Research of Ferroresonance in 6-35 kV Electrical Networks Taking Into Account the Dynamic Model of Non-Linear Inductivity of Power Transformer

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Abstract: Considering that distribution networks of 6-35 kV are the longest among electrical networks, one of the specialaspects of improving the reliability of power supply is the study of the effect of ferroresonance on the performance of voltage transformers (VT). Since the ferroresonant mode is quasi-stationary and occurs both at the fundamental frequency and at the subharmonic, the key role in the study is given to the creation of a dynamic model of the nonlinear inductance of the VT. The mathematical models and characteristics of the non-linear inductance of the VT and the resulting mathematical expressions proposed in well-known scientific papers are approximate and do not have sufficient accuracy for the analysis and qualitative assessment of ferroresonance in electrical networks of 6-35 kV. Since ferroresonance is characterized by non-linear abrupt modes of saturation of the VT magnetic circuit, the paper proposes a generalized dynamic model of the nonlinear VT inductance and more accurate analytical equations for the effective analysis of ferroresonance in 6-35 kV electrical networks.

1 INTRODUCTION

In any substation there are VTs containing ferromagnetic cores and mains capacitances, so under certain conditions ferroresonance can occur. For occurrence of ferroresonance processes two conditions must be present: currents in VTs must be sufficient for transition of magnetization curves into saturation area and input resistance of network connected to the winding must have capacitive character [1,2,3].

Considering that medium voltage distribution networks of 6-35 kV are the longest among high voltage networks, one particular aspect of improving the reliability of electrical networks is to investigate the effects of ferroresonance on the performance of VTs [4,5,6].

According to statistics over the last 30-40 years, in 6-35 kV networks, about 80% of the equipment damaged due to ferroresonance is VTs. Up to 10% of the installed power VTs are damaged annually in earth faults and ferroresonance. Practice has confirmed that the most frequent cause of damage is ferroresonance between the capacitance of the network and the inductance of the power VTs. Generally, ferroresonance leads to overvoltage’s on the bus bars and inadmissible currents will flow through the high voltage winding of the VTs, causing them to be damaged and causing a power failure. The consequence of such an overvoltage is shown in Figure 1 [5,6].

Figure 1: Damage to the voltage transformer.

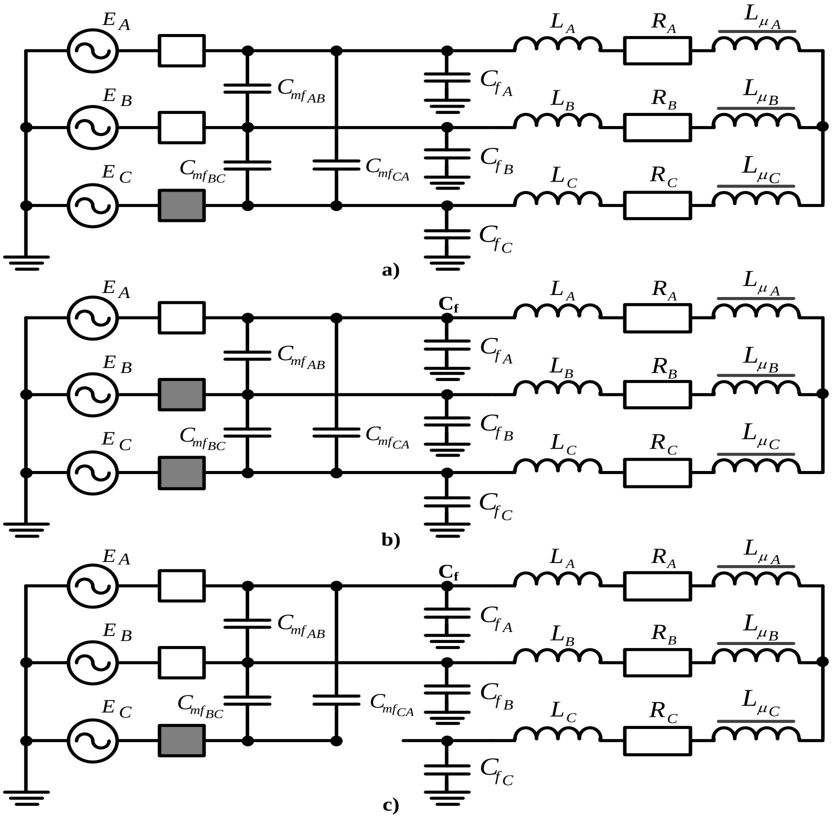

Figure 2: Diagrams of the possible occurrence of ferroresonance.

2 METHODS AND MATERIALS

The task of ferroresonance research is complicated by the fact that in complex three-phase high-voltage electrical networks, with limited experimental approaches due to the high cost of transformers, modeling and calculation of ferroresonance comes to the fore [6,7].

Despite the high level of development of existing mathematical models, which allow for the consideration of a variety of influencing factors, the main problems in the study of ferroresonance on VTs are the lack of:

- a reliable dynamic Weber-Ampere characteristic (WAC) of the VTs;
- accurate methods of determining this characteristic in VTs;
- determination of the range of possible changes in the nonlinear inductance (NI) of VTs;

A number of papers [8] have proposed investigations of ferroresonance in high voltage electrical networks by creating mathematical models of ferroresonance taking into account the influence of nonlinear parameters of VTs windings. However, the obtained mathematical expressions are complex and do not have sufficient accuracy to investigate ferroresonance in electrical networks.

Considering that ferroresonance is characterized by nonlinear jump-like modes of VTs magnetocarbon saturation, it is relevant to create:

- a generalised dynamic model of NI VTs;
- dynamic WAC of NI reflecting real dynamic hysteresis loop of VTs;
- more accurate analytical equations for determining equivalent NI VTs parameters.

In three-phase electrical networks, three most frequent cases of voltage ferroresonance are practically possible: single-phase connection of a line section with an idle transformer with insulated neutral point, Figure 2 a); two-phase connection of the same line, Figure 2 b); break of one phase with fall of a broken wire to ground from power supply side, Figure 2 c) [7,8].

Here, the inductance *L* takes into account the inductances of the mains and the line; the capacities C_f and C_{mf} correspond to the capacities of the network phases relative to ground and between phases; the active resistances *R is* entered to account for all types of active losses i.e. losses in the ground, in the line conductors, in the transformer steel; the inductance L corresponds to the magnetization of the transformer.

The generalized differential (1) of the phase voltages for the circuits (Figure 2) of possible ferroresonance are as follows:

$$\begin{aligned} U_0 + U_A &= i_A R_A + L_{\mu A}\frac{di_A}{dt} + w_A\frac{dF_A}{dt} + i_{A0}R_A \\ &+ L_{\mu A}\frac{di_{A0}}{dt} + w_A\frac{dF_{A0}}{dt} + \frac{1}{C}\int i_N dt; \\ U_0 + U_B &= i_B R_B + L_{\mu B}\frac{di_B}{dt} + w_B\frac{dF_B}{dt} + i_{B0}R_B \\ &+ L_{\mu B}\frac{di_{B0}}{dt} + w_B\frac{dF_{B0}}{dt} + \frac{1}{C}\int i_N dt; \\ U_0 + U_C &= i_C R_C + L_{\mu C}\frac{di_C}{dt} + w_C\frac{dF_C}{dt} + i_{C0}R_C \\ &+ L_{\mu C}\frac{di_{C0}}{dt} + w_C\frac{dF_{C0}}{dt} + \frac{1}{C}\int i_N dt; \end{aligned} \quad (1)$$

According to the method of symmetrical components, write down the currents on phases A, B, C and on the neutral conductor as follows;

$$\begin{aligned} i_a + i_{A0} = i_A;\ \ i_в + i_{B0} = i_B; \\ i_c + i_{C0} = i_C;\ \ \ i_A + i_B + i_C = i_N; \end{aligned} \quad (2)$$

Equations according to Kirchhoff's second law for the magnetic circuit of the phases

$$H_A l_A = w_A i_A;\ \ H_B l_B = w_B i_B;\ \ H_C l_C = w_C i_C. \quad (3)$$

By paralleling two phases which are in the same conditions with respect to the point of asymmetry (phases B and C in Figure 2 b; phases B and A in Figure 2 a), c) all three circuits can be reduced to a simplified form (Figure 3). Here, *Re, Le,* and *Ce* (C_1 and C_2) are the equivalent line and VTs parameters, respectively.

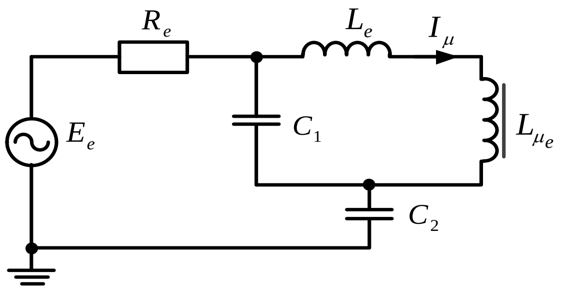

Figure 3: Simplified ferroresonance substitution diagram.

3 RESEARCH RELEVANCE

In [9-12] the NI substitution diagram (Figure 4) in general form and (4) which is its generalized dynamic model were developed

$$i = F_2\left(\Psi,\ \Psi^n;\ \frac{d\Psi}{dt},\ \frac{d^2\Psi}{dt^2}\dots\right). \quad (4)$$

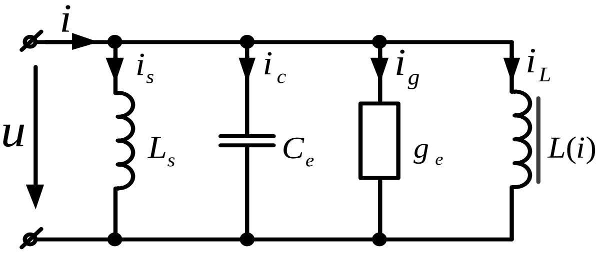

Figure 4: Diagram of the generalized dynamic NI model substitution.

In the schematic (Figure 4) L_s - leakage inductance, C_e - equivalent electromagnetic capacitance, $g_e=1\ /\ R_e$ - equivalent active conductance, are equivalent parameters of NI and if we take them as constant, we obtain in view (5).

$$i = C_e\frac{d^2\Psi}{dt^2} + g_e\frac{d\Psi}{dt} + a\Psi + b\Psi^n + \frac{\Psi}{L_S} \quad (5)$$

where $i_L = a\Psi + b\Psi^n$ is approximation of WAC of NI, obtained on the basis of magnetization curve $B = f(H)$.

The dynamic hysteresis loop approximation assumes that the dependence of the core demagnetization rate on the dynamic strength is linear, i.e. the faster the core demagnetization, the wider the dynamic hysteresis loop. The generalized equation that describes the magnetization and demagnetization processes of a NI core is as follows (6):

$$\frac{dB}{d\tau} = \frac{\mu_e}{\pi}(H \pm H_C) \quad (6)$$

It follows from (5) that for a particular conversion frequency, the dependence of the rate of change in the induction of NI on the dynamic field strength is linear. If we take the mains voltage $u = U_m cos\omega t$ and taking into account the accepted approximation of WAC of NI in the form of $i_L = a\Psi + b\Psi^n$ we obtain:

$$i = i_C + i_g + i_L = \left(a - \frac{I_{cm}}{\Psi_m}\right)\Psi + b\Psi^n \pm \frac{I_{gm}}{\Psi_m}\sqrt{\Psi_m^2 - \Psi^2} \quad (7)$$

Based on (7), the dynamic WAC of the generalised dynamic NI model is constructed, which describes its dynamic hysteresis loop (Figure 5) [13,14,15].

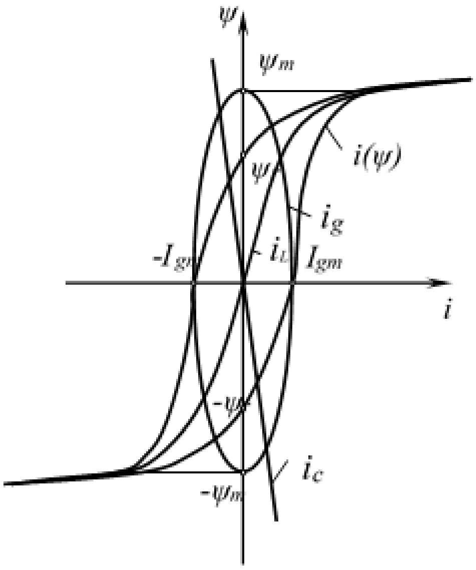

Figure 5: Dynamic characteristics of NI.

The equivalent parameters g_e, C_e, L_S of the dynamic NI model (Figure 4) are respectively determined from the following:

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

$$C_e = \frac{a\Psi_r + b\Psi_r^n - \frac{\omega}{R_e}\sqrt{\Psi_m^2 - \Psi_r^2}}{\omega^2 \Psi_r}, \quad (9)$$

$$L_S = \frac{\Psi_r}{\frac{1}{\Psi_m}\left(I_{cm}\Psi_r + I_{gm}\sqrt{\Psi_m^2 - \Psi_r^2}\right) - b\Psi_r^n}. \quad (10)$$

It should be noted that (8), (9) and (10) can be successfully applied to determine equivalent parameters R_e, C_e (C_1 and C_2), L_e and in a simplified ferroresonance substitution scheme (Figure 3) since they are equivalent parameters of NI VTs [16-19].

4 CONCLUSION

Therefore, the following conclusions are drawn from the generalized dynamic NI model and the analytical expressions for determining its equivalent parameters:

1) The generalized dynamic NI model describes analytically the non-linear WAC of NI VTs instantaneous basis and allows their equivalent parameters to be determined with high accuracy compared to known models.
2) Analytical expressions (8), (9) and (10) defining equivalent parameters Ge, Ce and Ls NI are simple and precise enough in comparison with known calculation equations. These equations adequately determine the equivalent parameters Re, Ce (C1 and C2), Le of NI VTs.
3) The application of a generalized dynamic model and analytical equations of equivalent NI parameters is an effective way to analyze and calculate ferroresonance in 6-35 kV electrical networks.

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