Jakub FURGAŁ

ORCID: 0000-0001-7968-6161

DOI: 10.15199/48.2025.05.02

Simulations of internal overvoltages in transformer windings using EMTP-ATP

Symulacje przepięć wewnętrznych w uzwojeniach transformatorów przy zastosowaniu programu EMTP-ATP

***Abstract**. Insulating systems of transformer windings are subjected to overvoltages during voltage tests and under operating conditions in electrical networks. Internal overvoltages in transformers are the result of the windings reacting to overvoltages at the input terminals. For the purpose of simulating overvoltages in transformers, winding models are used that reflect their complex structure and material properties. The article presents a selected model of transformer windings enabling simulation of internal overvoltages in transformers using the Electromagnetic Transients Program-Alternative Transients Program (EMTP-ATP.*

***Streszczenie:** Układy izolacyjne uzwojeń transformatorów poddawane są działaniu przepięć podczas prób napięciowych oraz w warunkach pracy w sieciach elektrycznych. Przepięcia wewnętrzne w transformatorach są efektem reakcji uzwojeń na przepięcia na zaciskach wejściowych. Dla celów symulacji przepięć w transformatorach stosowane są modele uzwojeń odzwierciedlające złożoną ich budowę oraz właściwości materiałów. W artykule przedstawiono wybrany model uzwojeń transformatorów umożliwiający symulacje przepięć wewnętrznych w transformatorach przy zastosowaniu programu Electromagnetic Transients Program-Alternative Transients Program (EMTP-ATP)*

Keywords: transformer windings, modelling, internal overvoltages, simulations of overvoltages, EMTP-ATP
Słowa kluczowe: uzwojenia transformatorów, modelowanie, przepięcia wewnętrzne, symulacje przepięć, EMTP-ATP

Introduction

The analysis of overvoltage exposures of insulation systems of power equipment is essential for assessing the operating conditions of devices in electrical networks, and is the basis for designing insulation systems and improving their design solutions. Among the devices installed in electrical networks, power transformers are of great importance for ensuring the reliability of the network. Insulating systems of transformer windings are subjected to the impact of overvoltages during voltage tests performed using impulse test voltages and in the operating conditions of transformers in power systems. Overvoltages appearing in power systems have two origins, first caused by external energy injection like atmospheric lightning's, the second caused by the inside system events like switching operations, faults, resonance events [1-4]. The transients waveforms and maximal values of internal winding overvoltages are related to the origins of overvoltages and transients phenomena in the windings [5-6]. The analysis of the most common failures in power transformer shows that more than 30 % of cases is associated with the dielectric failure of insulation systems [1-3]. The internal overvoltages are results of the response of the winding circuit which has complex structure reflecting the geometry of winding, material properties and capacitive and inductive couplings between every element in the power transformer [7-10].

The paper presents the R,L,C based circuit model of transformer windings for simulations of the internal overvoltages in the power transformer windings. The model was implemented in the Electromagnetic Transients Program/Alternative Transients Program (*EMTP/ATP)* [11]. The developed power transformer model was verified by the laboratory measurements. Practical applications of the model in *EMTP/ATP* program were shown. The simulations internal overvoltages in transformer windings during energization of cable line - power transformer system was done by use presented model generated in *EMTP/ATP* program.

Model of power transformer windings for simulation of internal overvoltages

The equivalent scheme of lumped R,L,C winding model is presented in Figure 1 [10,12,13].

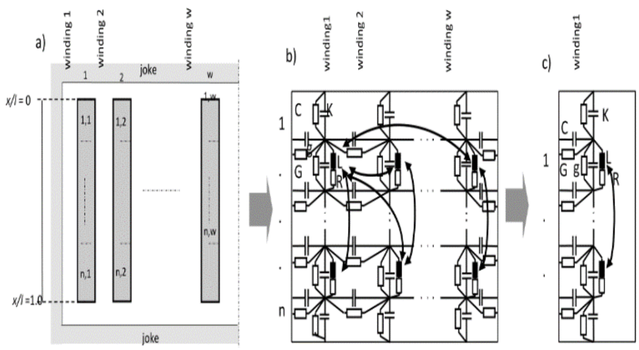

Fig. 1. Equivalent scheme of winding model with lumped R,L,C parameters: a - distribution of w turns in the single transformer winding, b - R,L,C topology of w windings, c - equivalent scheme of single winding; K,C - capacitances: longitudinal and to ground, L,M - self and mutual inductances between turn sections, R - resistance of turns, G,g - conductance of insulation system, $1,n$ - sections of winding

Self and mutual inductance of transformer windings is calculated assuming that for the steep and high frequency signals the transformer can be treated as linear time invariant class object neglecting the silicon steel magnetic core. The inductance of transformer winding coils is calculated from the formula [9,14]:

(1) $$L = \frac{\mu_o}{4\pi} N^2 d\Psi - \Delta$$

where: $d = 0,5\,(d_1+d_2)$, d_1,d_2 - internal and external diameters of the coils, m.

If: $\alpha_c \le \frac{3}{4}$

where: $\alpha_c = \frac{h}{d}$, h – height of the coils, m.

then:

(2) $$\Psi = \frac{\pi^2}{2\alpha_c^2}\left[\frac{1}{\beta} - \frac{8}{3\pi} - \frac{\beta^2}{8} + \frac{\beta^5}{16} - \frac{15}{128}\beta^7 + \cdots\right]$$

(3) $$\Delta = \frac{\pi}{8}\mu_o N^2 \frac{d}{\alpha_c^2}\left\{\frac{3}{4}\alpha_c \rho - \frac{N}{3}\alpha_c \rho^2 \left[\frac{N}{3\pi}\left(ln\frac{4}{\rho} - \frac{23}{12}\right) + \frac{\beta}{3} + \frac{\beta^5}{16} - \frac{15}{12}\beta^3 + \ldots\right] + \rho^4\left[\frac{1}{30\pi}\left(ln\frac{4}{\rho} - \frac{1}{20}\right) - \frac{\beta}{18} + \frac{17}{90} - \frac{5}{12}\beta^3 + \ldots\right]\right\}$$

in other case:

(4) $$\Psi = 2\pi\left[\left(1 + \frac{\alpha_c^2}{8} - \frac{\alpha_c^4}{64} - \ldots\right) ln\frac{4}{\alpha_c} - \frac{1}{2} - \frac{\alpha_c^2}{32} + \frac{\alpha_c^4}{96} + \ldots\right]$$

(5) $$\Delta = \frac{\mu_o}{2}N^2 d\left[\frac{\pi}{3}\gamma - \frac{25}{72}\gamma^2 + \frac{\rho^2}{8} - \ldots\left(\frac{\rho^2}{24} - \frac{7}{384}\alpha_c^2\rho^2 + \frac{11}{2880}\rho^2 + \ldots\right) ln\frac{4}{\alpha_c} - \left(\frac{\gamma}{6} - \frac{\rho^2\gamma^2}{120} + \ldots\right) ln\frac{1}{\gamma} + \ldots\right]$$

where: $\rho = \frac{d_2 - d_1}{2d}$; $\beta = \frac{1_1}{\sqrt{1+(2\alpha_c)^2}}$; $\gamma = \frac{\rho}{\alpha_c}$

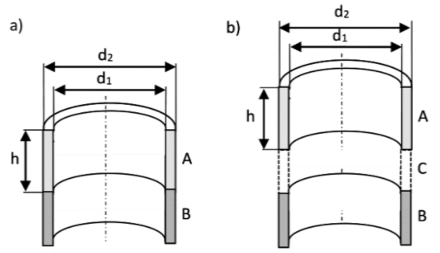

Fig. 2. Mutual position of the coils in the transformer windings

The mutual inductance of coils *A* and *B* (Figure 2a) can be obtained from the following formula:

(6) $$M_{AB} = \frac{1}{2}(L_{AB} - L_A - L_A)$$

where: L_A, L_A, L_{AB} – the self-inductance of the coils *A* and *B* and of the group *A-B, C*.

If coils are separated (Figure 2b) we introduce the imagine coil. The mutual inductance of the coil system *A-B* can be calculated by use the simply formula:

(7) $$M_{AB} = \frac{1}{2}(L_{ABC} + L_C - L_{AC} - L_{CB})$$

Capacitance to earth *C* of winding coils may be calculated by use of equation [9,15]:

(8) $$C = k_c \pi\, h\varepsilon_z \frac{d_1 + d'}{d_1 - d'}$$

where: h - height of the winding, m, k_c - coefficient (for high voltage transformers k=1), d' - substitute diameter of a core column, m, $d' = 0{,}5d_r + 0{,}65\sqrt{s_r}$, d_r - diameter of the core column, m, s_r - cross-section of the column, m^2, ε_z - dielectric permeability of the insulation between the winding and the core, Fm^{-1}.

For calculation of longitudinal capacitance *K* of the winding (Figure 3) we define a substitute capacitance K_z calculated by use of the formula:

(9) $$K_z = K_z' + K_z''$$

where: K_z', K_z''- capacitance representing energy in the insulation between the windings and between the coils, F.

Capacitance K_z' is given by the formula:

(10) $$K_z' = 0{,}5C_z(N - 1)$$

where: $C_z = \frac{\pi\varepsilon_p d_{\acute{s}r} a}{\delta}$, s - insulation thickness between the windings, m, $d_{\acute{s}r}$ - average coil diameter, m, ε_p - electrical permittivity of insulating paper, F m^{-1}, a - coil thickness, m.

The capacity *K* is calculated from the formula:

(11) $$K_z'' = \frac{1}{6}\left[K_{gw} + 1{,}25\left(K_{gz_1} + K_{gz_2}\right)\right]$$

where:

(12) $$K_{gz_1} = \frac{\pi\varepsilon_w d_{sr} B}{\Delta_c + \delta},$$

D_c - width of the channel between the coils, m, B - coil width, m, ε_w - electrical permittivity of the insulating system between the coils, Fm^{-1}.

The equation (12) enables also to calculate the capacitances K_{gz2} and K_{gw}.

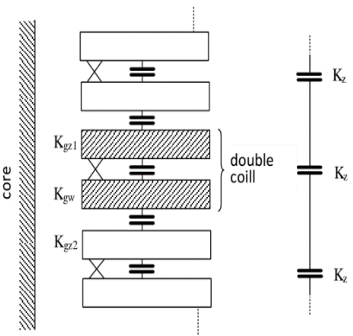

Fig. 3. The capacitance between the coils of the winding

The longitudinal capacitance *K* of the winding is calculated by dividing the capacitance value K_z by the number of coils.

The insulation conductance of the winding coils *G* can be calculated from the following dependence [16,17]:

(13) $$G = \frac{\omega C_c}{tg\,\delta}$$

where: ω - pulsation, s^{-1}, C_c - ground capacity of a section or capacity between adjacent sections, F, $tg\,\delta$ - dielectric losses coefficient of the insulating material, -

The resistance of the windings depends on the eddy currents in the wires and is a function of frequency. The impedance of the turn Z_w in the *k-th* layer of the winding is expressed by the following formula [16,18]:

(14) $$Z_w(\omega) = 2\pi R_w \xi\left[(k^2 r_k + (k-1)^2 r_{k-1})\coth(\xi) - 2k(k-1)\sqrt{r_k r_{k-1}}\cosh(\xi)\right])$$

where: $R_w = \frac{1}{\sigma h d}$, $\xi = \sqrt{j\omega\mu\sigma}\,d$, μ - magnetic permeability of the wire material, F m^{-1}, σ - conductivity of the cable material, S m^{-1}, ω - pulsation, s^{-1}, d - cable diameter, m, h - winding height, m, r_k - radius of the coil, m.

Verification of the transformer winding model for simulations of internal overvoltages

Transformer winding model, presented in the Figure 1, was verified by the comparison of simulation results to the measurement results done for HV winding of the transformer 20 kVA, 15/0.4 kV (Table 1).

Table 1. Rated and construction parameters of the transformer 20 kVA, 15/0.4 kV

Parameter	Value	
S_n, kVA	20	
U_{nHV}, kV	15	
U_{nLV}, kV	0.4	
U_z, %	4.2	
ΔP_{Fe}, kW	0.114	
ΔP_{Cu}, kW	0.525	
I_0 , %	2.8	
type of coils	*uc*[*]	*rc*[**]
number of turns in the coil, -	810	650
number of coils, -	4	4
height of the winding *l*, mm	280	260
internal diameter d_o, mm	157	157
external diameter d_i, mm	205	205
[*]*uc* - usual coils, [**]*rc* - reinforced coils		

The measurements were taken inside the transformer winding at selected points (1 - *x/l* = 0, 2 - *x/l* = 0.18, 3 - *x/l* = 0.33, 4 -*x/l* = 0.62) referring to the whole length of winding counting form the terminal. The simulations and measurements covered the transient overvoltages waveforms in transformer winding while action of rectangular surge at the transformer terminals. The frequency characteristics of overvoltages in selected points in HV side winding were also determined [5]. Simulations were obtained by use of the transformer winding model presented in Figure 1 implemented in the Electromagnetic Transients Program/ Alternative Transients Program (*EMTP/ATP*). The mutual inductances between winding coils of the transformer are not taken into account in the model (Figure 4). The simulation results are placed in Figure 5 but laboratory measurements are shown in Figure 6.

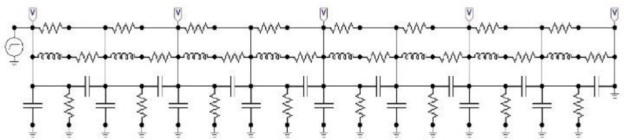

Fig. 4. Simulation model in *EMTP-ATP* software used for the overvoltage distribution analysis in the transformer winding (Table 1)

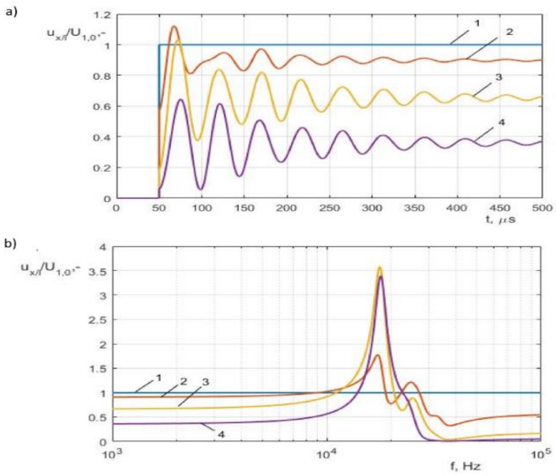

Fig. 5. Simulation results of overvoltages inside transformer winding (Table 1) at selected points *x/l*: a - waveforms $u_{x/l}=f(t)$ during the action of rectangle_impulse with the winding model considering only self-inductances of turn sections, b - frequency characteristics $u_{x/l}=g(f)$ of overvoltages: 1 - *x/l* = 0, 2 - *x/l* = 0.18, 3 - *x/l* = 0.33, 4 -*x/l* = 0.62

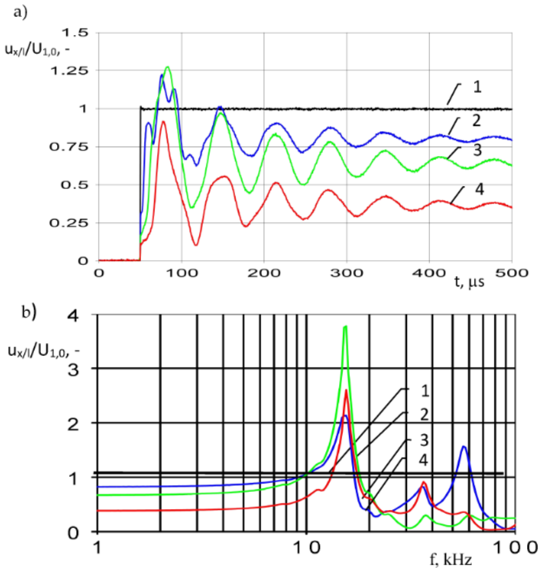

Fig. 6. Measurement results of overvoltages waveforms $u_{x/l}=f(t)$ and frequency characteristics $u_{x/l}=g(f)$ inside transformer winding at selected points *x/l* (Table 1): a - waveforms during the action of rectangle_impulse, b - frequency characteristics $u_{x/l}=g(f)$ of overvoltages; 1 - *x/l* = 0, 2 - *x/l* = 0.18; 3 - *x/l* = 0.33, 4 -*x/l* = 0.62

Presented simulations of overvoltages and frequency dependences of voltage inside the transformer, done by use of Electromagnetic Transients Program/Alternative Transients Program (*EMTP/ATP*), are similar to the experimental results. It confirm that the transformer winding model base on the *L*,*R*,*C* electrical parameters presented in the paper (Figure 1) can be used in simulations of internal overvoltages in transformers by use of this program which has wide range applications to simulations of transient states in electrical power systems.

Simulation of winding internal overvoltages during switching operation in an electrical network

By use of the transformer winding model presented in Figure 1 was done simulations of overvoltages in the HV winding of the transformer 20 kVA, 15/0.4 kV (Table 1) during turn on the transformer in the part of the electrical network presented the Figure 7. The network consists of the power transformer *tr*, cable line l_k (Table 2) with the different length, surge arresters *sa POLIM-D-12* [19] and vacuum circuit breaker *vb.* The cable line was modeled as *JMarti* procedure [11]. The surge arrester model was simulated as *IEEE WG 3.4.11* model [20].

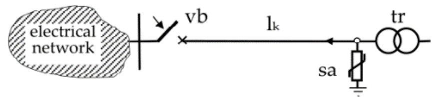

Fig. 7. Diagram of the 15 kV model network used in simulations of overvoltages in the winding during turn on the transformer

Table 2. Parameters of 15 kV cable line l_k

cross section	insulation thickness	screen thickness	outher diameter	*R*
mm²	mm	mm	mm	Ω
95	4.5	2.5	31.6	0.193

The overvoltages analysis covered the simulation during energization of the distribution transformer (Table 1) connected with line l_k with variable length (Figure 7). The internal overvoltages were normalized to the maximal value of the nominal voltage at the transformer terminals. Simulation model in *EMTP/ATP* software used for simulation is presented in Figure 8.

The scope of the simulation was following during closing circuit breaker *br* connected to the cable line l_k and HV transformer winding model, the variable length of cable was changing in range of 10 m to 60 km (Figure 7) [21]. Simulation results of overvoltages inside the transformer during exploitation shows that transient overvoltages appearing at transformer terminals during switching operation can be source of internal overvoltages which exceed the nominal values. The analysis of the results shows also that the length of cable has an impact on the overvoltages appearing in the transformer winding. For the analyzed case the critical length for the test object was 2290 m. For this cable length the overvoltages inside transformer at the section of turns in the middle part and at the end of the winding have higher values than the overvoltages at the transformer input terminal and at the upper part of winding (Figure 10).

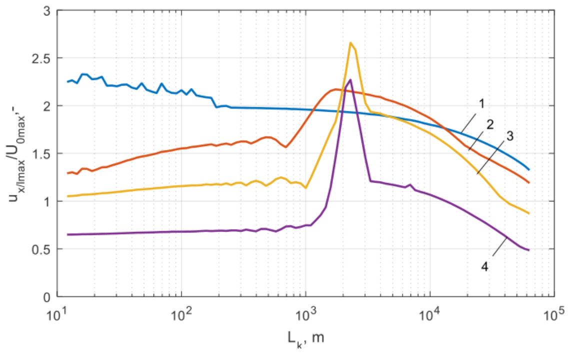

Fig. 9. Characteristics of overvoltages maximal values $u_{x/lmax}/U_{0max}$=f(l_k) in relation to cable length l_k determined in selected points *x/l* of HV winding, case for switching operation of circuit breaker 1 - *x/l* = 0, 2 - *x/l* = 0.18, 3 - *x/l* = 0.33, 4 - *x/l* = 0.62

Summary

The results presented in this article shows that the *R,L,C* model of transformer windings can be implemented in Electromagnetic Transients Program-Alternative Transients Program (*EMTP-ATP*) and can be used for simulation of internal overvoltages on transformer windings. Simulation results of internal overvoltages in the transformer done by use of the model are similar to the experimental ones. The presented model of transformer windings can be used as a tool for analysis of internal overvoltages in transformers during tests and exploitation in power systems.

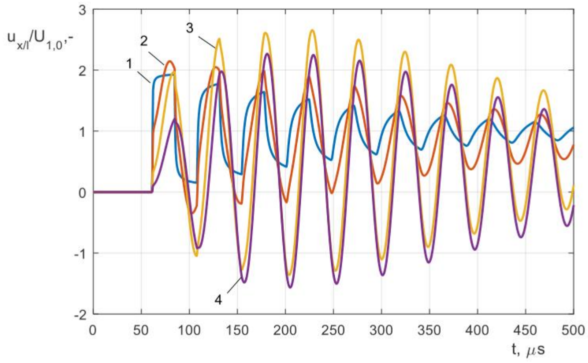

Fig. 10. Waveforms of overvoltages at selected points *x/l* of HV transformer winding during closing of circuit breaker, case with critical cable l_k length 2290 m: 1 - *x/l* = 0, 2-*x/l* = 0.18, 3 - *x/l* = 0.33, 4 - *x/l* = 0.62

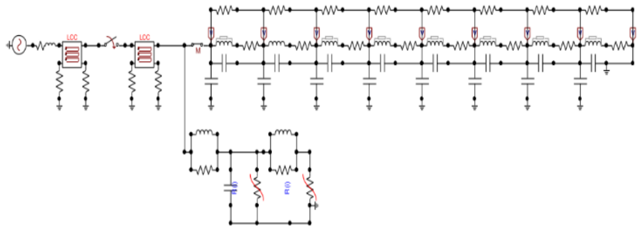

Fig. 8. Simulation model in *EMTP-ATP* software used for the switching overvoltage distribution analysis in the HV transformer winding in medium voltage 15 kV electrical network and variable length cable line l_k

Autor: *prof. dr hab. inż. Jakub Furgał, AGH University of Science and Technology, Department of Electrical and Power Engineering, al. Mickiewicza 30, 30-059 Kraków, E-mail: furgal@agh.edu.pl.*

REFERENCES

[1] Van der Sluis, L.: Transients in Power Systems, *John Wiley & Sons Ltd.* Hoboken, NJ, USA, 2001

[2] Greenwood A.: Electrical Transients in Power Systems, *John Wiley & Sons*. Inc. New York, Chichester, Toronto, 1991

[3] Larin V. S., Matveev D. A., Zhuikov A. V.: Approach to Analy-sis of Resonance Phenomena and Overvoltages Due to Interaction Between Power Transformer and External Network, *CIGRE SC A2 & C4 Joint Colloquium*, Zurich, (2013), 1-8

[4] Debnath, A. D., Chakrabarti, A. A.: Study on the Impact of Low-Amplitude Oscillatory Switching Transients on Grid Connected EHV Transformer Windings in a Longitudinal Power Supply System, *IEEE Trans. Power Deliv.,* 24 (2009), 679–686

[5] Florkowski, M., Furgał, J., Kuniewski, M.: Propagation of Overvoltages in Distribution Transformers with Silicon Steel and Amorphous Cores, *IET Gener. Trans. Distrib. 9* (2015), 2736–2742

[6] Florkowski, M., Furgał, J., Kuniewski, M.: Propagation of Overvoltages in the Form of Impulse, Chopped and Oscillating Waveforms in Transformer Windings-Time and Frequency Domain Approach. *Energies,* 13 (2020), 304

[7] Joint Working Group A2/C4.39-CIGRE.: Electrical Transient Interaction Between Transformers and the Power System (Part 1-Expertise, Part 2: Case Studies); *CIGRE; Paris,* 2014

[8] Furgał, J., Kuniewski, M., Pajak, P.: Propagation of Switching Overvoltages in Transformer Windings, *Przegląd Elektrotechniczny,* (2018), 61–64

[9] Heller B., Veverka, A.: Surge Phenomena in Electrical Machines, *Czechoslovak Academy of Sciences: Prague,* 1968

[10] Su, C. Q.: Electromagnetic Transients in Transformer and Rotating Machine Windings, *IGI Global: Hershey,* PA, USA, 2012

[11] Dommel, H. W.: Electromagnetic Transients Program Reference Manual (EMTP Theory Book); *Prepared for BPA: Portland*, OR, USA, 1986

[12] Florkowski, M.; Furgał, J.: Experimental and Theoretical Determination of Transfer Function of Transformer Windings. *Arch. Electr. Engin.* (2003), *52*, 137-152

[13] Rahimpour, E., Christian, J., Feser, K., Mohseni, H.: Modellierung der Transformatorwicklung zur Berechnung der Übertragungsfunktion für die Diagnose von Transformatoren. *Elektrie* (2000), *54*, 18-31

[14] Małecki R.: Modele cyfrowe do badania przebiegów impulsowych w transformatorach, *Zesz. Nauk. Polit. Łódzkie*j, Z. 80, 1986

[15] Hasterman Z., Mosiński F., Maliszewski A.: Wytrzymałość elektryczna transformatorów energetycznych, *WNT*, Warszawa,1983

[16] Lavers J.D.: Finite Element Solution of Nonlinear Two Dimensional Mode Eddy Current Problems, *IEEE Trans. on Magn*., 19, (1983), No. 5, 2201 - 2203

[17] de León F., Semlyen A.: Time Domain Modeling of Eddy Currents Effects for Transformer Transients*, IEEE Trans. on Pow. Deliv.*, 8, (1993), No. 1, 271- 280

[18] De Leon, F., Semlyen, A.: Detailed Modelling of Eddy Current Effects for Transformer Transients. *IEEE Trans. Power Deliv., 9* (1994), 1143-1150.

[19] Surge Arrester POLIM-D. Data Sheet. (*https://library.e.abb.com*)

[20] IEEE W G 3.4.11: Modelling of metal oxide surge arresters. *Trans. Power Deliv.,* 7 (1992), 302-309

[21] Furgał J., Kuniewski M., Pajak P.: Analysis of Internal Overvoltages in Transformer Windings During Transients in Electrical Networks, *Energies,* 13 (2020), No. 2644, 1-20