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FERRORESONANCE IN ELECTRICAL NETWORK 6-35 kV

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***Abstract**. Ferroresonance in 6-35kV electrical networks and the cause of power voltage transformer damage are considered. To study ferroresonance, a reliable dynamic model of nonlinear transformer inductance is established and more accurate equations for determining equivalent parameters are derived. On the basis of the dynamic model, the Weber-Ampere characteristic of the transformer core with instantaneous values of currents and flux-currents is constructed. Boundary conditions of ferroresonance stability and determination of boundary values of network capacitance are given on the example of calculation of equivalent parameters of energy-saving power voltage transformer TMG12-250/35.*

***Keywords**: 6-35kV electrical network, ferroresonance, power voltage transformer, nonlinear inductance, dynamic model, equivalent parameters, Weber-Ampere characteristic, boundary conditions of ferroresonance stability.*

INTRODUCTION

In a power supply system with 6-35kV distribution networks, under certain conditions ferroresonance (FR) occurs, as a result of which power voltage transformers (PVT) are damaged.

According to statistics, in various accidents in 6-35kV networks, PVTs account for about 80% of the damaged equipment. At the same time, about 10 per cent of installed PVTs are damaged annually in earth faults and FR. Practice confirms that FR between the network capacitance and the non-linear inductance (NI) of the transformer is often the cause of damage. As a rule, FR leads to overvoltages on the network busbars, and inadmissible currents flow through the PVT high voltage winding, which leads to their damage (Fig.1) [1-3].

Figure 1. Box of damaged transformers

Taking into account that 6-35kV distribution networks are the longest in the power supply system, one of the special aspects of increasing the reliability of power supply is the study of modes of occurrence and determination of boundary conditions of stability of FR between the network capacitance and inductance of PVT.

RESEARCH METHODS AND THE RECEIVED RESULTS

The task of investigating FR is complicated by the fact that in high voltage 6-35kV electrical networks in conditions of limited application of experimental approaches due to the high cost of PVT, the creation of a reliable mathematical model of NI transformers and determination of boundary conditions of FR occurrence come to the forefront [4-5].

In works [6-9] mathematical models of transformers NI are proposed taking into account the influence of nonlinear parameters of PVT windings. However, in the proposed models, the analytical expressions are complex and do not accurately describe the dynamic mode of PVT operation under FR. Taking into account that FR is characterised by nonlinear jumping modes of saturation of the PVT core, it is urgent to create:

A dynamic model of the transformer NI;

Weber-Ampere Characteristic (WAC) of the NI, reflecting the dynamic hysteresis loop of the transformer core;

More accurate analytical equations for determining the parameters of the transformer NI.

As it is known, the process of transformer core remagnetisation can be represented by the dependence of magnetic induction (*b*) and magnetic field strength (*h*) in the following form [10-11],

$$b = F_1\left(h, \frac{dh}{dt}, \ldots, \frac{db}{dt}, \frac{d^2b}{dt^2}, \ldots\right) \tag{1}$$

Practically, expression (1) can be applied as a relationship between current (*i*) and flux-current (ψ) in the form of (2), which describes the dynamic NI model of the transformer (Fig.2) [12-15],

$$i = F_2\left(\psi, \psi^n; \frac{d\psi}{dt}, \frac{d^2\psi}{dt^2} \ldots\right) \tag{2}$$

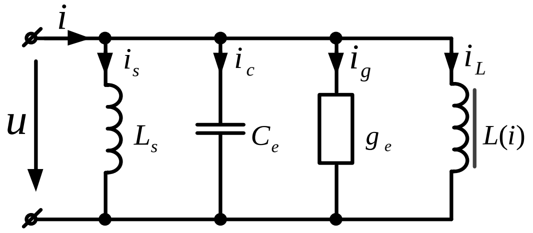

Figure 2. Dynamic model of NI transformer

Where, L_S - dissipation inductance, C_e - electromagnetic capacitance, g_e - active conductance, which are equivalent parameters of NI transformer. *L(i)*- inductance determined by the magnetic permeability of the ferromagnetic material of the transformer core.

From the condition of constancy of equivalent parameters and taking into account (2) on the basis of Kirchhoff's 1-law $i=i_C+i_g+i_L+i_S$ we receive

$$i = C_e\frac{d^2\psi}{dt^2} + g_e\frac{d\psi}{dt} + a\psi + b\psi^n + \frac{\psi}{L_s} \tag{3}$$

Here, $i_L = a\psi + b\psi^n$- is the approximation of the NI WAC obtained from the magnetisation curve *B=f(H)* of the transformer core. If we assume that the voltage $u = U_m cos\omega t$ and $\psi = \Psi_m sin\omega t$, and taking into account the adopted approximation, we obtain

$$\begin{cases} i_S = \dfrac{\psi}{L_S} = a\psi; \quad a = \dfrac{1}{L_S}; \\ i_C = -\omega^2 C_e \Psi_m \sin\omega t = -I_{Cm} \sin\omega t; \\ i_g == g_e \Psi_m \omega \cos\omega t = I_{gm} \cos\omega t. \end{cases} \tag{4}$$

From (4) we have

$$\begin{cases} i_C = -\dfrac{I_{cm}}{\Psi_m}\psi; \\ i_g = \pm\dfrac{I_{gm}}{\Psi_m}\sqrt{\Psi_m^2 - \psi^2}; \\ i_L = a\psi + b\psi^n, \end{cases} \tag{5}$$

Taking into account equations (4) and (5), equation (3) will take the form

$$i = \left(a - \frac{I_{cm}}{\Psi_m}\right)\psi + b\psi^n \pm \frac{I_{gm}}{\Psi_m}\sqrt{\Psi_m^2 - \psi^2} \tag{6}$$

Based on equation (6), the hysteresis loop of the dynamic model of the NI transformer (Fig.3) can be plotted [10].

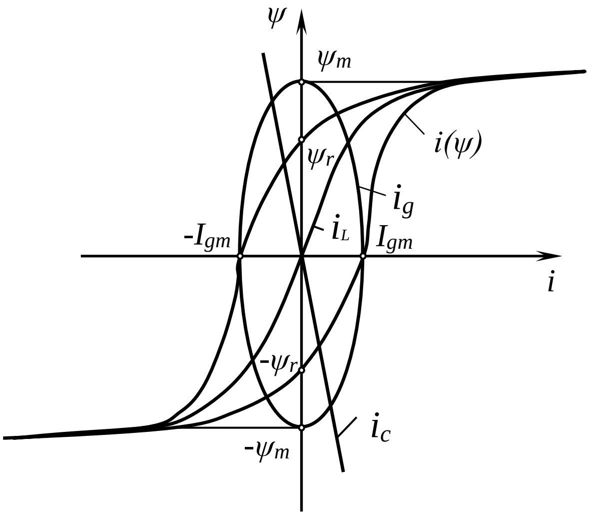

Figure 3. Hysteresis loop of the NI transformer dynamic model

Active equivalent conductivity (g_e) is determined from the dynamic coercive force H_{cd} of the transformer core. If, current I_{gm} equals

$$I_{gm} = Ug_e = \frac{H_{cd} l}{w} = \frac{l}{w}\left(H_C + 0{,}125\omega\sigma d^2 B_S \sqrt{2\varepsilon - 1}\right) \tag{7}$$

then from (7) we have

$$g_e = l\left(H_C + 0{,}125\omega\sigma d^2 B_S \sqrt{2\varepsilon - 1}\right) / \omega w^2 SB_m \tag{8}$$

where, B_S - saturation induction, H_C - coercive force, d - thickness of magnetic material, ε - specific electrical conductivity of magnetic material, $\sigma = \dfrac{B_m}{B_s}$ - core modulation factor, w - number of winding turns, l - average length of magnetic core.

We calculate the equivalent electromagnetic capacitance (C_e) and dissipation inductance (L_s) from the condition $\psi = \Psi_r = wSB_r$ and *i=0*. Then, from equation (6) we obtain

$$C_e = \frac{a\psi_r + b\psi_r{}^n - \omega g_e\sqrt{\Psi_m^2 - \Psi_r^2}}{\omega^2 \Psi_r} \qquad (9)$$

$$L_S = \frac{\psi_r}{\frac{1}{\psi_m}\left(I_{cm}\psi_r + I_{gm}\sqrt{\psi_m^2 - \psi_r^2}\right) - b\psi_r^n} \qquad (10)$$

The equivalent nonlinear core inductance $L(i)$ is determined from equation (6) assuming $\psi = \Psi_m = wSB_m$ and $i=0$,

$$L(i) = \frac{w\psi_m}{l(a\psi_r + b\psi_r{}^n)} \qquad (11)$$

As a result of analysing the dynamic model of the NI transformer, more accurate analytical equations (8),(9),(10) and (11) are obtained to determine the equivalent parameters g_e, C_e, L_s and $L(i)$ of the NI transformer. These equations prove that the equivalent parameters depend on both electrical and geometrical quantities as well as magnetic quantities of the transformer [14-15].

Considering that, in the FR mode, the saturation of the PVT core occurs and the input resistance of the network is capacitive, it is important to determine the boundary conditions for the stability of the FR [16].

Condition 1. The stability of FR is determined by the equivalent capacitance C_e of the network, which must be within the variation of the equivalent inductance PVT, i.e.

$$1/4\pi^2 f^2 L_0 \le C_e \le / 4\pi^2 f^2 L_r \qquad (12)$$

where,

L_0 - is the PVT no-load inductance;

L_r - inductance of incomplete saturation of PVT core;

f - frequency of mains voltage.

If we assume that in the FR mode, the PVT core reaches incomplete saturation ($\pm\psi_r$) (Fig.3), then the no-load inductance L_0 determine by the formula,

$$L_0 = U_{nf} / I_0 * \omega \qquad (13)$$

where,

I_0 - PVT idle current;

U_{nf} - the nominal phase voltage of the PVT.

Under the same conditions ($\pm\psi_r$) (Fig.3), the inductance of incomplete saturation L_r of the transformer core can be determined by the following equation,

$$L_r = 1{,}3\,(\pi w^2/4 * d^2\, K_\alpha\, \mu_0\, /a) \qquad (14)$$

where,

w - number of turns of the primary winding;

d - average diameter of the winding;

a - winding height;

K_α - coefficient of winding shape;

μ_0 - relative magnetic permeability of air.

Condition 2. The FR remains stable within the limits of the variation of the flux-coupling $\psi(i)$ in the $\pm\psi_r$ and $\pm\psi_m$ hysteresis loop of the dynamic model of the transformer NI (Fig.3), i.e.,

$$\pm i_L * L_r(i) \leq \psi(i) \leq \pm i_L * L(i) \qquad (15)$$

It should be noted that the stability condition of FR according to (12) and (15) depends on the magnetisation curve $B=f(H)$ or $\psi=f(i)$ of the core magnetosheet and equivalent parameters of transformers.

To determine the boundary conditions of stable FR, the calculation of boundary values of capacitance is considered C_e network on the example of energy-saving three-phase two-winding PVT of TMG12-250/35 brand with reference data (Table 1).

Table 1

Sign CTH	S_{nom}, kVA	Catalogue data						Calculation data	
		U_{nom}. kV - windings		U_k %	ΔP_k кVт	P_0 kVт	I_0 %	R_t Ohm	X_t Ohm
		HV	LV						
TMG12 -250/35	250	35	6	4,50	3,25	0,425	2,30	11,70	40,50
Geometric data									
w – number of primary winding turns		$d_{c.}$ mm - average diameter of primary winding		$d_н$ mm - primary winding outer diameter	a mm - average winding height	K_a - winding shape factor		μ_0 H/m - relative magnetic permeability of air	
21150		100		170	96	0,5615		$12{,}56 * 10^{-7}$	

1. Use formula (13) to find the no-load inductance of the transformer

$$L_0 = 6000 / 0{,}23 * 314 = 83{,}1\ H$$

2. Use formula (14) to calculate the inductance of incomplete saturation of the transformer core

$$L_r = 1{,}3 \cdot (\, 3{,}14 \cdot 21150^2 / \, 4 \cdot 100^2 \cdot 0{,}5615 \cdot 12{,}56 \cdot 10^{-7} / \, 96\,) = \ 25{,}8\ H$$

3. Taking into account the values $L_0 = 83{,}1\ H$ и $L_r = 25{,}8\ H$, according to equation (12) determine the boundary values of the capacity of the network C_e with one transformer TMG12-250/35

$$1/4 * 3{,}14^2 * 50^2 * 83{,}1 \leq C_э \leq 1/4 * 3{,}14^2 * 50^2 * 25{,}8$$

or

$$12{,}2\ nF \ \leq C_e \leq \ 157{,}2\ nF \qquad (12.1)$$

4. Determine the boundary conditions for a group of seven PVTs of TMG12-250/35 brand with cascade connection, taking the winding parameters equal (Table 1):

$$85{,}4\ nF \leq C_e \leq 1100{,}4\ nF$$

The boundary values of the network capacitance C_e (12.1) obtained as a result of calculation determine the condition of possible occurrence of stable FR on PVT of TMG12-250/35 brand. Beyond these values ferroresonance can be avoided, which is an important indicator for protection of transformers against possible overvoltages in the electric network.

The study of causes, effects, modes and boundary conditions of ferroresonance in a 6-35kV electrical network can be summarised as follows:

1. A dynamic model of NI transformer is proposed taking into account the equivalent parameters g_e, C_e, L_s and $L(i)$ (Fig.2).

2. Based on the dynamic NI model, a WAC reflecting the dynamic hysteresis loop of the transformer core is constructed (Fig.3).

3. More accurate analytical equations for calculation of equivalent parameters are obtained g_e, C_e, L_s and $L(i)$, which depend on both electrical and geometrical as well as magnetic parameters of the transformer.

4. Boundary conditions of FR stability and determination of boundary values of network capacity are given C_e on the example of calculation of equivalent parameters of energy-saving three-phase two-winding PVT of the brand TMG12-250/35.

CONCLUSION

Thus, FR is a special case in the power supply system and is observed in asymmetrical modes of electric networks, especially at incomplete phase switching of network sections.

In electric networks with voltage 6-35kV with isolated neutral, FR leads to the increase of flux-coupling on windings of each phase and deep saturation of PVT core. As a result, the increase in the maximum permissible value of magnetising current and, accordingly, voltage leads to overheating of windings and destruction of PVT (Fig.1).

The transformer core magnetization curve (Fig.3) takes into account the variation of instantaneous values of electrical and magnetic quantities, as well as equivalent parameters g_e, C_e, L_s и $L(i)$ NI in the dynamic mode of PVT operation.

Calculation of steady FR boundary conditions allows to determine the inductive parameters (L_0, L_r) of PVTs of different brands and the boundary values of capacitance (C_e) of high voltage electrical networks.

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