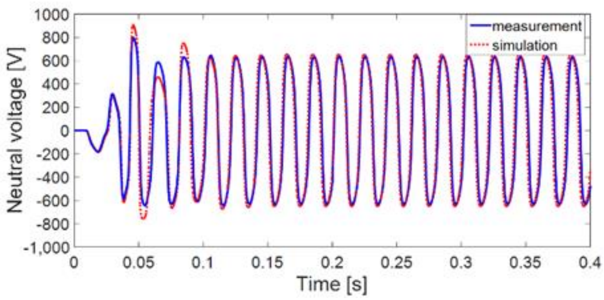

Figure 9. Neutral point voltage: simulation vs. measurement (Variant 1).

The peak values of the disagreement between the simulated and measured curves are analyzed and the relative error is calculated. The highest Variant 1 disagreement is 8.57 %. It occurs in phase 3. The average relative error of each voltage of Variant 1 is 4.82 %.

Figure 10 shows the equivalent circuit of the ferroresonant model of Variant 2 and Figures 11-13 show a comparison of the numerical results and measurements results.

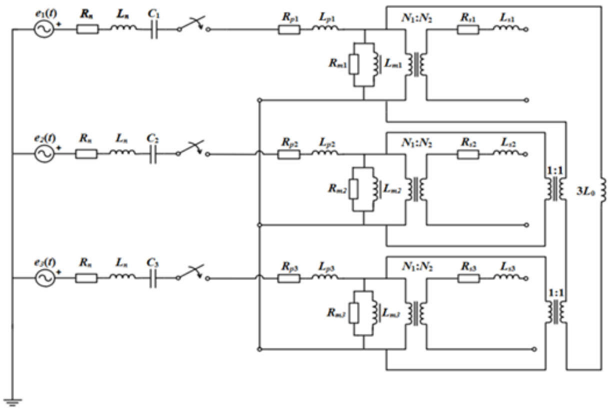

Figure 10. Equivalent circuit of the ferroresonant system – Variant 2.

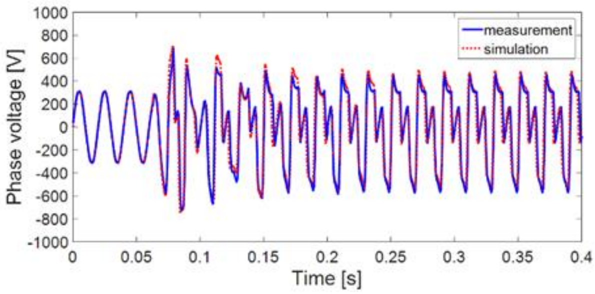

Figure 11. Phase 1 voltage: simulation vs. measurement (Variant 2).

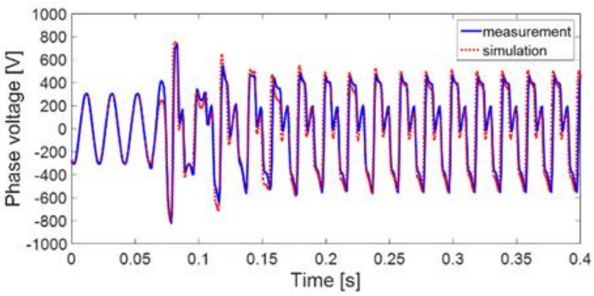

Figure 12. Phase 2 voltage: simulation vs. measurement (Variant 2).

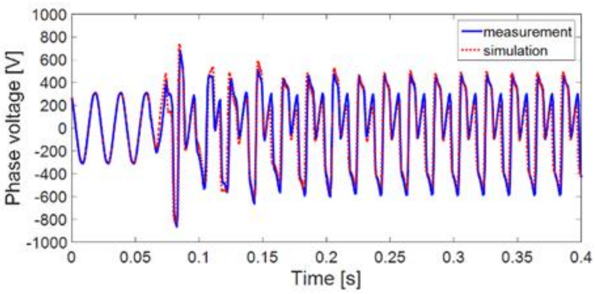

Figure 13. Phase 3 voltage: simulation vs. measurement (Variant 2).

The highest and average relative error of the simulated voltage of Variant 2 are 8.69 % and 6.38 %, respectively. The highest error appears in the phase voltage 3.

The disagreement between the simulated and measured peak voltage values is due to the measurement error caused by the inaccuracy of the used measuring devices, the numerical error of the simulation method and limitations of the developed mathematical model.

4 Conclusion

The paper presents ferroresonance measurement results of two different circuit configurations in which a three-phase three-legged power transformer is brought in various ferroresonant states by different switching operations.

A simplified transformer model that takes into account both the magnetic coupling of the legs over a neutral magnetizing inductance and the magnetic asymmetry of the transformer legs is used.

The approximated nonlinear instantaneous current–flux curves are, by using a double exponential function that contains parameters obtained using the least-squares method.

A comparison of the model and simulation results with the corresponding measurement results shows an excellent agreement.

In our future research of the ferroresonance phenomenon, the transformer model will be improved by taking into account the magnetic-core hysteresis.

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