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Simulation of Ferroresonance Phenomena in Power Systems

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Abstract: The paper deals with a comparison of two published approaches to modelling the properties of magnetic circuits leading to a dynamic description of hysteresis characteristic. The comparison of the two methods is carried out both theoretically and in practical measurements on instrument voltage transformer. The paper also deals with the possibility of employing the models for ferroresonance simulations in power systems.

Key-Words: Ferroresonance Phenomena, Power Systems, Modelling, Instrument Voltage Transformer

1 Introduction

In the simulation of transient phenomena in powers systems it is necessary to use models of elements which have electrical properties corresponding with real elements of power systems. Just the model of transformer which respect real hysteresis loop has been a subject of miscellaneous researches for a long time. For determining of exact model of hysteresis loop it is necessary to know a lot of parameters of magnetic circuit or to have a measurement behind knee of magnetization curve. Next it is possible to use calculated model in simulation of transient phenomena.

2 Measurement on Instrument Voltage Transformer

Prior to creating a faithful transformer model it was necessary to perform a series of measurements for different operating points. In view of the requirement to model a measuring voltage transformer, a transformer was chosen that can currently be found in HF power networks, namely the TJC4 transformer with a nominal transformer ratio of $\frac{11000/\sqrt{3}}{110/\sqrt{3}} = 100$. The measurement was performed in two stages. In the first stage, magnetic characteristic was measured on the lower-voltage side. Voltage on the higher-voltage side was detected using a HV probe. The voltage and current waveforms were recorded using an analyser with a sampling frequency of 100 kHz. In the second stage, a check measurement of magnetization characteristic was performed in a HV laboratory, with direct measurement of primary current using a milliammeter.

Fig.1 gives a comparison of the magnetization characteristics obtained from both measurements.

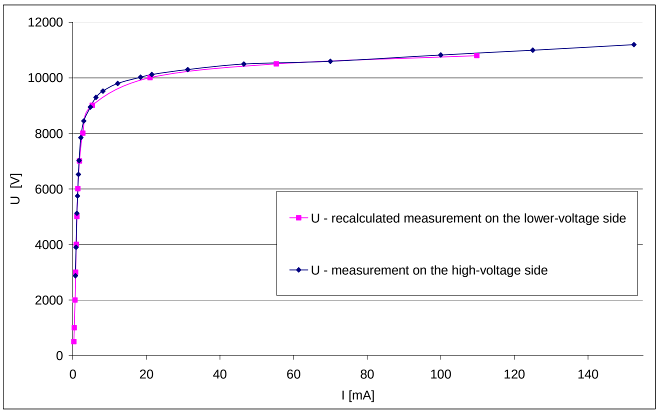

Fig.1 Magnetization characteristic of the TJC4 transformer

In this measurement, a total of 12 operating points were measured over the whole range of magnetization characteristic for the sake of additional verification of model functionality. Fig.2 gives the development of hysteresis loops for individual operating points.

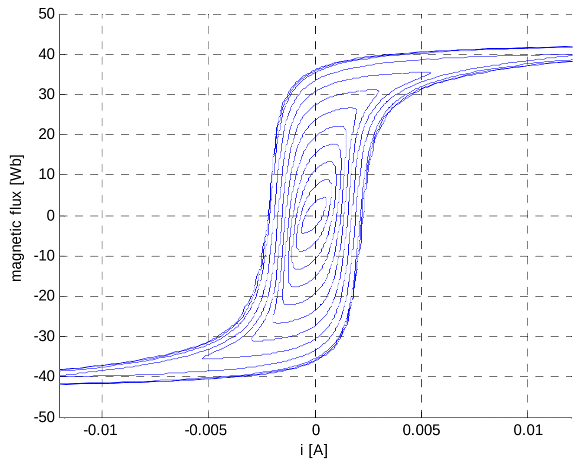

Fig.2 Hysteresis loops for the operating points measured

2.1 Calculation of transformer model

The Mathematica program environment was used in the calculations. Numerical voltage integration was performed for all the operating points measured. For the model, which depends on the current derivative**,** numerical differentiation was performed again for all the operating points measured. Thus in addition to the measured voltage waveforms *u(t)* and current waveforms *i(t)* the waveforms of conjugate magnetic flux *Ψ(t)* and current derivative *i'(t)* were obtained. These waveforms were sampled at a frequency of 50 kHz. Subsequently, the coefficients of individual models were calculated using the Lavemberk-Marquart method. We now have at our disposal all the data necessary for transformer modelling. In [9] a basic overview of published models is given, which will be applied to the above measurement.

2.1.1 Model 1

This model of hysteresis loop starts from [4] and is formed by the function

$$i(\Psi) = f_{ODD}(\Psi) + g_{EVEN}(\Psi)\frac{d\Psi}{dt} \qquad (1)$$

where

$$f_{ODD}(\Psi) = a_1\Psi + a_3\Psi^3 + a_5\Psi^5 + a_7\Psi^7 + a_9\Psi^9 + a_{11}\Psi^{11} + \ldots$$

$$g_{EVEN}(\Psi) = b_0 + b_2\Psi^2 + b_4\Psi^4 + b_6\Psi^6 + b_8\Psi^8 + b_{10}\Psi^{10} + \ldots$$

$$\Psi = \Psi(t)$$

If in order to obtain the model coefficients we apply the same procedure as in the preceding cases, we obtain an equation of the model. For the operating point being measured, this model (in red) exhibits a perfect agreement between the model and the measurement (in blue) the curves are almost identical, see Figs.3 and 4.

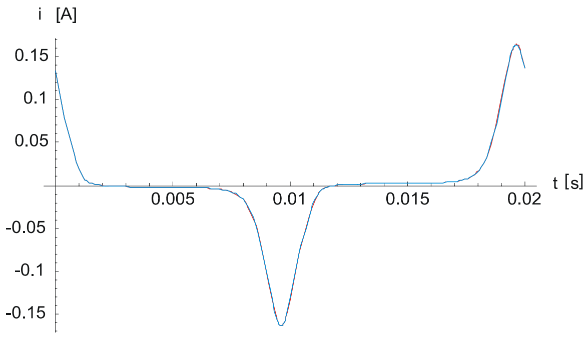

Fig.3 The waveforms of current

2.1.2 Model 2

This model starts from [2] and is formed by the function

$$F\left(i(t), i'(t), \Psi(t), \Psi'(t)\right) = 0 \qquad (2)$$

and it is possible write this function (equation 2) in next form (equation 3).

$$u(t) = q_1 \cdot \Psi(t) + \frac{q_2 \cdot i(t) + q_3 \cdot i'(t) + q_4 \cdot \Psi(t)}{1 + q_5 \cdot \left(i(t)^2\right)^{q_6} + q_7 \cdot \left(\Psi(t)^2\right)^{q_8}} \qquad (3)$$

A comparison of the model with the measurement for the last operating point is given in Fig. 5.

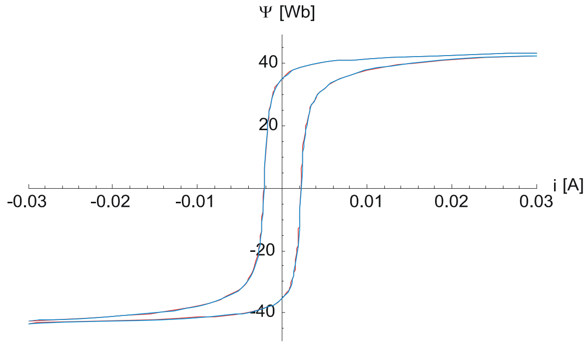

Fig.4 Hysteresis loops

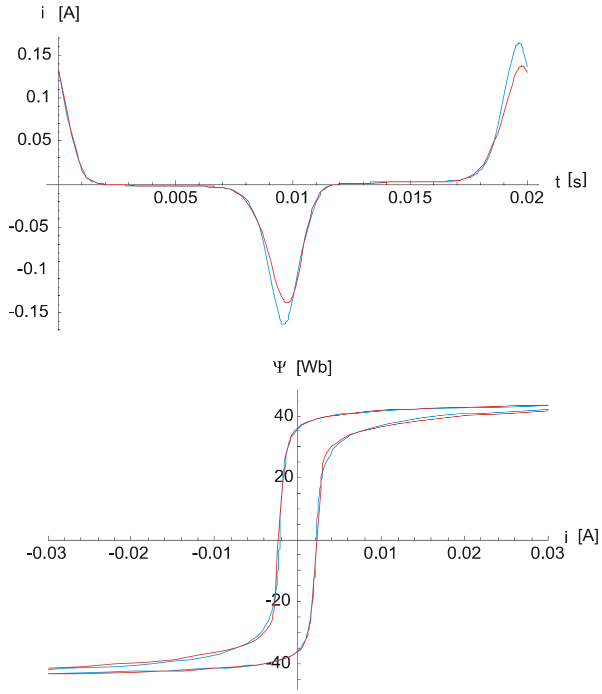

Fig.5 Current waveforms and hysteresis loops

For the solution of the model it is necessary to solve a first-order differential equation. In the experiments, some problems with the convergence of numerical solution were encountered.

3 Simulation of Simple Ferroresonance cicrcuit

Fig.6 gives the block arrangement of a series ferroresonance circuit in the Matlab Simulink environment. The circuit consists of an ideal ac supply source, its internal resistance and reactance (Ri, Xi), a series capacitor (C), a resistance and inductance representing the primary transformer winding, and a block representing the non-linear inductance of transformer with losses included.

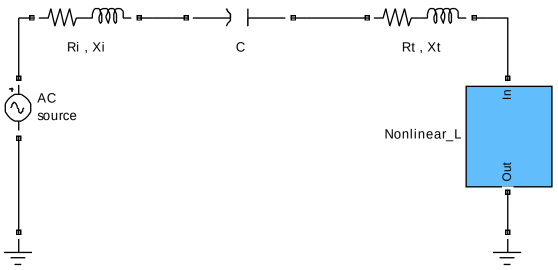

Fig.6 Simple series ferroresonance circuit

Fig.7 shows a comparison of voltage waveforms for individual models; the supply voltage of the circuit has an amplitude of 12000V and a capacitance of 6 nF.

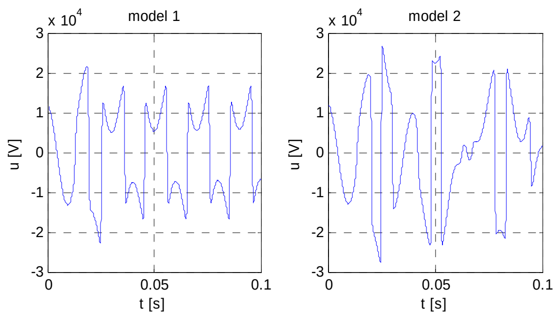

Fig.7 Comparison of the waveforms of both models

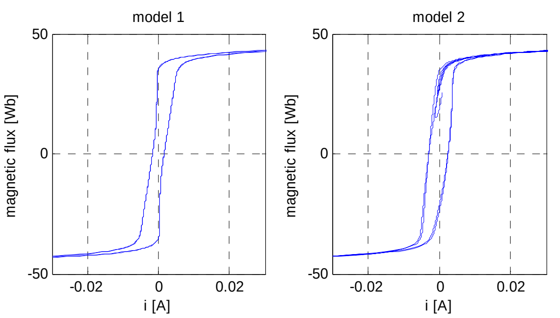

Fig.8 Comparison of the hysteresis loops

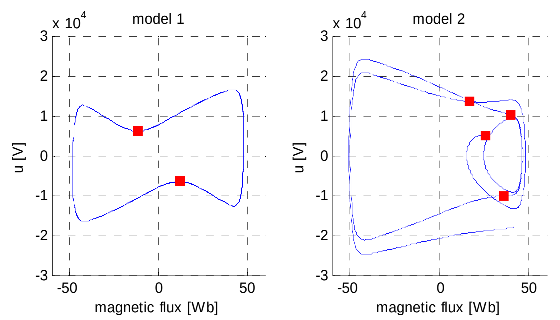

Fig.9 Comparison of the waveforms in the phase plane and semi-Poincaré representation

In Fig.8 the waveforms of hysteresis loops are compared while in Fig.9 the phase plane representations are compared. The red points represent the so-called ***S***-representation (semi-Poincaré). It is obvious that for model 1 the representation is symmetrical, i.e. a fundamental-frequency ferroresonance is concerned, while for model 2 the representation is unsymmetrical and the trajectory of motion in the phase plane reveals the doubling of periods. On close examination of the hysteresis loop this is also evident for model 2.

4 Modelling of a Real Network

To verify model functionality several typical configurations susceptible to ferroresonance appearance were chosen and simulated. In addition to verifying model functionality, these simulations are to demonstrate the complexity of check calculation for ferroresonance appearance when designing a new or reconstructing an existing power engineering plant. The Matlab-Simulink software was used in the simulation.

Fig.11 shows the connection of the line in the 110kV switching station in Bezdecin. This configuration belongs to configurations susceptible to ferroresonance appearance and thus needs to be examined more closely. Here the main elements of ferroresonance circuit are the non-loaded instrument voltage transformer and the control capacitance of the circuit breaker.

When switching off the circuit breaker V, with the bus disconnector O1 switched on and the outlet disconnector O2 switched off, the waveforms of the voltage measured on the instrument transformer were as shown in Fig.10.

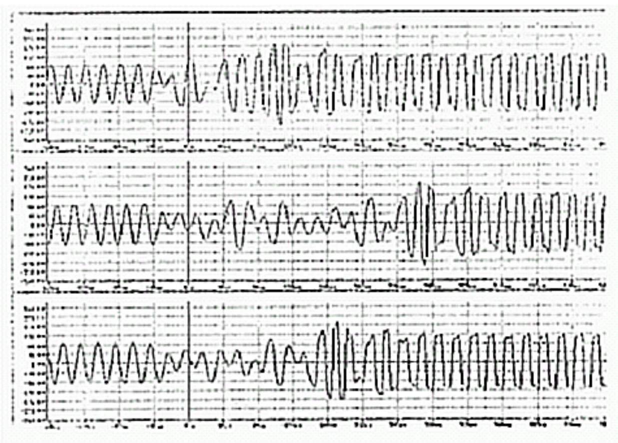

Fig.10 Voltage waveforms

The circuit in question is a series ferroresonance circuit, where the circuit breaker and disconnector determine the initial conditions given by the instant of connection. Other initial conditions may be given, for example, by residual magnetic flux or core premagnetization due to the dc component of voltage, etc. These conditions are not taken into consideration.

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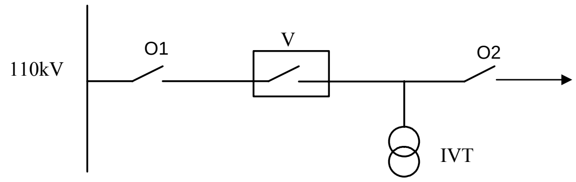

Fig.11 Scheme of the outlet in the switching station

4.1 Disconnecting by circuit breaker V, with disconnector O_1 connected and O_2 disconnected

As all ferroresonance circuits, this circuit, too, is very sensitive to initial conditions. The instant of disconnection, which forms the initial condition, is in this case firmly fixed by the circuit breaker, which will disconnect the circuit in current zero (Note: about current zero). Another initial condition, which we do not consider, may be the pre-magnetized core due to the dc component of voltage. In such a case the circuit is more susceptible to transferring to ferroresonance.

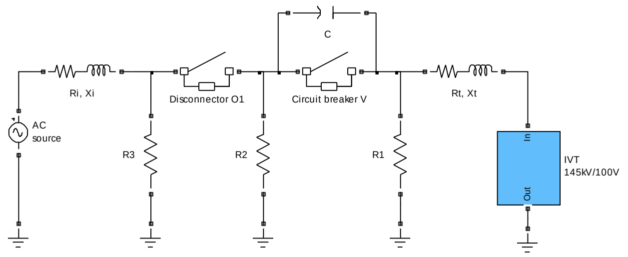

Fig.12 Schematic diagram of circuit

Simulation is thus conducted from steady state, and initial conditions are regarded as defined. The circuit is then created in the Simulink environment (Fig.12). The transformer block is identical with the block described above for model 1. When the circuit breaker contacts are disconnected, the control capacitance *C* comes into play. Parallel resistors are placed in the circuit because of the presence of the circuit breaker block. The circuit is solved by the method of nodal voltages, and to simulate the switching element it is necessary to define the circuit admittance matrix also without switching elements. The values of these resistors are, of course, large and have no effect on simulation results. Fig.13 gives the waveforms of voltage, current and conjugate magnetic flux for the simulation of disconnecting the outlet for capacitance *C = 60pF* and bus voltage amplitude *99kV*. This value corresponds to the nominal value of voltage increased by the tolerance (10%) for HV. This increased voltage is a common operating state – switching stations operate at this value in order to respect the permissible voltage drop at the end of the line. At time t = 0.04 the disconnection of the circuit breaker took place.

It can be seen that in the course of several periods ferroresonance with a maximum voltage of 200kV appeared in the circuit. The phenomenon became steady and it will not disappear until it is damped one way or another.

For damping it is possible to use, for example, a resistor in the secondary winding of instrument voltage transformer, a transformer with a higher value of nominal voltage, a circuit breaker with a lower control capacitance (Fig.14), etc.

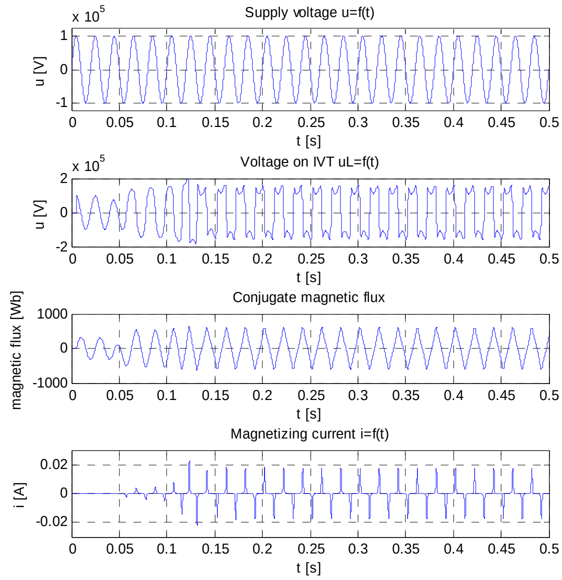

Fig.13 Voltage, magnetic flux and current waveforms

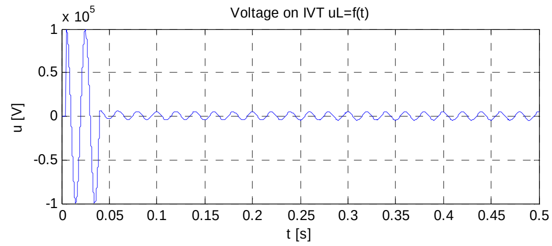

Fig.14 Voltage waveform for 1pF control capacitance of the circuit breaker

5 Conclusion

Two models of electrical properties of transformers are presented in the paper. What is common to both models is the way they are obtained, namely from measuring in oversaturated region (as far behind the bend of magnetization characteristic as possible). Model 1, presented in [4], can be seen as more faithful. The concluding part deals with the simulation of disconnecting the outlet of a 110kV switching station, with a good agreement between the measured and the simulated voltage waveforms.

Practical experience shows that a reduction of the losses in magnetic circuits of transformers is ever more frequently accompanied by the appearance of ferroresonance phenomena in power networks. It is obvious that it will be necessary to include the calculation of ferroresonance phenomena in the methodology of designing MV and HV facilities.

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