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FERRORESONANCE IN THREE-PHASE ELECTRICAL NETWORKS

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Abstract: *Possible modes of ferroresonance in three-phase electric networks and analysis of substitution schemes where ferroresonance voltage increase is observed are considered. The most complete magnetization curve of the transformer core and the analysis of the generalized equivalent substitution scheme are presented, as a result of which more accurate formulas for determining the values of equivalent parameters of the electrical network and voltage transformer in ferroresonance mode are obtained. Factor of ferroresonance voltage increase is introduced, which determines ratio between amplitude values of transformer phase voltage and mains voltage. The method of determination of boundary conditions of steady ferroresonance voltage increase is given on the example of calculation of energy-saving three-phase double-winding voltage transformer of TMG12-250/15 grade, as an important factor of reliable operation of electric network. The results obtained can be applied to the analysis of ferroresonance in power supply systems of both low and high voltage.*

Keywords: *Ferroresonance voltage boost, voltage transformer, core magnetization curve, generalized equivalent equivalent circuit, equivalent parameters, ferroresonance voltage boost coefficient, boundary conditions of stable ferroresonance.*

Annotatsiya: *Uch fazali kuchlanishli elektr tarmoqlarda ferrorezonansning sodir bo'lish rejimlari va ferrorezonansda kuchlanishning oshishi kuzatiladigan almashtirish sxemalari tahlili keltirilgan. Kuchlanish transformatori o'zagining eng to'liq magnitlanish egri chizig'i keltirilgan va umumlashtirilgan ekvivalent almashtirish sxemasi tahlili natijasida, ferrorezonansda elektr tarmog'i va kuchlanish transformatori ekvivalent parametrlarining qiymatlarini aniqlash uchun yanada aniqroq tenglamalar olingan. Ferrorezonansda kuchlanishning oshishi koeffitsiyenti kiritilgan va bu koeffitsiyent transformator faza kuchlanishi amplituda qiymati bilan tarmoq kuchlanishi amplituda qiymati o'rtasidagi nisbatdan aniqlagan. Elektr tarmog'i ishonchli ishlashining muhim omili sifatida, TMG12-250/15 markali energiya tejamkor uch fazali ikki cho'lg'amli kuchlanish transformatorini hisoblash misolida, ferrorezonansda kuchlanish barqaror oshishining chegaraviy shartlarini aniqlash usuli berilgan. Olingan natijalar past va yuqori kuchlanishli elektr ta'minoti tizimlarida ferrorezonansni tahlil qilishda qo'llanilishi mumkin.*

Tayanch so'zlar: *Ferrorezonansda kuchlanishning oshishi, kuchlanish transformatori, o'zakning magnitlanish egri chizig'i, umumlashtirilgan ekvivalent almashtirish sxemasi, ekvivalent parametrlar, ferrorezonansda kuchlanishining oshish koeffitsiyenti, barqaror ferrorezonansning chegaraviy shartlari.*

Аннотация: *Рассмотрены возможные режимы феррорезонанса в трехфазных электрических сетях и анализ схем замещения где наблюдается феррорезонансное повышение напряжения. Представлена, наиболее полная кривая намагничивания сердечника трансформатора и анализ обобщенной эквивалентной схемы замещения, в результате чего получены более точные формулы определения значений эквивалентных параметров электрической сети и трансформатора напряжения в режиме феррорезонанса. Введен коэффициент феррорезонансного повышения напряжения, который определяет соотношение между амплитудными значениями фазного напряжения трансформатора и напряжения сети. Приведен метод определение граничных условий устойчивого феррорезонансного повышения напряжения на примере расчета энергосберегающего трёхфазного двухобмоточного трансформатора напряжения марки ТМГ12-250/15, как важный фактор надёжной работы электрической сети. Полученные результаты могут быть применены для анализа феррорезонанса в системах электроснабжения как низкого, так и высокого напряжения.*

Ключевые слова: *Феррорезонансное повышение напряжения, трансформатор напряжения, кривая намагничивания сердечника, обобщенная эквивалентная схема*

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замещения, эквивалентные параметры, коэффициент феррорезонансного повышения напряжения, граничные условия устойчивого феррорезонанса.

Introduction

Three-phase voltage electrical networks contain ferromagnetic cores on transformers and capacitance on power lines, and therefore, under certain conditions, a ferroresonant voltage rise (FRVR) is possible [1-3]. So, FRVR occurs when there are at least two conditions; the currents in the windings of voltage transformers (VT) must be sufficient to transfer the magnetization curves *Ψ=f (i)* of the core to the saturation region (Fig.1), and the input resistance of the network connected to the winding must be capacitive [4-6]. Practice shows that the most dangerous modes in relation to FRVR are idling or predominance of reactive load [7-8].

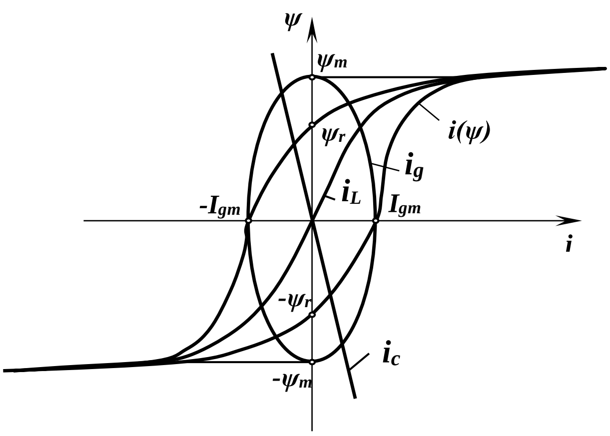

Fig.1. Magnetization curve Ψ=f (i) of the TN core.

In three-phase electric networks, the FRVR mode can be basic, subharmonic, quasi-periodic or chaotic. In the main mode, fluctuations in currents and voltages correspond to a 50Hz mains frequency. For example, in 6-35kV electric networks with electromagnetic VT, the following options are possible for the development of FRVR [12-17]:

-attenuation of nonlinear ferroresonance oscillations and the return of the network to a stable mode of operation with sinusoidal currents and voltages;

-an endless continuation of periodic nonlinear ferroresonance oscillations at a network frequency of 50Hz;

-an endless chaotic continuation of non-periodic nonlinear ferroresonance oscillations.

In 6-35 kV networks with an isolated neutral, it is possible to operate on subharmonic oscillations 1/2; 1/3; 1/5, where the frequency of the 50Hz network remains the main harmonic. FRVR is observed on VT with relatively small capacities of short lines. At the same time, on the windings of each phase, the flow coupling increases by more than 2 times, the core is deeply saturated and the magnetizing current exceeds the maximum permissible value, which leads to overheating of the windings and destruction of the VT. Damage to single-phase VT 6-35kV is widespread with FRVR at subharmonic 1/2 or at a frequency close to it, if 5-10km of 6-35kV overhead line account for each three-phase VT group [18-21].

Quasi-periodic ferroresonance is not periodic and the spectrum of harmonic components in this mode is discrete. Chaotic ferroresonance is also not periodic. The corresponding spectrum of harmonic components is continuous, that is, they do not pass a single frequency. FRVR in quasi-periodic and chaotic modes depend on network parameters and initial conditions and are rare [22-25].

In symmetrical modes of three-phase electrical networks, the capacitive elements are shunted by a low input resistance of the supply network, which is inductive in nature, therefore, under normal operating conditions, the ferroresonance mode is unlikely. Possible conditions for the emergence and development of FRVR are created in asymmetric modes of the system, especially with incomplete phase inclusions of network sections. Ferroresonance often occurs in incomplete-phase network modes with an isolated neutral, when the network capacity relative to the ground is connected in series with the windings of the VT. Such an incomplete-phase network mode occurs when one of the phases is broken and there is an incomplete switching on or an unbalanced short circuit.

The most common schemes for the occurrence of FRVR in three-phase networks are as follows (Fig.2) [15-17]:

- single-phase switching on of a line section with an idle transformer with an isolated neutral, Fig.2a;

- two-phase switching on of a line section with an idle transformer with an isolated neutral, Fig.2b;

- the rupture of one phase with the fall of a broken wire to the ground from the side of the power supply, Fig.2в.

Here, *L* - takes into account the inductance of the supply network and the line; $C_{ф}$ and $C_{мф}$ - are the capacities of the network phases relative to the ground and between phases; *R* - active resistances to account for all types of active losses (losses in the ground, in the line wires, in the VT core); L_{μ} - is the saturation inductance of the VT core.

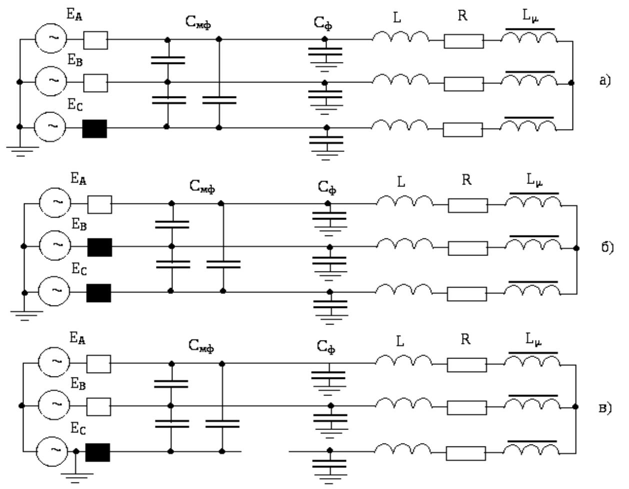

Fig.2. Schemes of the occurrence of FRVR in three-phase networks.

Research Methods and the Received Results

Considering that phases B and A in Fig.2a,в and phases B and C in Fig.2b are under the same conditions relative to the point of asymmetry, all three schemes can be reduced to a generalized substitution scheme (GSS) (Fig.3) with the calculated equivalent parameters $R_э$, C_1, C_2, $E_э$, $L_э$ and $L_{μэ}$ and the maximum values of the FRVR (U_m) presented in Table 1. In this case, the value of the equivalent electromotive force ($E_э$) is determined for asymmetric emergency modes. In the diagrams Fig.2a,b it is assumed that the neutral of the network from the supply side remains at a potential close to zero due to the large values of the capacitances of the phases of the network, and in the diagram Fig.2в the neutral of the supply network is considered isolated.

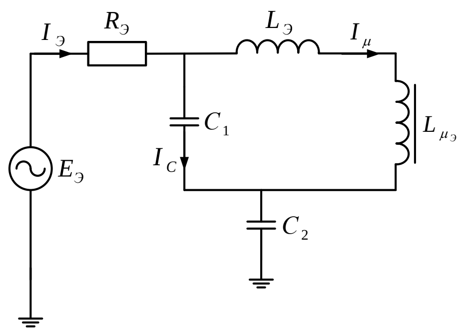

Fig.3. Generalized equivalent FRVR substitution scheme in three-phase networks.

Table 1

Design equivalent parameters of FRVR occurrence schemes in three-phase networks

The type of asymmetric mode	U_m	Parameters			
		C_1	C_2	$E_э$	$L_{μэ}$
Only one phase is enabled (Fig.2a)	$2{,}5E_m$	$2C_{мф}$	$2C_ф$	E	$1{,}5L_μ$
Two phases are included (Fig.2b)	$1{,}25E_m$	$2C_{мф}$	$C_ф$	$0{,}5E$	$1{,}5L_μ$
The rupture of one phase (Fig.2в)	$3{,}75E_m$	$2C_{мф}$	$C_ф$	$1{,}5E$	$1{,}5L_μ$

In the process of calculating the equivalent parameters of the FRVR replacement circuit (Fig.3), it is assumed that the magnetization curve of the core of the power VT (Fig.1) is obtained in the symmetrical mode of a three-phase network. The saturation inductance ($L_{μэ}$) of the VT core is determined by the amplitude value of the magnetization current ($I_μ$), which is twice the values of the currents in other phases, moreover, if the current of the first phase flows from the input to the neutral, then in the other two it is directed from the neutral to the inputs. In all FRVR circuits (Fig.2), there is a similar distribution of magnetization currents by phases. Then, the analysis of the ferroresonance at the first harmonic can be reduced to an GSS with a sequential oscillatory circuit for all FRVR circuits (Fig.2) with the following calculation formulas for equivalent parameters:

For the diagram in Fig. 2a:

$$L_{μэ} = 1{,}5\, L_μ;\quad C_э = 2\,(C_ф + C_{мф});\quad E_э = U_ф\,(C_ф / C_ф + C_{мф}). \tag{1}$$

For the diagram in Fig. 2б:

$$L_{μэ} = 1{,}5\, L_μ;\quad C_э = C_ф + 2C_{мф};\quad E_э = U_ф\,(C_ф / C_ф + 2C_{мф}). \tag{2}$$

For the diagram in Fig. 2в:

$$L_{μэ} = 1{,}5\, L_μ;\quad C_э = C_ф + 2C_{мф};\quad E_э = U_ф\,(C_ф / C_ф + 2C_{мф}). \tag{3}$$

Figure 4 shows a graph of ferroresonant fluctuations in the amplitude of the phase voltage (phase A) in a three-phase network with a single-phase connection of a section of the line with a dummy voltage transformer with an isolated neutral (Fig.2a).

As a result of the FRVR, the maximum voltage (U_m) is 2,5 times higher than the amplitude value of the emf (E_m)

$$U_m = 2{,}5\, E_m \tag{4}$$

The FRVR coefficient (K_{FRVR}) is determined from (4) taking into account the type of asymmetrical mode in a three-phase network (Table 1.) as,

$$K_{FRVR} = U_m / E_m \tag{5}$$

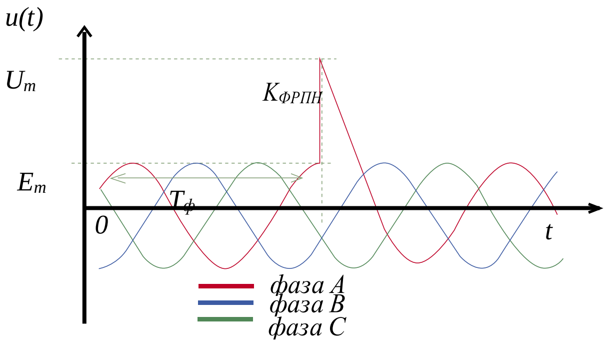

Fig.4. Ferroresonance in a three-phase network with a single-phase connection of a line section with an idle VT with an isolated neutral

If we assume that the equivalent parameters $L_э$, $C_э$ and $R_э$ in the circuit (Fig. 3) are constant, then for the instantaneous value of the current $I_э$ we obtain

$$i_э = C_э \frac{d^2\psi}{dt^2} + g_э \frac{d\psi}{dt} + a\psi + b\psi^n + \frac{\psi}{L_э}$$
(6)

where $a\psi + b\psi^n = i_\mu$ approximation of the Weber-Ampere characteristic of saturation inductance (L_μ), obtained on the basis of the magnetization curve $\Psi = f(i)$ (Fig.1), $g_э = 1/R_э$ - equivalent active conductivity taking into account active losses in the steel of the VT core;

Taking the voltage at the equivalent electromotive force ($E_э$) $u = U_m Cos\omega t$ and taking into account the adopted approximation, from (6) it follows:

$$\begin{cases} i_C = -\frac{I_{cm}}{\psi_m}\psi; \\ i_э = i_g = \pm\frac{I_{эm}}{\psi_m}\sqrt{\psi_m^2 - \psi^2}; \\ i_\mu = a\psi + b\psi^n, \end{cases} \quad (7)$$

Taking into account (7), we write equation (6) in the form,

$$i = \left(a - \frac{I_{cm}}{\psi_m}\right)\psi + b\psi^n \pm \frac{I_{gm}}{\psi_m}\sqrt{\psi_m^2 - \psi^2} \quad (8)$$

Here, the current I_{gm} depends on the dynamic coercive force H_{cd} of the VT core. If induction $B = B_m Cos\omega t$, then equals H_{cd}

$$H_{cd} = H_C + 0{,}125\omega\sigma d^2 B_S\sqrt{2\varepsilon - 1} \quad (9)$$

where,

B_S - saturation induction; H_c - coercive force; d - thickness of the magnetic material; ε - specific electrical conductivity of the magnetic material; $\sigma = \frac{B_m}{B_s}$ - core modulation coefficient.

Considering that the current

$$I_g = \frac{U}{R_э} = \frac{H_{cd} l}{w} = \frac{l}{w}\left(H_C + 0{,}125\omega\sigma d^2 B_S\sqrt{2\varepsilon - 1}\right) \quad (10)$$

then from (10) for the equivalent resistance we have

$$R_э = \frac{\omega w^2 SB}{l\left(H_C + 0{,}125\omega\sigma d^2 B_S\sqrt{2\varepsilon - 1}\right)} \quad (11)$$

where,

w - is the number of turns of the winding; l - is the average length of the magnetic circuit.

The value of the equivalent capacitance can be calculated from the following condition for the flux linkage on the VT core, if

$$\psi = \psi_r = wSB_r \quad (12)$$

then

$$i = 0 \Rightarrow i_\mu + i_C + i_g = 0 \quad (13)$$

where B_r - is the residual magnetic induction.

Then from (8) for the equivalent inductance and capacitance we obtain

$$C_э = \frac{a\psi_r + b\psi_r^n - \frac{\omega}{R_э}\sqrt{\psi_m^2 - \psi_r^2}}{\omega^2\psi} \quad (14)$$

$$L_э = \frac{\psi_r}{\frac{1}{\psi_m}\left(I_{cm}\psi_r + I_{gm}\sqrt{\psi_m^2 - \psi_r^2}\right) - b\psi_r^n} \quad (15)$$

As a result, from the obtained equations (11), (14) and (15) it is clear that the equivalent parameters $L_э$, $C_э$ and $R_э$ VT depend on both the electrical and geometric parameters and its magnetic parameters [9-11].

Considering that the condition for the occurrence of ferroresonance is transient processes with saturation of the VT core and with the capacitive nature of the input resistance of the network, it is important to determine the boundary conditions of a stable FRVR [14-16].

The boundary condition for a stable FRVR is determined by the equivalent capacitance ($C_э$) of the network, which must be within the limits of the change in the equivalent inductance ($L_{\mu э}$) of the VT, i.e.

$$1/4\pi^2 f^2 L_{xx} \le C_э \le / 4\pi^2 f^2 L_s \quad (16)$$

where,

L_{xx} - linear inductance of the VT no-load circuit [H]; L_s - saturation inductance of the VT core [H];

f - mains voltage frequency [Hz].

If we accept that in the ferroresonance mode the VT core reaches incomplete saturation, then to determine L_s we will accept the formula

$$L_s = 1{,}3\,(\pi w^2/4 * d^2 K_a \mu_0 / a) \quad (17)$$

where,

w - number of turns of the primary winding; d - average winding diameter, m; a - winding height, m;

K_a - winding shape coefficients; μ_0 - relative magnetic permeability of air.

The no-load inductance of a transformer can be determined by the formula:

$$L_{xx} = U_{нф} / I_{xx} * \omega \quad (18)$$

where,
I_{xx} - VT no-load current; $U_{нф}$ - rated phase voltage of the TN.

In order to determine the boundary conditions of a stable FRVR, we present a methodology for calculating the boundary values of the $C_э$ network based on an energy-saving three-phase two-winding VT brand TMG12-250/15 with reference data [27-28]:

Table 2

Reference data of energy-saving three-phase two-winding VT grade TMG12-250/15

Brand VT	S_{nom} kVA	Catalog data						Calculation data	
		U_{nom} kV windings		$U_к$ %	$\Delta P_к$ kW	P_x kW	I_x %	$R_т$ Ohm	$X_т$ Ohm
		HV	LV						
TMG12-250/15	250	15	0,40	4,50	3,25	0,425	2,30	11,70	40,50
Geometric and magnetic data									
w - number of turns of the primary winding		d_c мм - average diameter of primary winding		$d_н$ мм - outer diameter of primary winding	a мм-average winding height	K_a - winding shape factor		μ_0 Н/м - relative magnetic permeability of air	
21150		100		170	96	0,5615		$12{,}56 * 10^{-7}$	

1. Using formula (17), we calculate the saturation inductance of the transformer

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

2. Using formula (18), we find the no-load inductance of the transformer

$L_{xx} = 15000 / 0{,}23 * 314 = 207{,}7$ H

3. Taking into account the values of $L_s = 25{,}8$ H and $L_{xx} = 207{,}7$ H according to equation (16), we determine the boundary values of Se for a network with one VT brand TMG12-250/15

$1/4 * 3{,}14^2 * 50^2 * 207{,}7 \leq C_э \leq 1/4 * 3{,}14^2 * 50^2 * 25{,}8$

or 19,5 nF $\leq C_э \leq$ 157,2 nF (*)

4. Let us determine the boundary conditions for a group of seven VT brand TMG12-250/15 with a cascade connection, taking the winding parameters equal (Table 2):

136,5 nF $\leq C_э \leq$ 1100,4 nF (**)

The boundary values $C_э$ (*) and (**) obtained as a result of the calculation determine the condition for the possible occurrence of a stable FRVR on VT brand TMG12-250/15. Beyond these values, ferroresonance can be avoided, which is important for protecting VT from possible overvoltage in the electrical network.

Results

Taking into account that up to 10-12% of installed power transformers are damaged annually due to FRVR, having studied the causes, modes and boundary conditions of ferroresonance, and having determined more accurate equivalent parameters of the transformer transformer and the electrical network, the following results were obtained:

1. The most accurate magnetization curve of the VT core has been proposed (Fig. 1).

2. The causes and patterns of the occurrence of FRVR in a three-phase electrical network of 6-35 kV (Fig. 2), which is the longest power supply line, are analyzed.

3. Schemes for the occurrence of the FRVR in the 6-35 kV electrical network (Fig. 2) are reduced to the GSS (Fig. 3) with calculation formulas (1,2,3) for equivalent parameters (Table 1).

4. The FRVR coefficient was introduced (Fig.4), taking into account the type of asymmetric mode in a three-phase network (Table 1).

5. Taking into account the magnetization curve of the VT core (Fig. 1), more accurate equations were obtained to determine the equivalent parameters $L_э$, $C_э$ and $R_э$ (12,15,16) of the GSS, which depend on both the electrical and geometric, as well as the magnetic parameters of the VT.

6. In order to determine the boundary conditions of a stable FRVR, a methodology is given for calculating the boundary values of the network capacity ($C_э$) based on an energy-saving three-phase two-winding VT brand TMG12-250/15 with reference data (Table 2).

Conclusion

Thus, FRVR is a special case in the power supply system and is observed in asymmetrical modes of electrical networks, especially with incomplete phase connections of network sections.

In three-phase electrical networks of 6-35 kV with an isolated neutral, ferroresonance leads to an increase in flux linkage on the windings of each phase and deep saturation of the core (Fig. 1) of the VT. As a result, an increase in the maximum permissible value of the magnetizing current and, accordingly, voltage (Fig. 4) leads to overheating of the windings and destruction of the VT.

The core magnetization curve (Fig. 1) takes into account the change in instantaneous electrical and magnetic quantities, as well as the equivalent parameters $L_э$, $C_э$ and $R_э$ in the dynamic mode of operation of the VT.

The method for determining the boundary conditions of stable ferroresonance makes it possible to determine the inductive parameters (L_{xx}, L_s) of VT of various brands and the boundary values of the capacitance ($C_э$) of high-voltage electrical networks.

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