ANALYSIS OF FERRORESONANCE PROCESSES AT OPEN-PHASE OPERATİNG CONDİTİONS OF TRANSMİSSİON LINES: COMPUTER MODELLING

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ABSTRACT

Proposed equations allow to make calculation of ferroresonance processes and their suppression in double-circuit lines at open faults as well as perform computer modelling of ferroresonance overvoltages.

Keywords: ferroresonance, suppression, computer modelling, overvoltages, autotransformer.

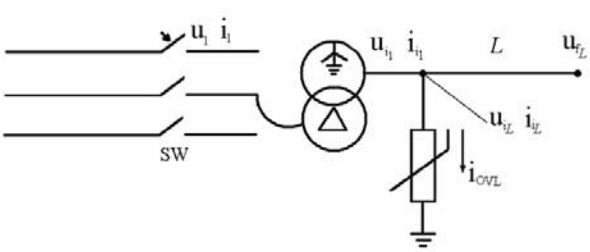
I. INTRODUCTION

Overvoltages in open-phase operating conditions of ETL occur at single- phase or two-phase switching-on. These overvoltages occur in packaged scheme, if transformer and autotransformer available in the line have a wiring completed in triangle. Disconnection and refusal from triangle on transformers and autotransformers [1] is provided in such schemes at open-phase operating conditions for limitation of overvoltages. Triangle is disconnected for the period of commutation. However, during of commutation the accompaniment time increases with increase in overvoltages.

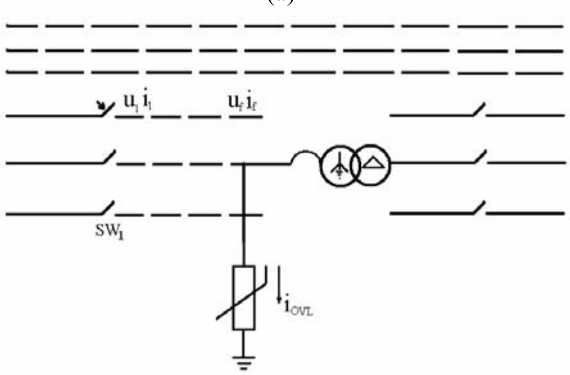
As protection against open-phase operating condition of line is analysed, it is considered expedient to review also issues of modelling of open-phase operating condition of line with autotransformer with tertiary winding completed in triangle. The purpose of this development is a description of calculation formula and algorithm for computer modelling of studied phenomenon and their approbation to proposed algorithm of protection against overvoltages connected through open-phase operating condition of ETL. Adaptation of nature-different models such as ferroresonance model on electric transmissions with tap and model of the same phenomenon on packaged or semi-packaged circuits is not a simple task in view of both production of algorithm and appropriate program. Without having proper algorithm it is impossible to secure necessary quality level of computer modeling and practical solution of the task of protection against open-phase operating condition with consideration of nonlinear factor such as saturation of autotransformer, surface effect and crowning of wires of line and overvoltages limiter. Computation algorithm shall be produced so that it has block of commutation of switches and calculation of voltages and currents in elements of line and switchgear, which secures permanent coordination between commutation and element models. Logical operations of switch are commutation and elements of computation diagram are the element model.

II. THEORY

Use of commutation and element model allows using single algorithm to perform calculation of open-phase operation of ETL with autotransformers under scheme given at Figure 1.



(a)



(b)

Figure 1. Calculation schemes for computer modelling of open-phase operating condition of ETL with autotransformer

Nodes in scheme, in which autotransformer and switching unit are shown, are chosen for that purpose.
The matrix equations, which meet the scheme given at Figure 1,a can be produced for autotransformer.

$$u_i = \frac{d\psi_i}{dt} - L\frac{di_i}{dt} - r_i i_i$$
$$u_1 - u_i = \frac{d\psi_1}{dt} + L\frac{di_1}{dt} + r_1 i_1 \quad (1)$$
$$0 = \frac{d\psi_0}{dt} - L_3\frac{di_{03}}{dt} - r_3 i_{0_3}$$

where ψ_1, ψ_i, ψ_0 - linkages relating to longitudinal, common and tertiary windings and winding of shunt of magnetization at zero sequence; L_1, L_i, L_0 - inductances, corresponding to longitudinal, common and tertiary windings of autotransformer; r_1, r_i, r_3 - active resistances of longitudinal, common and tertiary windings of autotransformer; u_1, u_i, i_1, i_i - voltages and currents respectively relating to longitudinal and common windings of autotransformer; $u_1 \cdot u_i^{-1} = k$, $\psi_1 \cdot \psi_i^{-1} = k$ - transformation coefficient, $\psi_1 \cdot \psi_i$ – parameters of windings, which are brought to longitudinal windings of autotransformer.
Variables and coefficients are matrixes and are as follows:

$$u_1 = \begin{vmatrix} u_{1_A} \\ u_{1_B} \\ u_{1_C} \end{vmatrix},\ u_i = \begin{vmatrix} u_{i_A} \\ u_{i_B} \\ u_{i_C} \end{vmatrix},\ \psi_1 = \begin{vmatrix} \psi_{1_A} \\ \psi_{1_B} \\ \psi_{1_C} \end{vmatrix},\ \psi_2 = \begin{vmatrix} \psi_{2_A} \\ \psi_{2_B} \\ \psi_{2_C} \end{vmatrix},\ \psi_0 = \begin{vmatrix} \psi_{0_A} \\ \psi_{0_B} \\ \psi_{0_C} \end{vmatrix}$$

$$i_1 = \begin{vmatrix} i_{1_A} \\ i_{1_B} \\ i_{1_C} \end{vmatrix},\quad i_2 = \begin{vmatrix} i_{i_A} \\ i_{i_B} \\ i_{i_C} \end{vmatrix},\quad L_1 = \begin{vmatrix} L_{1_{11}} & 0 & 0 \\ 0 & L_{1_{22}} & 0 \\ 0 & 0 & L_{1_{33}} \end{vmatrix},$$

$$L_i = \begin{vmatrix} L_{i_{11}} & 0 & 0 \\ 0 & L_{i_{22}} & 0 \\ 0 & 0 & L_{i_{33}} \end{vmatrix},\quad r_1 = \begin{vmatrix} r_{1_{11}} & 0 & 0 \\ 0 & r_{1_{22}} & 0 \\ 0 & 0 & r_{1_{33}} \end{vmatrix},$$

$$r_2 = \begin{vmatrix} r_{i_{11}} & 0 & 0 \\ 0 & r_{i_{22}} & 0 \\ 0 & 0 & r_{i_{33}} \end{vmatrix}.$$

To allow for current of magnetization of autotransformer we use expressions [2]:

$$i_\mu = 0{,}7\psi + 0{,}3\psi^{13}$$

The following can be written for node:

$$i_1 + i_i + i_0 = i_\mu \quad (2)$$

or

$$\frac{di_1}{dt} + \frac{di_i}{dt} + \frac{di_0}{dt} = \frac{di_\mu}{dt} = f(\psi)\frac{d\psi_0}{dt} \quad (3)$$

$$\psi_0 = \psi_1 - \psi_i \text{ or } \frac{d\psi_0}{dt} = \frac{d\psi_1}{dt} - \frac{d\psi_i}{dt} \quad (4)$$

To obtain calculation expressions it is necessary to calculate ψ. Let's therefore write equation (1) as follows:

$$\frac{di_i}{dt} = L_i^{-1}\left(-u_i + \frac{d\psi_i}{dt} - r_i i_i\right)$$
$$\frac{di_1}{dt} = L_1^{-1}\left(u_1 - u_i - \frac{d\psi_1}{dt} - r_1 i_1\right) \quad (5)$$
$$\frac{di_{0_3}}{dt} = L_3^{-1}\left(\frac{d\psi_0}{dt} - r_3 i_{0_3}\right)$$

Taking sets (4) and (5) into consideration, equations (3) look as follows:

$$-L_i^{-1}\cdot u_i + L_i^{-1}\frac{d\psi_i}{dt} - L_i^{-1}\cdot r_i i_i + k^{-1}\cdot L_1^{-1}\cdot(u_1 - u_i) - k^{-1}L_1^{-1}\frac{d\psi_1}{dt} -$$
$$-L_1^{-1}\cdot k^{-1}\cdot r_1\cdot i_1 + L_3^{-1}\cdot k^{-1}\frac{d\psi_0}{dt} - L_3^{-1}\cdot k^{-1}\cdot r_3\cdot i_{0_3} = f(\psi)\frac{d\psi_0}{dt}$$

Given that $L_i^{-1} = k^{-1}\cdot L_1^{-1}$, then

$$-L_i^{-1}\cdot u_i + i_i^{-1}\left(\frac{d\psi_i}{dt} - \frac{d\psi_1}{dt}\right) - L_i^{-1}\cdot r_i i_i + L_i^{-1}\cdot u_1 - L_i^{-1}u_i - L_i^{-1}r_1 i_1 +$$
$$+ L_3^{-1}\cdot k^{-1}\frac{d\psi_0}{dt} - L_3^{-1}\cdot k^{-1}\cdot r_3\cdot i_{0_3} = f(\psi_0)\frac{d\psi_0}{dt}$$

or

$$L_i^{-1}(u_1 - 2u_i) - L_i^{-1}\frac{d\psi_0}{dt} - L_i^{-1}(r_1 i_1 - r_i i_i) +$$
$$+ L_3^{-1}\cdot k^{-1}\frac{d\psi_0}{dt} - L_3^{-1}\cdot k^{-1} r_3 i_{0_3} = f(\psi_0)\frac{d\psi_0}{dt}$$

Based on above, we can write:

$$\frac{d\psi_0}{dt} = \left[f(\psi_0) + L_i^{-1} - L_3^{-1}k^{-1}\right]^{-1}\left[L_i^{-1}(u_1 - 2u_i + r_1 i_1 + r_i i_i)\right]; \quad (6)$$

In matrix:

$$\frac{d}{dt}\begin{bmatrix} \psi_A \\ \psi_B \\ \psi_C \end{bmatrix} = \begin{bmatrix} \sigma_A & 0 & 0 \\ 0 & \sigma_B & 0 \\ 0 & 0 & \sigma_C \end{bmatrix}^{-1}\left(\begin{bmatrix} L_{i_A}^{-1} & 0 & 0 \\ 0 & L_{i_B}^{-1} & 0 \\ 0 & 0 & L_{i_C}^{-1} \end{bmatrix}\begin{bmatrix} u_{1_A} - 2u_{i_A} \\ u_{1_B} - 2u_{i_B} \\ u_{1_C} - 2u_{i_C} \end{bmatrix} + \right.$$
$$\left. + \begin{bmatrix} r_{1_A} & 0 & 0 \\ 0 & r_{1_B} & 0 \\ 0 & 0 & r_{1_C} \end{bmatrix}\begin{bmatrix} r_{1_A} \\ r_{1_B} \\ r_{1_C} \end{bmatrix} + \begin{bmatrix} r_{i_A} & 0 & 0 \\ 0 & r_{i_B} & 0 \\ 0 & 0 & r_{i_C} \end{bmatrix}\begin{bmatrix} i_{i_A} \\ i_{i_B} \\ i_{i_C} \end{bmatrix}\right) \quad (7)$$

Given that $\frac{d\psi}{dt} = f(\psi)\frac{di_\mu}{dt}$, then set of equations (7) shall be solved taking function $f(\psi)$ into consideration. Variables obtained from set of equations are also brought to longitudinal windings, therefore after computation they shall be brought to appropriate voltages. To make computations with indicated set of equations they shall be added with equations of line, which together with these equations constitute entire set, where number of equations equals to number of unknowns.
If overvoltages limiter is followed by autotransformer in the circuit and commutation is made by switch *B* (figure 1,a), then the second equation of the offered set is used to determine u_i, i_i and i_{OVL}.

$$\left(1+hz\sum_{k=1}^{4}G_k\right)\cdot u_{d_2}+\left(z+z_s\right)i_{d_2}=\upsilon_{p_2};$$

$$-\left(1+hz\sum_{k=1}^{4}G_k\right)\cdot u_{d_2}+\left(z+z_s\right)i_{d_2}=\upsilon_{q_2}. \qquad (8)$$

In this case the following can be written:

$$i_{i_L}=i_i-i_{OVL}, \qquad (9)$$

If there is an overvoltages limiter on the side of high voltage of autotransformer then (Figure 1,б)

$$i_f=i_{OVL}+i_l \qquad (10)$$

Modeling of node with ETL wire break. Mathematical models of switching nodes with transformer and autotransformer and so on and algorithm with taking these nodes into account at computer modelling of open-phase operating condition of ETL have been considered above. However at numerical experiments of ferroresonance process it becomes necessary to calculate voltages and current at ETL open fault [3].

In accordance with this, calculation equations of nodes with ETL phase break are produced at development of algorithm of modelling of ferroresonance processes. To provide multi-variance of obtained set of equations, double-circuit line was considered. Calculation scheme is given at Figure 2.

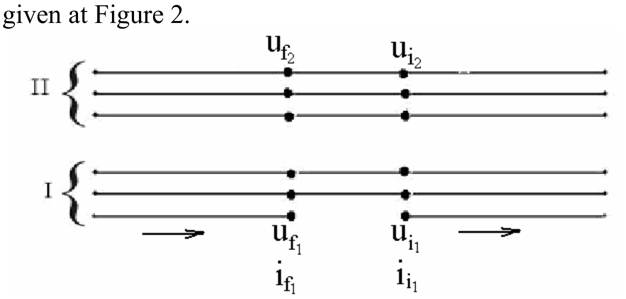


Figure 2. Calculation scheme of break of ETL wire

In case of break of phase A on the first line of double-circuit ETL, taking condition $i_{f_{1A}}=0,\ i_{i_{1A}}=0,$ $u_{f_{1A}}\neq u_{i_{1B}},\ u_{f_{1B}}=u_{i_{2B}}, i_{f_{1C}}==i_{i_{1C}},\ i_{f_{1B}}=i_{i_{1B}}, u_{f_{2A,B,C}}=u_{i_{2A,B,C}},$ $i_{f_{2A,B,C}}=i_{i_{2A,B,C}}$ into consideration, the following can be written [ ]:

$$\begin{vmatrix}u_{f_{1A}}\\u_{f_{1B}}\\u_{f_{1C}}\end{vmatrix}+\begin{vmatrix}z_{11}&z_{12}&z_{13}\\z_{21}&z_{22}&z_{23}\\z_{31}&z_{32}&z_{33}\end{vmatrix}\begin{vmatrix}0\\i_{f_{1B}}\\i_{f_{1C}}\end{vmatrix}+\begin{vmatrix}z_{14}&z_{15}&z_{16}\\z_{24}&z_{25}&z_{26}\\z_{34}&z_{35}&z_{36}\end{vmatrix}\begin{vmatrix}i_{f_{2A}}\\i_{f_{2B}}\\i_{f_{2C}}\end{vmatrix}=\begin{vmatrix}\upsilon_{p_{1A}}\\\upsilon_{p_{1B}}\\\upsilon_{p_{1C}}\end{vmatrix}; \qquad (11)$$

$$-\begin{vmatrix}u_{i_{1A}}\\u_{i_{1B}}\\u_{i_{1C}}\end{vmatrix}+\begin{vmatrix}z_{11}&z_{12}&z_{13}\\z_{21}&z_{22}&z_{23}\\z_{31}&z_{32}&z_{33}\end{vmatrix}\begin{vmatrix}0\\i_{i_{1B}}\\i_{i_{1C}}\end{vmatrix}+\begin{vmatrix}z_{14}&z_{15}&z_{16}\\z_{24}&z_{25}&z_{26}\\z_{34}&z_{35}&z_{36}\end{vmatrix}\begin{vmatrix}i_{i_{2A}}\\i_{i_{2B}}\\i_{i_{2C}}\end{vmatrix}=\begin{vmatrix}\upsilon_{q_{1A}}\\\upsilon_{q_{1B}}\\\upsilon_{q_{1C}}\end{vmatrix};$$

$$\begin{vmatrix}u_{f_{2A}}\\u_{f_{2B}}\\u_{f_{2C}}\end{vmatrix}+\begin{vmatrix}z_{44}&z_{45}&z_{46}\\z_{54}&z_{55}&z_{56}\\z_{64}&z_{65}&z_{66}\end{vmatrix}\begin{vmatrix}i_{f_{2A}}\\i_{f_{2B}}\\i_{f_{2C}}\end{vmatrix}+\begin{vmatrix}z_{41}&z_{42}&z_{43}\\z_{51}&z_{52}&z_{53}\\z_{61}&z_{62}&z_{63}\end{vmatrix}\begin{vmatrix}0\\i_{f_{1B}}\\i_{f_{1C}}\end{vmatrix}=\begin{vmatrix}\upsilon_{p_{IIA}}\\\upsilon_{p_{IIB}}\\\upsilon_{p_{IIC}}\end{vmatrix}; \qquad (12)$$

$$-\begin{vmatrix}u_{i_{2A}}\\u_{i_{2B}}\\u_{i_{2C}}\end{vmatrix}+\begin{vmatrix}z_{44}&z_{45}&z_{46}\\z_{54}&z_{55}&z_{56}\\z_{64}&z_{65}&z_{66}\end{vmatrix}\begin{vmatrix}i_{i_{2A}}\\i_{i_{2B}}\\i_{i_{2C}}\end{vmatrix}+\begin{vmatrix}z_{41}&z_{42}&z_{43}\\z_{51}&z_{52}&z_{53}\\z_{61}&z_{62}&z_{63}\end{vmatrix}\begin{vmatrix}0\\i_{i_{1B}}\\i_{i_{1C}}\end{vmatrix}=\begin{vmatrix}\upsilon_{q_{IIA}}\\\upsilon_{q_{IIB}}\\\upsilon_{q_{IIC}}\end{vmatrix}.$$

where indexes I and II relates to the first and second circuit of ETL respectively, and 1,2,…6 mean number of phases starting from the I circuit and ending with number 6 II of ETL circuit.

Identical variables relating to healthy phases are determined at first from equation (11). In terms of that (11) can be written as follows:

$$\begin{vmatrix}u_{f_{1B}}\\u_{f_{1C}}\end{vmatrix}+\begin{vmatrix}z_{22}&z_{23}\\z_{32}&z_{33}\end{vmatrix}\begin{vmatrix}i_{f_{1B}}\\i_{f_{1C}}\end{vmatrix}+\begin{vmatrix}z_{25}&z_{26}\\z_{35}&z_{36}\end{vmatrix}\begin{vmatrix}i_{f_{2B}}\\i_{f_{2C}}\end{vmatrix}+\begin{vmatrix}z_{24}i_{f_{2A}}\\z_{34}i_{f_{2A}}\end{vmatrix}=\begin{vmatrix}\upsilon_{p_{1B}}\\\upsilon_{p_{1C}}\end{vmatrix}$$

$$-\begin{vmatrix}u_{i_{1B}}\\u_{i_{1C}}\end{vmatrix}+\begin{vmatrix}z_{22}&z_{23}\\z_{32}&z_{33}\end{vmatrix}\begin{vmatrix}i_{i_{1B}}\\i_{i_{1C}}\end{vmatrix}+\begin{vmatrix}z_{25}&z_{26}\\z_{35}&z_{36}\end{vmatrix}\begin{vmatrix}i_{i_{2B}}\\i_{i_{2C}}\end{vmatrix}+\begin{vmatrix}z_{24}i_{i_{2A}}\\z_{34}i_{i_{2A}}\end{vmatrix}=\begin{vmatrix}\upsilon_{q_{1B}}\\\upsilon_{q_{1C}}\end{vmatrix} \qquad (13)$$

Given that $u_{1B}=u_{i_{1B}}, u_{i_{1C}}=u_{i_{1C}}, i_{f_{1B}}=i_{i_{1B}},\ i_{f_{1C}}=i_{i_{1C}},$ $i_{f_{2B}}=i_{i_{2B}},\ i_{f_{2C}}=i_{i_{2C}},$ we will obtain:

$$\begin{vmatrix}u_{f_{1B}}\\u_{f_{1C}}\end{vmatrix}=\begin{vmatrix}u_{i_{1B}}\\u_{i_{1C}}\end{vmatrix}=0,5\begin{vmatrix}\upsilon_{p_{1B}}-\upsilon_{q_{1B}}\\\upsilon_{p_{1C}}-\upsilon_{q_{1C}}\end{vmatrix} \qquad (14)$$

$$2\begin{vmatrix}z_{22}&z_{23}\\z_{33}&z_{33}\end{vmatrix}\begin{vmatrix}i_{f_{1B}}\\i_{f_{1C}}\end{vmatrix}+2\begin{vmatrix}z_{25}&z_{26}\\z_{35}&z_{36}\end{vmatrix}\begin{vmatrix}i_{f_{2B}}\\i_{f_{2C}}\end{vmatrix}+2\begin{vmatrix}z_{24}i_{i_{2A}}\\z_{34}i_{i_{2A}}\end{vmatrix}=\begin{vmatrix}\upsilon_{p_{1B}}+\upsilon_{q_{1B}}\\\upsilon_{p_{1C}}+\upsilon_{q_{1C}}\end{vmatrix}$$

The following can be similarly obtained from equation (11):

$$\begin{vmatrix}u_{f_{2B}}\\u_{f_{2C}}\end{vmatrix}=\begin{vmatrix}u_{i_{2B}}\\u_{i_{2C}}\end{vmatrix}=0,5\begin{vmatrix}\upsilon_{p_{IIB}}-\upsilon_{q_{IIB}}\\\upsilon_{p_{IIC}}-\upsilon_{q_{IIC}}\end{vmatrix} \qquad (15)$$

$$2\begin{vmatrix}z_{55}&z_{56}\\z_{64}&z_{66}\end{vmatrix}\begin{vmatrix}i_{f_{21B}}\\i_{f_{21C}}\end{vmatrix}+2\begin{vmatrix}z_{52}&z_{53}\\z_{62}&z_{63}\end{vmatrix}\begin{vmatrix}i_{f_{1B}}\\i_{f_{1C}}\end{vmatrix}+\begin{vmatrix}z_{54}i_{i_{2A}}\\z_{64}i_{i_{2A}}\end{vmatrix}=\begin{vmatrix}\upsilon_{p_{IIB}}+\upsilon_{q_{IIB}}\\\upsilon_{p_{IIC}}+\upsilon_{q_{IIC}}\end{vmatrix}$$

Variables relating to healthy phases are determined from set of equations (14) and (15), then using (11) and (12), we will find:

$$u_{f_{1A}}=\upsilon_{p_{1A}}-z_{12}i_{f_{1B}}-z_{13}i_{f_{1C}}-z_{14}i_{f_{2A}}-z_{15}i_{f_{2B}}-z_{16}i_{f_{2C}}$$

$$u_{i_{1A}}=z_{12}i_{i_{1B}}+z_{13}i_{i_{1C}}+z_{14}i_{i_{2A}}+z_{15}i_{i_{2B}}+z_{16}i_{i_{2C}}-\upsilon_{q_{1A}} \qquad (16)$$

After determination of $u_{f_{1A}}, u_{i_{1A}}$, $i_{f_{1A}}$ and $i_{i_{1C}}$ are calculated.

III. CONCLUSIONS

Obtained equations allow making calculation of ferroresonance processes and their protection in double-circuit lines at phase-breaks.

Thus, computation formulas for some specific nodes, which are necessary at numerical experiments of open-phase operation of line and organization of its protection, have been obtained. Obtained formulas allow performing in single algorithm of computer modelling of ferroresonance overvoltages against phase spread, at line energization, wire break and at the same time taking of operation of overvoltages limiter in multi-wire ETL into consideration.

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