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MODEL OF ELECTROMAGNETIC VOLTAGE TRANSFORMER FOR STUDY OF FERRORESONANCE PROCESSES

Mathematical model of electromagnetic voltage transformer has been developed. The phenomenon of hysteresis is simulated on Jiles-Atherton model, that takes into consideration the impact of reversal of magnetization speed on the value of coercive force.

Key words: *ferroresonance, basic curve of magnetization, hysteresis, model of Jiles-Atherton.*

Introduction

Problems, dealing with realization of field study of ferroresonance processes (FRP) and danger of damaging the equipment of substations, contributed to the formation of mathematical simulation, as the main tool for studying FRP. The most complex part of mathematical model for FRP investigation is the model of non-linear electromagnetic voltage transformer (VT). Many papers both of Ukrainian and foreign authors are devoted to the problem of FRP study, but there are reasons to think that the problem has not been solved yet. As a rule, the authors in the process of formation of mathematical model of electromagnetic VT perform considerable simplifications: they take into account magnetic system only by main magnetization curve, without taking into consideration the stage character, use piecewise-linear approximation, etc. [1, 2]. Taking into consideration high sensitivity of ferroresonance process development character to initial conditions and accuracy of equivalent circuit elements parameters description, any simplifications of calculation circuit result in considerable errors in the process of simulation.

The aim of the given study is to develop mathematical model of electromagnetic voltage transformer for investigation of ferroresonance processes in distributive devices, taking into account the phenomenon of hysteresis and stage character.

Equivalent circuit of electromagnetic voltage transformer

Electromagnetic transformer of HK Φ type, used in distributive devices (DD) of substations of 110 – 500 kV electric grids are of stage form realization. Each stage is separate transformer with single - path magnetic circuit (Fig. 1). That is why, magnetic flux across all the coils of one stage may be considered to be uniform.

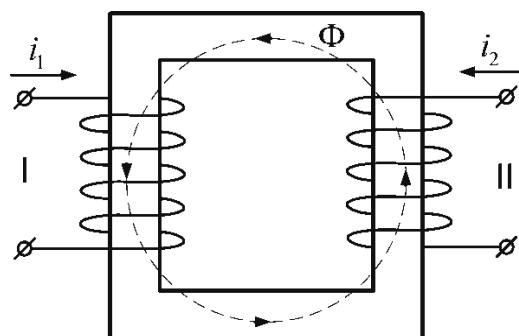


Fig. 1. Magnetic system of VT stage

Electric equivalent circuit of VT stage is presented in Fig. 2. Active resistances and leakage inductances are presented by elements R_1, R_2, L_1, L_2 . n_1, n_2 – number of turns of primary and secondary windings, correspondingly.

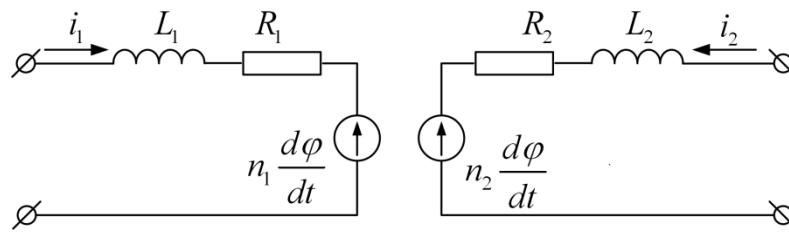


Fig. 2. Electric equivalent circuit of transformer stage

Magnetic intensity, caused by currents in transformer windings, is determined by the relation:

$$H = \frac{i_1 n_1 + i_2 n_2}{l_{av}}, \quad (1)$$

where l_{av} – average length of magnetic line of force.

Magnetic flux may be calculated by the formula:

$$\varphi = B(H) \cdot S, \quad (2)$$

where S – cross-section of VT magnetic circuit.

Approximation functions of magnetization curves

Main magnetization curve is often used for simulation of non-linear inductive elements, this curve is a geometric place of hysteresis cycles vertices, obtained during cycle reversal of magnetization of the core. It may be presented in the form of magnetic-flux linkage dependences on magnetizing current of winding $\Psi = f(i)$ or magnetic induction from magnetic field intensity $B = f(H)$. Also inverse functional dependences may be used. In [3] some variants of magnetization curves approximation are presented. We will consider them in details.

Piecewise-linear approximation provides replacement of real curve by broken one with several breakpoints. The number of linear sections depends on the necessary accuracy of magnetization curve representation and the range of its change. Main advantage of using piecewise-linear approximation is the possibility of transition to solution of the linear problem. But the main drawback of the given approximation is discontinuous change of the derivative during the transition from one section to another, that may lead to inadmissible errors while using numerical methods. That is why, in the process of investigation of ferroresonance circuits usage of the given approximation functions is limited.

Logarithmic and exponential approximations are limited by the problems of calculation of magnetic circuits with static fields, that is why, in the process of ferroresonance circuits study the usage of the given approximation functions is unreasonable. Hyperbolic approximation of the main magnetization curve has approximation to real curve only in the areas of strong fields, hence, in the process of ferroresonance circuits study, the usage of the given approximation is inadmissible.

On the whole, power functions are widely used, because they allow to carry out calculations of magnetic circuits with varying magnetic fields. Accuracy of approximation of real curve by power polynomial is proportional to the number of polynomial members. However, increase of the number of polynomial members leads to complication of polynomial coefficients determination. Functions of hyperbolic sine and tangent while expansion into a series are transformed into power polynomials.

Approximations by hyperbolic sine and tangent are close to the approximation by power polynomial and in many cases coincide with the data of field experiments. Method of splines is rather efficient on condition of rigid requirements to the approximation accuracy of magnetization curve. As a result of application of various approximating functions at certain sections of magnetization curve continuity not only of spline-function itself but also its derivative is achieved.

Limitation of spline-method usage is cumbersome calculations.

High accuracy of magnetization curve approximation can be achieved, using rational functions. However, for determination of approximation coefficients it is necessary to use a large number of experimental points ($2n+1$), but this is not always possible because of output data limitation.

Functions with arc tangent are widely used while approximation of magnetization curves of non-linear inductive elements, as the functions itself and its derivative are calculated rather easy in case of sufficient correspondence with the original. That is why, for further research, the arc tangent function of approximation with three coefficients and linear member was used as a model [2]:

$$B = \alpha \cdot \arctg(\beta H) + \gamma H, \quad (3)$$

where α , β , γ – approximation coefficients.

Simulation of magnetic hysteresis

In the course of ferroresonance processes simulation by the main magnetization curve the phenomenon of hysteresis is suggested to be taken into consideration by introducing into calculation model active transversal conductance. However, such account of the hysteresis phenomenon causes certain inaccuracy, which in combination with sensitivity of ferroresonance processes may lead to erroneous results of simulation. That is why, during simulation of ferroresonance processes hysteresis models should be used. In greater part of computer simulators the phenomenon of hysteresis is described, using models of J. Chan [4] and Jiles-Atherton [5]. J. Chan model is simpler, but it does not allow to reproduce with sufficient accuracy main magnetization curve, that is very important for ferroresonance processes simulation. The basis of Jiles-Atherton models is non-hysteresis curve, that is the dependence of non-hysteresis magnetization on the magnetic field intensity. Jiles-Atherton model allows to represent very accurately main magnetization curve, that is why, for simulation of ferroresonance processes it is expedient to use this model.

The connection between magnetic induction, magnetic field intensity and magnetization is described by the relation:

$$B = \mu_0(M + H). \quad (4)$$

Having expressed from the given equality the magnetization and substituted magnetic induction from (3), we obtain the dependence of non-hysteresis magnetization on magnetic field intensity:

$$M_{an}(H) = \frac{1}{\mu_0} B_{an}(H) - H = \frac{\alpha}{\mu_0} \cdot \arctg(\beta H) + H \left(\frac{\gamma}{\mu_0} - 1 \right). \quad (5)$$

The derivative of non-hysteresis magnetization from magnetic field intensity has rather simple mathematical notation:

$$\frac{dM_{an}}{dH} = \frac{1}{\mu_0} \left(\gamma + \frac{\alpha \cdot \beta}{1 + (\beta \cdot H)^2} \right) - 1 \quad (6)$$

The description of hysteresis processes in ferromagnet is based on the theory of domain walls motion in varying magnetic field. The effect of internal field lag while reversal of magnetization is similar to the effect of dry friction between the domain walls. Real processes of reversal magnetization of ferromagnetic materials are accompanied by elastic bend of domain boundaries. That is why, hysteresis model must take into account the effect of viscous friction, that is achieved by account of addition of proportional to the derivative non-hysteresis magnetization from the intensity of magnetic field. As a result, we obtain equation:

$$\frac{dM}{dH} = \frac{M_{an} - M}{K} \cdot \delta + \frac{C}{1 + C} \cdot \frac{dM_{an}}{dH} \quad (7)$$

where K – value of coercive force of hysteresis loop; δ – coefficient that takes into account the

direction of reversal of magnetization.

One of the main characteristics of ferroresonance processes is considerable distortion of the form of current and voltage curves, i. e. arising of higher harmonic components. Another characteristic feature of ferroresonance circuits is the possibility of origination of stable oscillations on the frequencies, different from the frequency of the grid, first of all, on the third subharmonic.

Jiles-Atherton model at variable values of magnetization rate, taking place during ferroresonance, has the discrepancy with experimental results. Main parameter, characterizing dynamic properties (first of all losses) of ferromagnetic materials is the dependence of coercive force on reversal of magnetization rate. In [6] the authors propose to approximate the above-mentioned dependence by the linear function of the type:

$$H_C = H_{C0} + K_{hcf} \cdot \left| \frac{dH}{dt} \right|, \quad (8)$$

where H_{C0} , K_{hcf} – coefficients of linear regression.

Having substituted the value of coercive force, calculated by (8) in the equation (7) we obtain the complete equation of reversal of magnetization of ferromagnetic core of VT:

$$\frac{dM}{dH} = \frac{M_{an} - M}{H_{C0} + K_{hcf} \cdot \left| \frac{dH}{dt} \right|} \cdot \delta + \frac{C}{1+C} \cdot \frac{dM_{an}}{dH} \quad (9)$$

The obtained equations (2), (3) and (7) represent final model for the description of magnetic system of each separate stage of electromagnetic voltage transformer. The developed model was realized in the environment Matlab. Hysteresis curve, obtained for one stage HKΦ-330 is shown in Fig. 3.

The results of numerical modeling, using the developed model of VT stage, showed that taking into account the phenomenon of hysteresis performs considerable impact, first of all, on the boundaries of areas, where ferroresonance processes exist, also on origination and the course of ferroresonance processes on subharmonics.

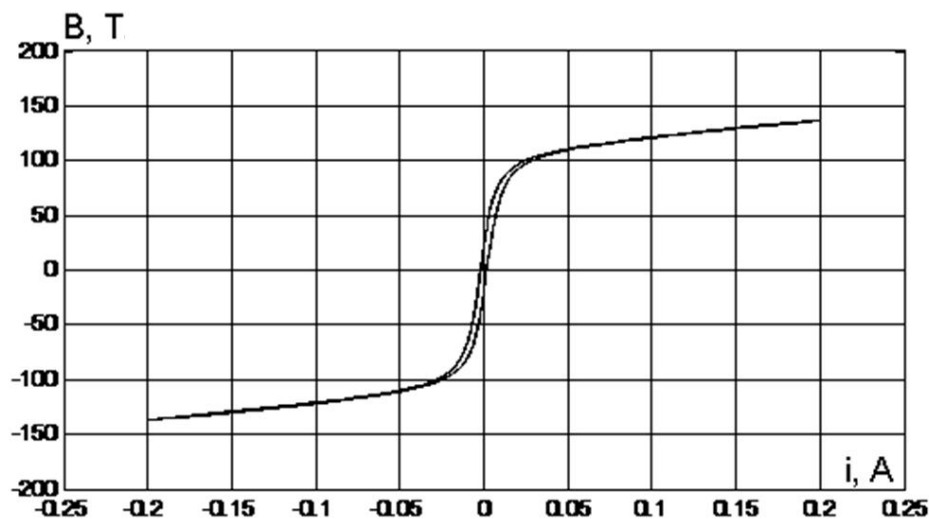


Fig. 3. Hysteresis curve of one stage of HKΦ-330

Conclusions

The model of voltage transformer, that takes into account stages and hysteresis phenomenon has been developed. The impact of reversal of magnetization rate of transformer core on the value of active energy losses is taken into consideration, it is extremely important, because ferroresonance processes are accompanied by considerable distortion of current curve form and may appear at the

frequencies, different from the basic one.

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