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## 20. Study Of Ferroresonance In Electric Networks Taking Into Account The Generalized Model Of Nonlinear Inductance

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**Abstract:** Requirements for reliable power supply of consumers determine the need to study operating modes of electrical systems with the problem of damage to electrical equipment in electrical networks due to ferroresonance phenomena. In this regard, an effective method is proposed for the analysis of ferroresonance arising in electrical networks between electromagnetic transformers and network capacities, taking into account the generalized model of the nonlinear inductance of the voltage transformer. The analysis method makes it possible to obtain qualitatively new and fairly accurate analytical expressions for the numerical calculation of ferroresonant equivalent circuits.

**Key words:** ferroresonance phenomena, electromagnetic transformers and network capacities, generalized model of nonlinear inductance, equivalent electromagnetic capacitance and active conductivity, leakage inductance, dynamic hysteresis loop.

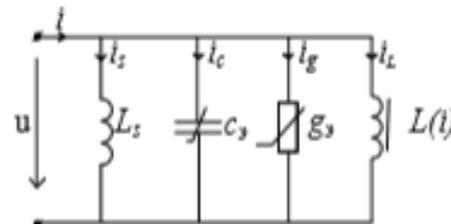
Requirements for reliable power supply to consumers determine the need to study the operating modes of electrical systems that lead to damage to electrical equipment and disruption of power supply. One of the important reasons for the emergence of such modes is ferroresonance phenomena (FA). It is argued that the most common causes of damage to insulation monitoring voltage transformers are earth arc faults and ferroresonance between the network capacitance and the inductance of the power step-down transformer.

In the electric power industry, FY occurs in electrical networks during the formation of circuits with electromagnetic transformers (EMT) and network capacities, characterized by long-term overvoltages and current overloads of voltage transformer windings due to abrupt saturation of the transformer magnetic circuits.

Overvoltages arising in this case are also dangerous for measuring equipment and protection means of power equipment. [1]

The task of analyzing FA in electrical networks requires the creation of mathematical models and an analytical calculation of ferroresonance that allow one to obtain qualitative characteristics of the process.

Based on the importance of the problem of reliable power supply to consumers, it is proposed to analyze the equivalent circuit of ferroresonance with EMT and network capacities (Fig. 1) taking into account the generalized model of nonlinear



inductance (Ni) [2,3] of a ferromagnetic coil EMT (Fig. 2).

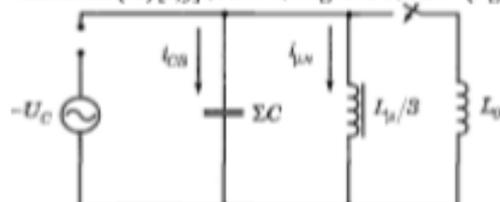


Fig. 2. Generalized Ni model ferromagnetic coil

Fig. 1. Equivalent circuit ferroresonance EMT and network capacities

If we assume that the equivalent parameters  $g_e$ ,  $C_e$ , and  $L_s$  in the equivalent circuit of the generalized Ni model are constant, then

$$\text{we get } i - C \frac{d^2 \psi}{dt^2} + g \frac{d\psi}{dt} + a\psi + b\psi^n + \frac{\psi}{L_S} \quad (1)$$

where is the approximation of the Weber-ampere characteristic of Ni, obtained on the basis of the magnetization curve  $B = f(H)$ ,  $C_e$  is the equivalent electromagnetic capacitance of Ni,  $g_e$  is the equivalent active conductivity of Ni;  $L_s$  is the leakage inductance of Ni.

We apply expression (1) for the equivalent circuit of ferroresonance EMT and network capacities (Fig. 1) with the assumption that the parameters  $g$ ,  $C$  and  $L_0$  are constant and then we have

$$i = \Sigma C \frac{d^2 \psi}{dt^2} + \Sigma g \frac{d\psi}{dt} + a\psi + b\psi^n + \frac{\psi}{L_0}$$

(2)

where  $\Sigma C$  is the total electromagnetic capacitance of the NI EMT voltage, is the approximation of the Weber-ampere characteristic of the NI EMT voltage, is the active conductivity of the NI EMT voltage;  $L_0$  - dissipation inductance NI EMT voltage [4].

Taking the voltage of the transformer and taking into account the accepted approximation of the Weber-ampere characteristic of the NI, it follows:

$$\begin{cases} i_c = -\frac{I_{cm}}{\Psi_m} \psi; \\ i_g = \pm \frac{I_{gm}}{\Psi_m} \sqrt{\Psi_m^2 - \psi^2}; \\ i_{,n} = a\psi + b\psi^n, \end{cases} \quad (3)$$

From system (3) we obtain

$$i = i_c + i_g + i_{,n} = \left( a - \frac{I_{cm}}{\Psi_m} \right) \psi + b\psi^n \pm \frac{I_{gm}}{\Psi_m} \sqrt{\Psi_m^2 - \psi^2} \quad (4)$$

Based on (3), it is possible to construct the dynamic characteristic of the NI EMT voltage, which is its dynamic hysteresis loop (Fig. 3) [5].

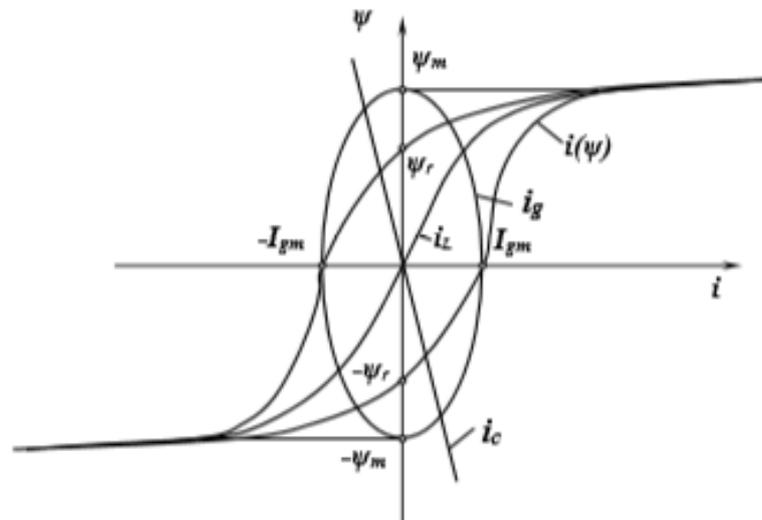


Fig. 3. Dynamic hysteresis loops of nonlinear inductance

$\Sigma g = \Sigma \frac{1}{R}$  - the total active conductivity of the NI EMT voltage is determined by the dynamic coercive force of the magnetic core material. If, induction then,

$$H_{cd} = H_c + 0,125\omega\sigma d^2 B_s \sqrt{2\varepsilon - 1} \quad (5) \quad \text{where is the saturation induction;}$$

coercive force; - the thickness of the magnetic material; - electrical conductivity of the magnetic material; is the modulation factor of the core.

With considering,

$$\frac{U}{R} = \frac{H_{cd} l}{w} = \frac{l}{w} (H_c + 0,125\omega\sigma d^2 B_s \sqrt{2\varepsilon - 1}) \quad (6)$$

Let's get the equivalent active resistance of NI EMT voltage.

$$R = \frac{Uw}{l(H_c + 0,125\omega\sigma d^2 B_s \sqrt{2\varepsilon - 1})} = \frac{\omega w^2 SB}{l(H_c + 0,125\omega\sigma d^2 B_s \sqrt{2\varepsilon - 1})} \quad (7)$$

From (2) we determine the equivalent parameters C and Lo of the NI EMT voltage.

$$C = \frac{a\Psi_r + b\Psi_r^n - \frac{1}{R} \sqrt{U_m^2 - \Psi_r^2 \omega^2}}{\omega^2 \Psi_r} = \frac{a\Psi_r + b\Psi_r^n - \frac{\omega}{R} \sqrt{\Psi_m^2 - \Psi_r^2}}{\omega^2 \Psi_r} \quad (8)$$

$$L_0 = \frac{\Psi_r}{\frac{1}{\Psi_m} (I_{cm}\Psi_r + I_{gm} \sqrt{\Psi_m^2 - \Psi_r^2}) - b\Psi_r^n} \quad (9)$$

Thus, expressions (7), (8) and (9) defining the equivalent parameters R, C and Lo of the NI EMT voltage are characterized by a sufficiently high accuracy in comparison with the known calculation formulas.

The use of the equivalent parameters of the generalized NI model allows obtaining more accurate analytical expressions when calculating the equivalent circuit of ferroresonance with EMT and network capacities.

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Study of ferroresonance in electrical networks taking into account the generalized model of nonlinear inductance  
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