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Software and hardware tools of the real-time power three-phase transformers simulation in electric power systems

Abstract. *The substantiation of the necessity of increasing the completeness and reliability of processes modeling in electric power systems is given in this article. The synthesis of universal three-phase mathematical model of a power transformer (autotransformer), reproducing a significant spectrum of normal and abnormal processes in a transformer, taking into account the magnetization curve, is presented. The description of software and hardware simulation tools providing a methodically accurate solution of synthesized universal model in real time is described. The obtained simulation results confirm the adequacy of developed tools and the possibility of using in analysis and research of processes in electric power systems.*

Streszczenie*. Przedstawiono model matematyczny t– autotransformator, procesy zachodzące w transformatorze z uwzględnieniem krzywej magnesowania. Zaproponowano opragramowanie I bazę sprzętową do syntezy w czasie rzeczywistym.* ***Oprogramowanie I sprzęt do symulacji w czasie rzeczywistym trójfazowego transformatora***

Keyword—power system simulation, mathematical model of power three-phase transformers, hybrid simulation, HRTSim.
Słowa kluczowe: system energetyczny, symulacja, transformator

Introduction

According to statistics [1], [2] about 50% of severe accidents in electric power systems (EPS), is caused by incorrect actions of the dispatching personnel and the emergency automatic systems, the main reason of which is the use in the design, research and operation of EPS insufficiently complete and reliable information about all possible processes, especially emergency ones, in EPS.

The specific operation of EPS practically excludes the possibility of obtaining this information, and the extreme complexity of modern EPS significantly limits the applicability of their physical modeling. As a result, mathematical modeling is the main approach to obtain the information about all possible normal and emergency processes in EPS. The mentioned constantly high percent of the accident in EPS clearly indicates that the existing digital simulation tools do not provide the required completeness and reliability of mathematical simulation, and the efficiency, required for effective dispatch control of EPS. A detailed analysis of these factors is presented in [3].

The level of mathematical description of processes in various elements of power equipment reached by now allows to solve the problems of the development of mathematical models for all types of equipment of EPS, for example [4], [5], describing the whole spectrum of processes without any decomposition. Power transformers and autotransformers as a part of EPS have significant impact on the processes in EPS as a whole, so mathematical models of power transformers and autotransformers should be sufficiently adequate and take into account the technologically and constructively variety. The listed types of transformers and autotransformers can be combined with a virtual adaptive five-winding transformer and take it as a prototype for the synthesis of a universal mathematical model for all these types.

The foregoing determines the urgency of development of software and hardware simulation tools that provides a continuous and non-decomposition, methodically accurate solution of the universal mathematical model of the transformer in real time and on an unlimited interval with guaranteed acceptable instrumental error, as well as the reproduction of all possible three-phase longitudinal and transverse commutations, various control of parameters of the modeled transformer and other necessary information-control functions, including in the corresponding simulation tools of EPS.

Universal mathematical model of power three-phase transformers

When forming a system of equations describing the processes in such transformer, constructive designs of windings and magnetic cores, including armored rod engines, are taken into account, which, in particular, allow to neglect the electromagnetic interference of the windings of different phases without significant damage to the accuracy of reproduction of processes and take into account the interaction of the windings of each phase only with its own magnetic leakage flux and the main magnetic flux of its phase, as well as the possibility of saturation of the magnetic circuit for this flow [6], [7]. This representation allows three-phase group and actually three-phase transformers and autotransformers also to display the designated universal mathematical model. In addition, it becomes possible to introduce, if necessary, an asymmetry of the phases.

The universal mathematical model should combine the following equation systems of all winding of three phases:
1) the equation of winding magnetically connected by phases flux

$$W_{i\xi}\frac{d\Phi_{\xi}}{dt}+L_{i\xi}\frac{di_{i\xi}}{dt}+r_{i\xi}\cdot i_{i\xi}\pm u_{i\xi}=0, \quad (1)$$

where $W_{i\xi}$ – number of turns of the *i*-th winding $(i=1\div n)$ phase $\xi=A,B,C$; Φ_{ξ} – instantaneous value of the main magnetic flux of the phase ξ; $L_{i\xi}$ – leakage inductance of the *i*-th winding phase ξ; $r_{i\xi}$ – active resistance $W_{i\xi}$; $i_{i\xi}$ – instantaneous value of the current in $W_{i\xi}$; $u_{i\xi}$ – instantaneous value of the voltage of $W_{i\xi}$, the sign "-" is corresponded to the exciting windings;
2) the equation of magnetomotive forces balance for each phase $\xi=A,B,C$

$$\sum_{i=1}^{n}i_{i\xi}W_{i\xi}=F_{\mu\xi}=K_{\mu\xi}\cdot i_{\mu\xi}, \quad (2)$$

where $F_{\mu\xi}$ – magnetizing forces of phase ξ of modeled transformers and autotransformers; $i_{\mu\xi}$ – instantaneous value of magnetizing current of phase ξ; $K_{\mu\xi}$ – coefficient of dimension.

$$(3)\qquad \begin{cases} \dfrac{W_{1\xi}}{W_{i\xi}} = K_{iT}; \ \dfrac{d\left(\dfrac{1}{K_{iT}}\Phi_\xi + K_{iT}L_{i\xi}\cdot i_{i\xi}\right)}{dt} + K_{iT}\left(r_{i\xi}\cdot i_{i\xi} \pm u_{i\xi}\right) = 0; \\ \dfrac{dP_{i\xi}}{dt} = K_{iT}\left(r_{i\xi}\cdot i_{i\xi} \pm u_{i\xi}\right); \ \dfrac{1}{K_{iT}}\Phi_\xi + K_{iT}L_{i\xi}\cdot i_{i\xi} + P_{i\xi} = 0, \end{cases}$$

where $P_{i\xi}$ – the change of variables, K_{iT} – the corresponding transformation ratios; the solution occurs with zero initial conditions; the second equation is obtained by transforming the equation 1 for system consist of *i*-th windings on the magnetic core and interacting between themselves, it is carried out by K_{iT}.

After reduction and transformation (equation 3) the above-mentioned equations 1,2 form for each winding of phase $\xi = A,B,C$ system of equations (equation 4):

$$(4)\qquad \begin{cases} \dfrac{dP_{i\xi}}{dt} = K_{iT}\left(r_{i\xi}\cdot i_{i\xi} \pm u_{i\xi}\right); \ i_{i\xi} = \dfrac{1}{K_{iT}\cdot L_{i\xi}}\left(\dfrac{1}{K_{iT}}\Phi_\xi - P_{i\xi}\right); \\ \sum\limits_{i=1}^{n}\dfrac{1}{K_{iT}}\cdot i_{i\xi} = i_{\mu\xi}, \Phi_\xi = f\left(K_{\mu\xi}i_{\mu\xi}\right), \end{cases}$$

where depending on the connection scheme of the windings: $u_{iA} = u_{Ai}$, $u_{iB} = u_{Bi}$ and $u_{iC} = u_{Ci}$ – instantaneous phase voltage for Y0, Y connection; $u_{iA} = \frac{u_{Ai} - u_{Bi}}{\sqrt{3}}$, $u_{iB} = \frac{u_{Bi} - u_{Ci}}{\sqrt{3}}$ and $u_{iC} = \frac{u_{Ci} - u_{Ai}}{\sqrt{3}}$ – instantaneous phase voltage for Δ connection, the connection scheme of the windings is implemented by special jumper, it provides a natural formation of the corresponding voltages in any states.

An adapted hyperbolic approximation [8] with a proportional of $i_{\mu\xi}$ additive component ($K_4 i_{\mu\xi}$), which by changing K_4 the slope of the magnetization curve at the saturation section of the magnetic circuit is used for an adequate continuous reproduction of the magnetization curves:

$$(5)\qquad \Phi_\xi = \frac{K_1 i_{\mu\xi}}{K_2 + K_3 i_{\mu\xi}} + K_4 i_{\mu\xi},$$

where $K_1 = \frac{K_{\mu\xi}}{K_{iT}}$; K_2 and K_3 - determine the approximating magnetization curve, as well as the slope of its section to saturation.

In addition, to exclude zero-sequence currents in the Y-winding connection scheme and to provide various kinds of unregulated functionality associated with the zero sequence, the following equations are included in the system under consideration:

$$(6)\qquad \begin{cases} i_{iA} = i_{iA} - K_{0i}\cdot i_{i0}; \ i_{iB} = i_{iB} - K_{0i}\cdot i_{i0}; \\ i_{iC} = i_{iC} - K_{0i}\cdot i_{i0}; \ i_{i0} = \dfrac{1}{3}(i_{iA} + i_{iB} + i_{iC}), \end{cases}$$

where i_{iA}, i_{iB}, i_{iC} – instantaneous values of the corresponding phase currents; K_{0i} – adjustable coefficient, the intermediate (between the extreme) values of which allow, if necessary, to simulate specific conditions for the flow of the zero sequence current.

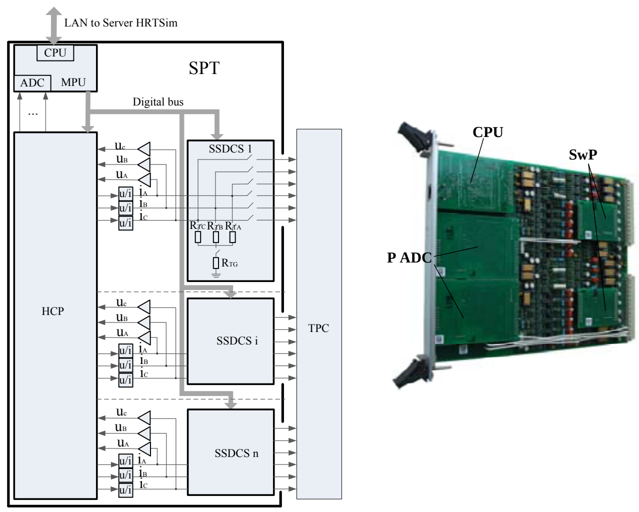
Since at least one of the windings, for example W_1, of any transformer is necessarily exciting (feeding), and one of the windings, for example W_n, turns out to be passive (receiving), the signs in equations for the contours and magnetomotive forces of these windings become definite. At the same time, the signs in equations of the remaining windings depend on the specific purpose of the latter.

It can be seen from the above system of equations that by setting and varying the parameters of a mathematical model (coefficients in equations), any type of power transformer and autotransformer can be modeled.

Realization and experimental studies of the universal mathematical model of a transformer

When using such universal mathematical model, as well as similar mathematical models of other power equipment, the total mathematical model of any real EPS, even with allowable partial equivalence, inevitably contains a stiff, nonlinear and extremely large size system of differential equations. A satisfactory solution of such system by numerical methods used in the basic tools of EPS modeling is unlikely [9], [10], and the simplifications and limitations applied in such tools become unavoidable. In addition, regardless of this, in the numerical integration of differential equations, the methodical error of their solution is always unknown [11], [12].

An alternative direction to solve this problem is the developed concept of hybrid simulation, described in detail in [3], [13]. It defines common principles for constructing software and hardware simulation tools for all elements of EPS, including for transformers. The structural scheme and visual view of the specialized processor of the universal mathematical model of the transformer, corresponding to the principles of the indicated concept, are shown in figure 1.



a) b)

Fig. 1. The structural diagram (a) and visual view (b) of Specialized processor of transformer (SPT): CPU - central processing unit; ADC –analog-to-digital converter; MPU - microprocessor unit; LAN – local area network; HCP – hybrid co-processor; u/i - voltage-current converter; SSDCS - series and shunt digitally controlled three-phase switches; R_{TA}, R_{TB}, R_{TC}, R_{TG} - transient resistance; TPC – three-phase commutator; SwP- switching processor; P ADC - processors of analog-to-digital converters.

The specialized parallel digital-analog structure is based on integrated operational amplifiers, integrated digital-to-analog converters, approximators based on integrated signal multipliers, and forms a hybrid transformer co-processor (HCP). A fragment of the HCP structure for solving phase A equations is shown in figure 2.

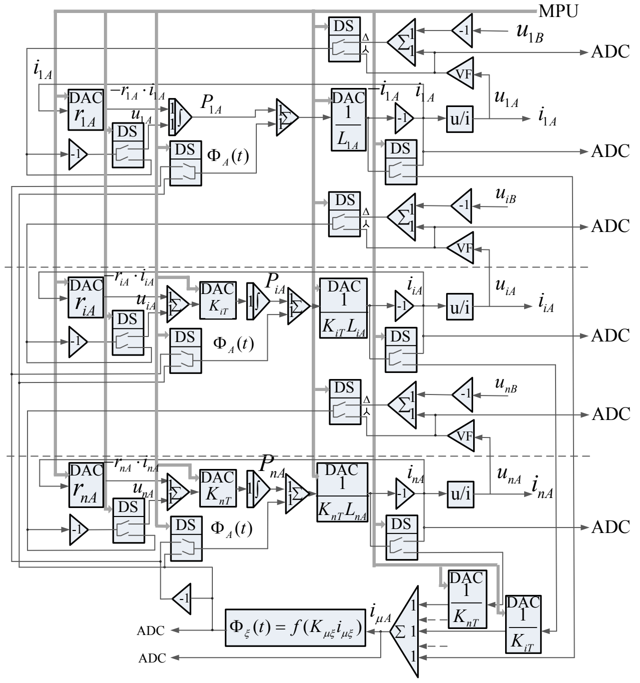


Fig. 2. The functional diagram for ξ=A (identical for ξ=B,C) of HCP with *n*-windings of SPT: DAC – digital-to-analog converter; DS – digitally controlled three-phase switches; VF – voltage follower

The realization in this HCP scheme of the approximating magnetization curve is carried out using a functional converter based on an integrated microelectronic multiplier of continuous signals DA (figure 3).

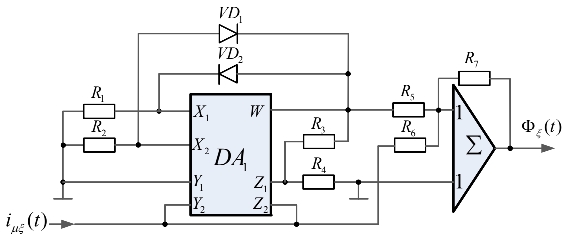


Fig. 3. Functional converter for continuous simulation of the magnetization curve

Taking into account the transfer function DA

(7) $$W = A\left(\frac{(X_1-X_2)(Y_1-Y_2)}{SF} - (Z_1-Z_2)\right),$$

where $A=10^5$, $SF=10$, the presented circuit of the functional converter ensures continuous wideband reproduction of the approximated nonlinear dependence:

(8) $$\Phi_\xi(t) = \frac{-\frac{R_7}{R_5} i_{\mu\xi}(t)}{\frac{1}{A} + \frac{R_4}{R_3+R_4} + \frac{i_{\mu\xi}(t)\left(\frac{R_1}{R_1+R_{VD1}} - \frac{R_2}{R_2+R_{VD2}}\right)}{SF}} - \frac{R_7}{R_6} i_{\mu\xi}(t).$$

The relation R_7 and R_5 determines K_1, R_7 and R_6 – slope of the magnetization curve in the saturation area, R_3 and R_4 the slope of the initial part of the curve. To confirm the adequacy of reproduction of the magnetization curve, a comparison is made with a curve based on the reference data for cold-rolled steel 3413 (figure 4).

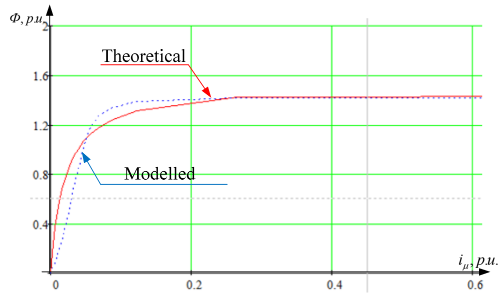
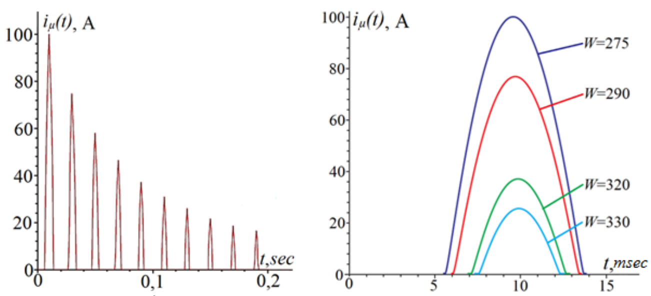


Fig. 4. Testing of the magnetization curve simulation

To ensure the interaction of the mathematical level of the HCP with the physical level, integral voltage/current converters (*u/i*) are used. In the same way, the schemes for solving the remaining equations are realized in HCP.

All the necessary information and control properties and capabilities associated with the transformation, display, control of information is carried out with the help of the MPU containing: a central processor, a functional peripheral controller and an integral analog-to-digital converter. The MPU of the transformer and the MPU of other EPS elements through the network switches are connected to each other and to the server by a local computer network. In accordance with the topology of the modeled EPS, the functional interrelations of the specialized processors are realized through TPC. Similarly, specialized processors of all EPS elements were implemented. The SPT developed in this way is adapted for use in the Hybrid real time power system simulator (HRTSim). HRTSim is a parallel, multi-processor, software and hardware real-time system of hybrid type, combining an adaptable set of specialized processors of all elements of the simulated EPS scheme and information-control system [3], [13].

For testing the developed SPT a single-phase ideal voltage source with a frequency of 50 Hz was connected to the input of the model primary winding. When voltage is supplied to the transformer's winding, the inrush currents arise due to saturation of the magnetic system of the transformer. When supplied the transformer without load, the current amplitude, depending on the type of transformer, is 3-5 times higher than its nominal value. The transient current of SPT in open-circuit test is shown in figure 5a. Since the developed model of transformer is universal, testing was carried out at various parameters of the model, including different number of turns (figure 5b).



a) b)

Fig. 5. Oscillograms of the magnetization current of the SPT in open-circuit test

Oscillograms of SPT open-circuit test are shown in figure 6, 7. Moreover, the transformer parameters can be set in a wide range (figure 8). The short circuit test of developed SPT is shown in figure 9, the on-load test is shown in figure 10.

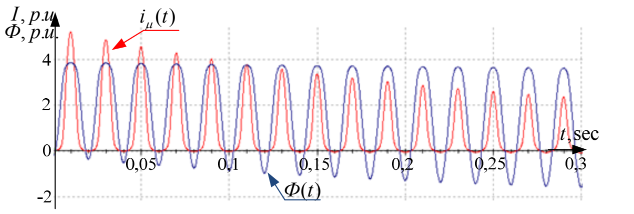


Fig. 6. Oscillograms of the magnetization current and the magnetic flux of ξ -phase of the SPT in open-circuit test

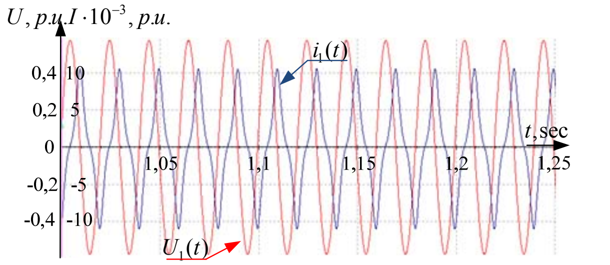


Fig. 7. Oscillograms of the current and voltage of ξ -phase primary winding of the SPT in open-circuit test

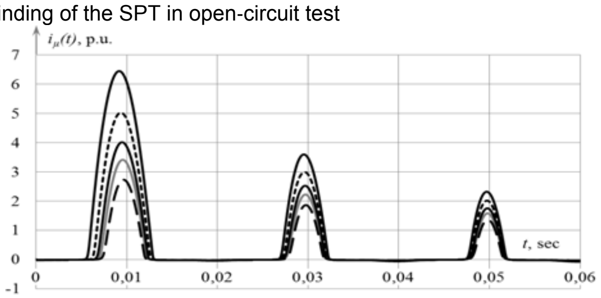


Fig. 8. Oscillograms of the magnetization current of SPT at various parameters in open-circuit test

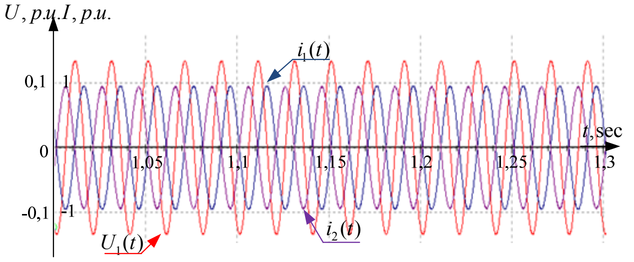


Fig. 9. Oscillograms of the current, voltage of primary winding and the current of secondary winding of ξ -phase of the SPT in short-circuit test

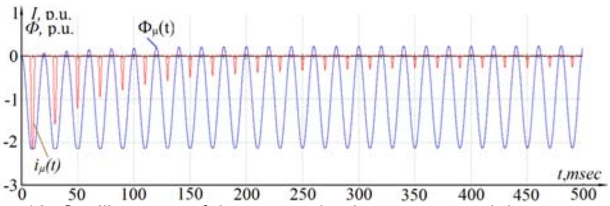


Fig. 10. Oscillograms of the magnetization current and the magnetic flux of ξ -phase of the SPT in on-load test

The developed SPT is reliably and comprehensively tested and also, most importantly and convincingly, in practice as part of the practical use of HRTSim [3], [13]. Obtained results confirm the reliability of the developed model and its hardware implementation scheme.

Conclusion

1. A universal mathematical model of power transformers and autotransformers was synthesized. The required quality of the reproduction of processes is confirmed, including the experience of using the developed model in the corresponding simulation tools.
2. The considered universal mathematical model allows, without decomposition, to reproduce more accurately the full spectrum of processes in any power transformers and autotransformers used in EPS, and its application in modeling the processes in EPS allows significantly increasing the reliability of calculations.

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