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TOMASZ LERCH*, TOMASZ MATRAS**

MODELING THE PHENOMENON OF FREE AND FORCED MAGNETIZATION IN THREE-PHASE TRANSFORMERS

MODELOWANIE ZJAWISKA MAGNESOWANIA SWOBODNEGO I WYMUSZONEGO W TRANSFORMATORACH TRÓJFAZOWYCH

A b s t r a c t

This article presents the results of modeling the phenomenon of free and forced magnetization in three-phase, three-legged transformers. The no-load state of the transformer has been modeled using the program including a circuit model of the transformer. The results obtained have been compared with measurements carried out in the laboratory for the various circuits connection of the transformer.

Keywords: *transformer*, *free and forced magnetization*

S t r e s z c z e n i e

Artykuł przedstawia wyniki modelowania zjawiska magnesowania swobodnego i wymuszonego w transformatorach trójfazowych trójkolumnowych. Stan biegu jałowego transformatora modelowano za pomocą programów zawierających modele obwodowe transformatorów. Otrzymane wyniki porównywano z pomiarami przeprowadzonymi w laboratorium dla różnych układów połączeń transformatora.

Słowa kluczowe: *transformator*, *magnesowanie swobodne i wymuszone*

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* Ph.D. Eng. Tomasz Lerch, assistant professor, Department of Power Electronics and Energy Control Systems, Faculty of Electrical Engineering, Automatics, Computer Science and Biomedical Engineering, AGH University of Science and Technology.

** M.Sc. Eng. Tomasz Matras, Enprom Sp. z o.o. [Ltd], Krzeszowice.

1. Introduction

The aim of this study was the modeling of the phenomenon of free and forced magnetization in three-phase transformers. For this purpose, the available programs, EMTP-ATP and Matlab-Simulink have been used for simulation of transients of the transformers. The programs take into account the unsymmetrical construction and non-linearity of the magnetic core. The calculation of currents and voltages has been performed for selected winding connections of the transformer.

Supplying the transformer winding with sinusoidal voltage, the magnetic flux and flux density are also sinusoidal. The relationship between flux density and no-load current for the ferromagnetic transformer core describes a hysteresis loop. Therefore, Fourier decomposition of the magnetizing current contains odd harmonics which are related to the amplitude of the saturation of the core. Such a case is called free magnetization of the transformer. If the higher harmonics of the current cannot flow in the transformer windings, especially the third one, then magnetic flux is deformed. Such a case is called a forced magnetization [3, 4].

2. No-load current of the transformer

Registrations of no-load current were performed for a three-phase, three-legged transformer with a capacity of S_N = 10 kVA. To register, Hall effect current transducers and a PC with a data acquisition card were used. An example of the no-load current waveform during free magnetization (*Y*0*y* connection) is shown in Fig. 1. Registration was performed for the selected windings connection where free and forced magnetization are present. The analysis of harmonic currents in each phase for *Y*0*y* and *Yy* windings connection are shown in Fig. 2.

The analysis of the currents shows that the third and fifth harmonics have the largest share of magnetizing current of the transformer besides the basic harmonic. It can also be noted that the amplitude of the fifth harmonic hardly depends on the windings connections. The third harmonic can flow to the windings of the transformer only in the four-wire system (*Y*0*y*).

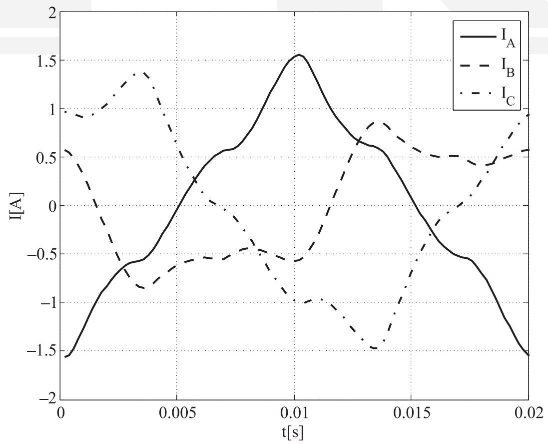

Fig. 1. No-load current – free magnetization

In the current spectrum of the three-wire system (*Yy*), current component with a frequency of 150 Hz can also be seen, but it does not create the zero-order system. In this case, the phase angles of phases A and C are identical while phase B is in antiphase to them. The current component of 150 Hz in the *Yy* connection system is caused by asymmetry of the three-legged transformer core.

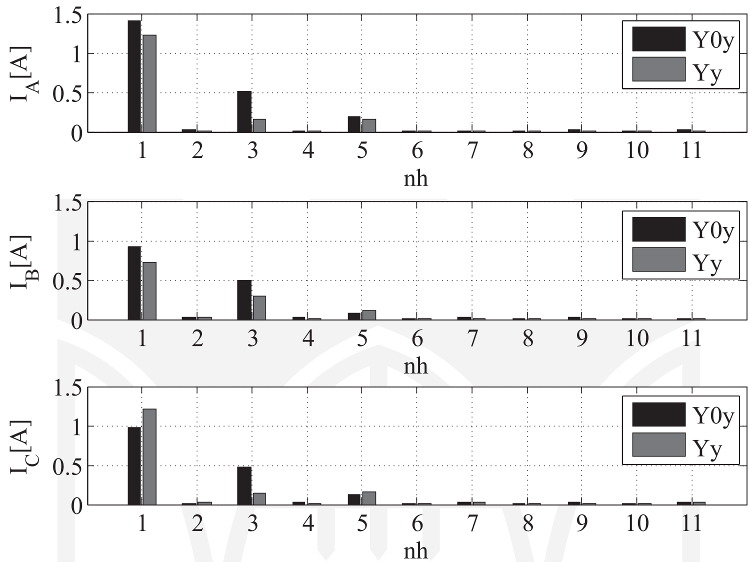

Fig. 2. Spectrum of no-load currents

3. Modeling of no-load current of the transformer

To model the studied phenomenon, available computational packages EMTP-ATP and Matlab-Simulink has been used. Models available in these packages allow to take into account non-linearity of magnetization characteristics of the transformer core.

ATP (Alternative Transients Program) is a non-commercial version of the EMTP (Electromagnetic Transients Program) developed in the frame of open access to the program. ATP is the universal program for the digital simulation of transient states of electromagnetic phenomena.

In the ATP package, there are two types of transformer models – a simplified model of SAT (saturable) and the hybrid model XFMR that takes into account the geometry of the transformer.

The SAT model takes into account the non-linear magnetization characteristic of the core. The input data for the primary and secondary side needed for simulation are: voltage; winding resistance; inductance; resistance for zero sequence. In the model, the windings connection and the number of columns of the core are also declared. Characteristics of magnetization are entered as a secondary side voltage dependence of the no-load primary side current of the transformer.

The operation of the XFMR model consist of topologically correct mapping of the substitute windings disposed on the surface of the core [6]. Individual branches are established for magnetizing yokes and columns depending on their length and area. Characteristics of the magnetization are described by the Frolich equation whose coefficients are adapted to the measurement data. This improves the extrapolation of saturation over the range of the measurement data. In the model also are taken into account the shunt capacities and dependence the winding resistance on the frequency.

The equivalent circuit model of the transformer takes into account four main aspects: the leakage inductance; windings capacitance; core nonlinearity; the impact of the frequency on winding resistance. This scheme is shown in Fig. 3.

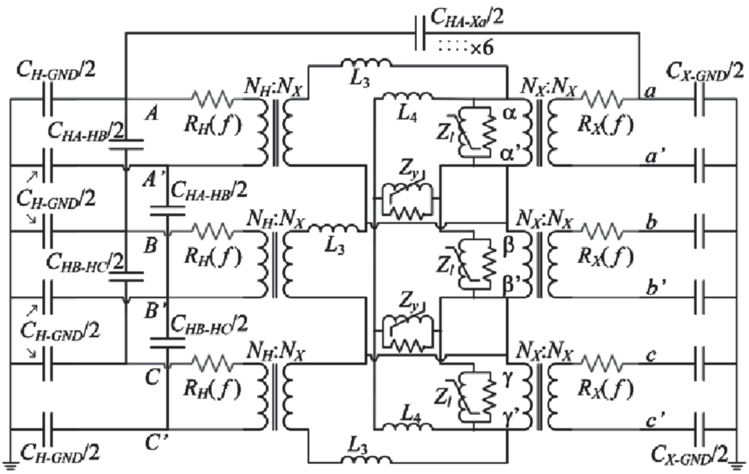

Fig. 3. Equivalent circuit of three-phase three-legged transformer

Matlab-Simulink is a software package for modeling, simulation and analysis of dynamic systems. Linear and nonlinear systems can be implemented and modeled in continuous or discrete time. After defining the model, the simulations are carried out using the integral method selected from the package menu or by typing the appropriate commands in the MATLAB command window. The transformer model used for simulation is defined by the parameters of the equivalent circuit and the characteristics of magnetization. This model does not take into account the asymmetry of the construction of the three-legged transformer core [5].

4. Simulation of no-load current of the transformer

Simulations were performed for two winding connections of the transformer – *Yy* where the magnetization is forced and *Y0y* where the magnetization is free. Both system connections have been simulated using the program EMTP-ATP model SAT and XFMR and Matlab-Simulink. The results of the simulation in each case were compared with laboratory measurements.

The first case concerns the forced magnetization in system *Yy*. Figure 4 shows the results of a SAT model simulation summarized with measurements results.

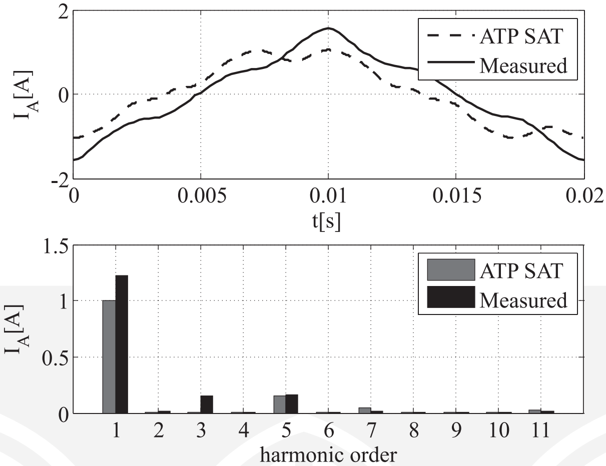

Fig. 4. *Yy* connection SAT model

Using the SAT model, where the construction of the transformer is given in a simplified manner, the calculated no-load current (in terms of amplitude and harmonic content) deviates from the measured current waveform. In particular, the simulated current waveform does not contain a 150 Hz component.

For the same case of study, but using the XFMR model, the calculated no-load current very well reflects the measured current waveform. This current waveform is shown in Fig. 5. The model which takes into account the core structure and the location of the individual windings better appoints the amplitude of the waveform and amplitude spectrum, including the component of frequency 150 Hz.

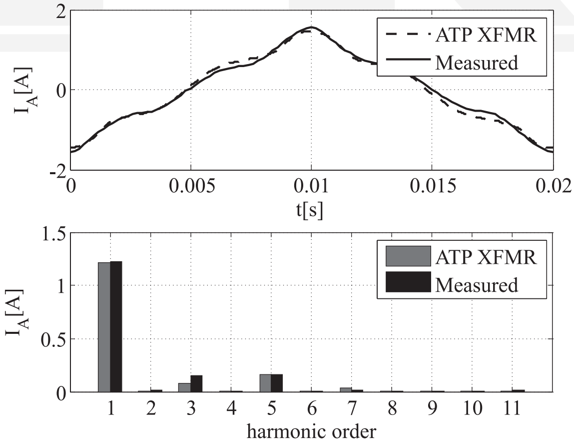

Fig. 5. *Yy* connection XFMR model

The no-load current for free magnetization has been simulated also using the model available in Matlab-Simulink. The simulation results are shown in Fig. 6.

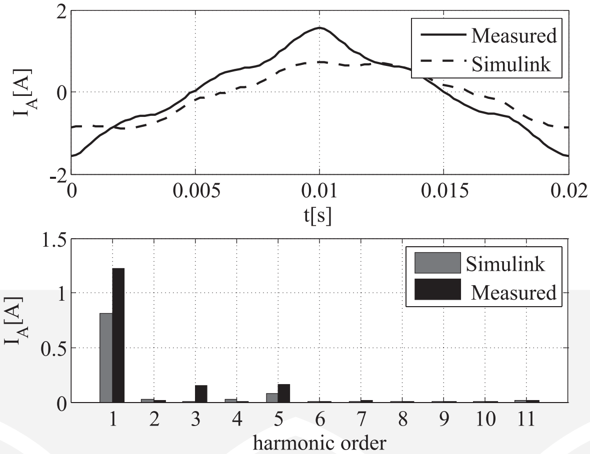

Fig. 6. *Yy* connection Simulink model

The transformer model available in Matlab-Simulink does not take into account the asymmetry and structure of the core. The waveforms are calculated only on the basis of equivalent circuit parameters and the magnetizing characteristics. As can seen in the above figure, this approach does not allow us to properly determine the amplitude and harmonic content of the current.

A second series of simulations was performed for the *Y0y* connection, i.e., for the case of the free magnetization. For this case, there is a closed path for the third harmonic current flow through the neutral wire as shown in the waveform in Fig. 2. The results of simulations performed on the SAT model EMTP-ATP package are shown in Fig. 7.

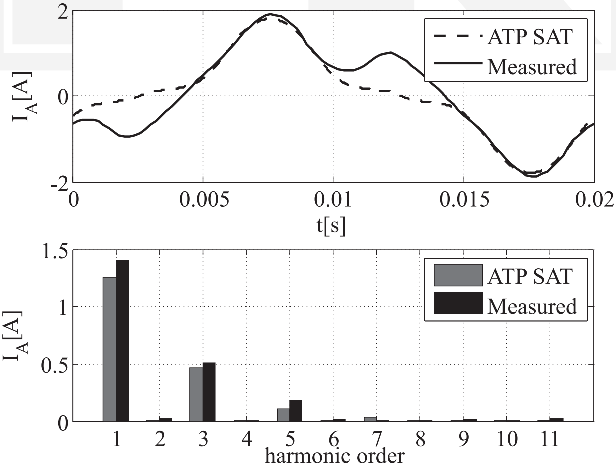

Fig. 7. *Y0y* connection SAT model

The harmonic analysis shows that in the case of the free magnetization, the no-load current has been calculated with a small error when compared to the results of the *Yy* connection (Fig. 4). Quite opposite results has been obtained using the model XFMR. Comparing the results obtained for the *Y0y* connection (shown in Fig. 8) with the results of the *Yy* connection (Fig. 5), it shows that in the case of the free magnetization, the model gives results significantly different from the measured. Despite consideration of the core geometry and winding arrangement in the model, the value of the third harmonic current (dominant in the case of the free magnetization), is several times smaller than the measured one.

The simulation results of no-load current using the model available in Matlab-Simulink (Fig. 9) are different from the measured waveforms as in the previous case. The model that does not consider the core geometry and winding arrangement gives correct results in any of the tested cases in terms of amplitude and harmonic current components.

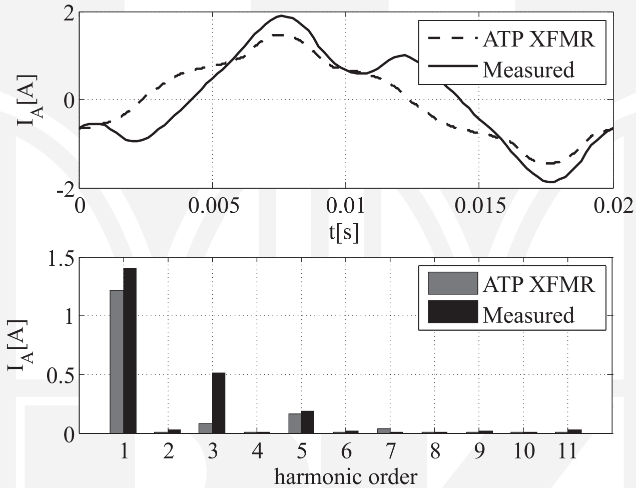

Fig. 8. *Y0y* connection XFMR model

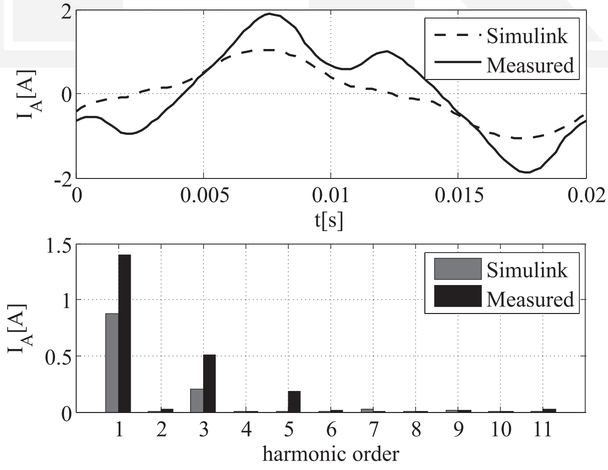

Fig. 9. *Y0y* connection Simulink model

5. Conclusion

Modeling the phenomenon of free and forced magnetization for three-phase three-legged transformers is a difficult issue because the core asymmetry and nonlinearity of the magnetizing characteristic has to be considered [1, 2]. It turns out, however, that the simulation results of the no-load current obtained using advanced models as XMFR type may be far from the measured. From the performed research, it can be concluded that the development of a universal circuit model of a three-phase three-legged transformer that allows us to simulate the phenomenon of free and forced magnetization for the various circuits connection is very difficult or even impossible.

References

[1] Chen X.S., Neudorfer P., *Digital model for transient studies of a three-phase five-legged trans-former*, IEE Proceedings C (Generation, Transmission and Distribution), Vol. 139, Issue 4, July 1992, pp. 351–358.
[2] Furgał J., *Symulacje prądów załączania transformatorów*, Przegląd Elektrotechniczny, 7.08.2007.
[3] Jezierski E., *Transformatory: budowa i projektowanie*, Wydawnictwa Naukowo-Techniczne, Warszawa 1963.
[4] Plamitzer A., *Maszyny elektryczne*, Wydawnictwa Naukowo-Techniczne, Warszawa 1982.
[5] Tomera M., *Wprowadzenie do Simulinka*, http://am.gdynia.pl/~tomera/ts/simulink_lab.pdf.
[6] Opis pakietu EMTP, http://www.emtp.org/.