CALCULATION OF THE FERRORESONANCE OVERVOLTAGES AT OPEN-PHASE OPERATING CONDITIONS WITH AND WITHOUT OVERVOLTAGE LIMITERS

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ABSTRACT

This paper is devoted to studies of the ferroresonance processes in the 500 kV electric power network at open-phase energization of the line with autotransformer with and without non-linear Overvoltage Limiters (OVL). An analysis of the ferroresonance processes is done by use of computer simulation. We have obtained calculation formulae for certain characteristic node points, which are necessary for numerical experiments of the open-phase operating conditions of the transmission line. Performed studies show that an increase of the autotransformer power and line length does not influence neither to form nor to the quantity of peaks in one period of voltage variation in case of including of OVL.

I. INTRODUCTION

Ferroresonance processes cause long-term overvoltages on buses of distribution devices being dangerous for Overvoltage Limiters (OVL) and other distribution devices equipments.

For suppression of the ferroresonance overvoltages at open-phase energization of the line various protection approaches are proposed. All of these proposals have their advantages and disadvantages [1, 2].

Analysis and investigation of all ferroresonance cases at open-phase operating conditions by the use of unique approach is impossible due to difference characters of the ferroresonance occurrence, electric circuit configurations and types of equipments included in these circuits.

If to take into account that, we analyse problems of protection against open-phase operating conditions of line, then we need to study problems of modelling of open-phase operating conditions of line with autotransformer tertiary connected as delta. Our aim is to provide a calculation formula and algorithm for computer simulation of the phenomena under consideration as well as their approvement to probable protection algorithm against overvoltages caused by open-phase operating conditions.

Adaptation of various models, such as ferroresonance model of the electricity transmission with tapping and same phenomena on block or semi-block schemes is a complicated problem from the point of view both compilation of the algorithm and corresponding computer programme. Without appropriate algorithm, it is impossible to provide necessary reliability of the computer simulation and practical solution of the protection against open-phase operating conditions.

In July 2002 within the Azerbaijan power supply system, emergency failure in electric power supply of large scale consumers occurred, leading to the shutdown of the high-voltage 500 kV transmission line Mingachevir (Azerbaijan Hydroelectric power station) - Absheron (Second Absheron Line). Basic model of the similar substation is depicted in Figure 1. Cause and consequences of this accident are described in [3]. Similar analysis of the ferroresonance overvoltages and protection against them in case of switching operations of the block autotransformer-unloaded 500 kV overhead transmission line is presented in [4].

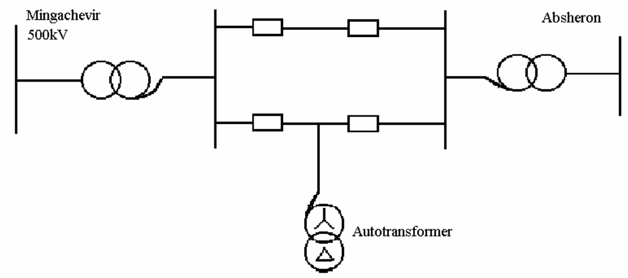

Figure 1. Circuit scheme of the substation

Use of commutation and element model allows by the use of unique algorithm to perform calculation of the open-phase operating conditions of transmission line with autotransformers by model shown in Figure 2 that corresponds to the basic model of the substation of high-voltage 500 kV line Mingachevir-Absheron.

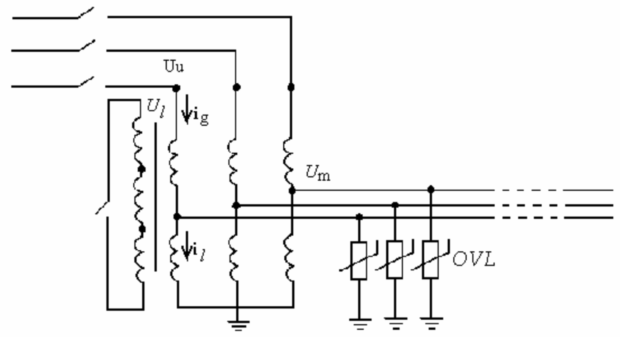

Figure 2. Calculation scheme for computer modelling and analysis of open-phase operating condition of TL with autotransformer

II. CALCULATION METHOD

We consider an autotransformer with tertiary winding connected as delta. One can choose node points in the scheme with autotransformer and switching unit. Then we formulate equations of the following form:

$$\frac{d\psi}{dt}=\frac{L_g^{-1}(u_m-u_l)+L_l^{-1}k(u_u-u_m)+L_{lv}^{-1}u_{lv}-L_g^{-1}r_g\cdot i_g}{L_g^{-1}+L_l^{-1}+L_{lv}^{-1}+a+bn\psi^{n-1}+cm\psi^{m-1}},$$

$$\frac{di_g}{dt}=L_g^{-1}\left(-\frac{d\psi}{dt}+u_m-u_l+r_gi_g\right),$$

$$\frac{di_l}{dt}=L_l^{-1}\left[\frac{d\psi}{dt}-(u_u-u_m)k\right],$$

where i_g, i_l are matrices of current of general and longitudinal windings, L_g, L_l are quadratic matrices of inductance of common and longitudinal windings, moreover, matrix L_g in addition can contain inductance of the reactor in neutral L_r:

$$L_g=\begin{vmatrix} L_g+L_r & L_r & L_r \\ L_r & L_g+L_r & L_r \\ L_r & L_r & L_g+L_r \end{vmatrix},$$

r_g is general resistance of the resistor in neutral chain for limitation of shock currents, u_m, u_u and u_l correspond to the matrices of voltages on inputs of middle, upper and lower voltages, and inductance on the winding of the lower voltage L_{lv} is determined by following way:

$$L_{lv}=\begin{vmatrix} L_{lv} & 0 & 0 \\ 0 & L_{lv} & 0 \\ 0 & 0 & L_{lv} \end{vmatrix}, \qquad L_l=\begin{vmatrix} L_l & 0 & 0 \\ 0 & L_l & 0 \\ 0 & 0 & L_l \end{vmatrix},$$

$$r_g=\begin{vmatrix} r_r & r_r & r_r \\ r_r & r_r & r_r \\ r_r & r_r & r_r \end{vmatrix}.$$

Ferroresonance overvoltages under the open-phase energization of the electrical transmission line with transformer on tapping and insulated neutral already are studied in detail. However, actions on the ferroresonance prevention are not sufficient.

In case of open-phase energization of the electrical transmission line with unloaded transformer operating with insulated neutral, an occurrence of ferroresonance overvoltages with amplitudes two times higher than the value of the rated voltage is possible on the disconnected phase. Theoretical analysis of such kind of overvoltages is necessary to validate the ferroresonance recognition method for further reliable disconnection.

Possibility of the ferroresonance occurrence is considered by the use of circuit presented in Figure 3, where autotransformers are modelled by one transformer since they were disconnected from the direction of middle and lower voltages.

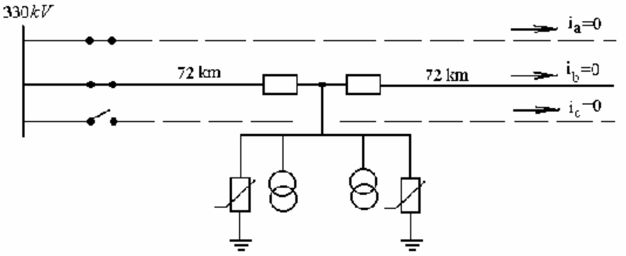

Figure 3. Calculation scheme for computer modelling and analysis of open-phase operating condition of TL with unloaded transformer

Open-phase energizated 330 kV line with total length 144 km on distance 72 km has a substation with two (one) autotransformers 330/220 kV per 240 MVA. Aim of the calculation is identification of the voltage form of disconnected phase and influence on its amplitude the corona effect on wires and operation of the OVL.

Conditions on the initial point of line are:

$$u_a = U_m \cdot \sin \omega t \,, u_b = U_m \sin\left(\omega t + \frac{2\pi}{3}\right), i_c = 0 \,,$$

whereas, conditions on the final point of line are:

$$i_a = i_b = i_c = 0 \,.$$

Conditions in intermediate substation require expression of the magnetic flux in the transformer by following equation:

$$\frac{d}{dt}\begin{vmatrix}\varphi_1\\ \varphi_2\\ \varphi_3\end{vmatrix} = \begin{vmatrix} 1 + L_1\psi(\varphi_1) - L_1L_2^{-1}\frac{1}{3} & -\frac{1}{3}L_1L_2^{-1} & -\frac{1}{3}L_1L_2^{-1} \\ -\frac{1}{3}L_1L_2^{-1} & 1 + L_1\psi(\varphi_1) - L_1L_2^{-1}\frac{1}{3} & -\frac{1}{3}L_1L_2^{-1} \\ -\frac{1}{3}L_1L_2^{-1} & -\frac{1}{3}L_1L_2^{-1} & 1 + L_1\psi(\varphi_1) - L_1L_2^{-1}\frac{1}{3} \end{vmatrix}.$$

Currents in primary winding are following:

$$\frac{di_1}{dt} = L_1^{-1}\left(u_1 - \frac{d\varphi_1}{dt}\right),$$

$$\frac{di_2}{dt} = L_1^{-1}\left(u_2 - \frac{d\varphi_2}{dt}\right),$$

$$\frac{di_3}{dt} = L_1^{-1}\left(u_3 - \frac{d\varphi_3}{dt}\right),$$

and magnetizing currents have following form:

$$i_{\mu_1} = a\varphi_1 + b\varphi_1^n + c\varphi_1^m \,,$$

$$i_{\mu_2} = a\varphi_2 + b\varphi_2^n + c\varphi_2^m \,,$$

$$i_{\mu_3} = a\varphi_3 + b\varphi_3^n + c\varphi_3^m \,,$$

$$\frac{di_{\mu_1}}{dt} = \psi(\varphi_1)\frac{d\varphi_1}{dt} \,,$$

$$\frac{di_{\mu_2}}{dt} = \psi(\varphi_2)\frac{d\varphi_2}{dt} \,,$$

$$\frac{di_{\mu_3}}{dt} = \psi(\varphi_3)\frac{d\varphi_3}{dt} \,,$$

$$\psi(\varphi_1) = a + nb\varphi_1^{n-1} + cm\varphi_1^{m-1} \,,$$

$$\psi(\varphi_2) = a + nb\varphi_2^{n-1} + cm\varphi_2^{m-1} \,,$$

$$\psi(\varphi_3) = a + nb\varphi_3^{n-1} + cm\varphi_3^{m-1} \,.$$

Electrical transmission line is modelled by the use [5] taking into account corona effect and by the use [6] without taking into account corona effect. OVL is modelled by the use [7, 8].

Only reliable method to investigate ferroresonance phenomenon in multi-wire line is to simulate transients by the use of computer programmes allowing us to simulate multi-wire lines and node points with joint solution of the transient equations. Simulations were done by the use of computer programme for calculation of transients in arbitrary circuits, developed in FORTRAN environment by IP ANAS. Analysis of ferroresonance processes is performed for TL length 72 km taking into account or without taking into account OVL.

III. RESULTS AND DISCUSSION

A Voltage-Current characteristic of OVL for autotransformer 330/220kV corresponds to the largest sustained voltage $U_{p\max} = 270kV$. For operating current $630A$ the residual voltage is $U_{res} = 545kV$, or for current value $100A$ the voltage is $U_{100} = 415kV$ and $U_{p\max}/U_{100} = 0.6$ [9].

As a result of computer simulations, curves of voltages and currents of transients and quasisteady processes in case of energization of autotransformer with single phase with and without OVL are presented in Figure 4 and 5.

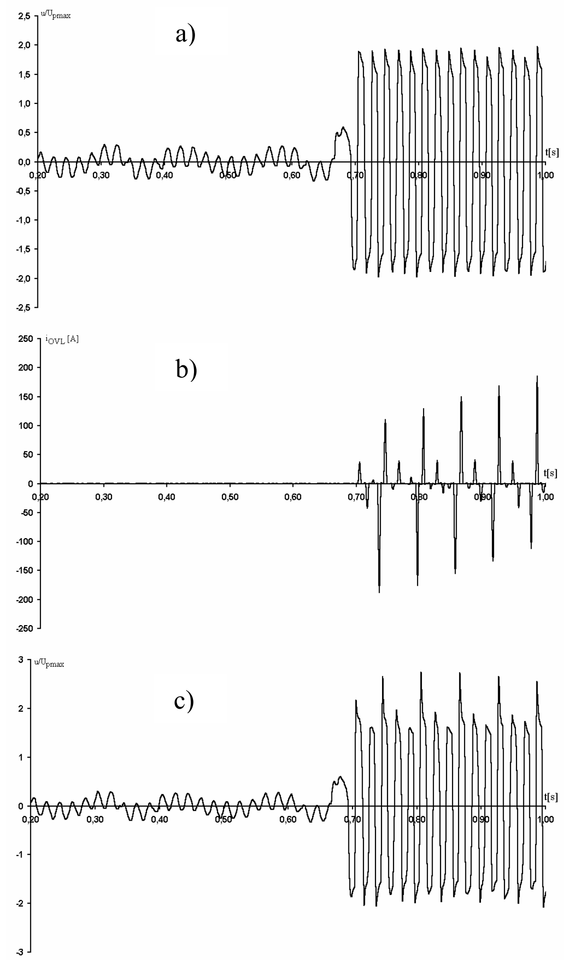

Figure 4. Ferroresonance process at energization of the autotransformer 330/220 kV taking into account OVL (TL length is 72 km): a) voltage at the disconnected phase; b) phase current through OVL; c) voltage at the end of line

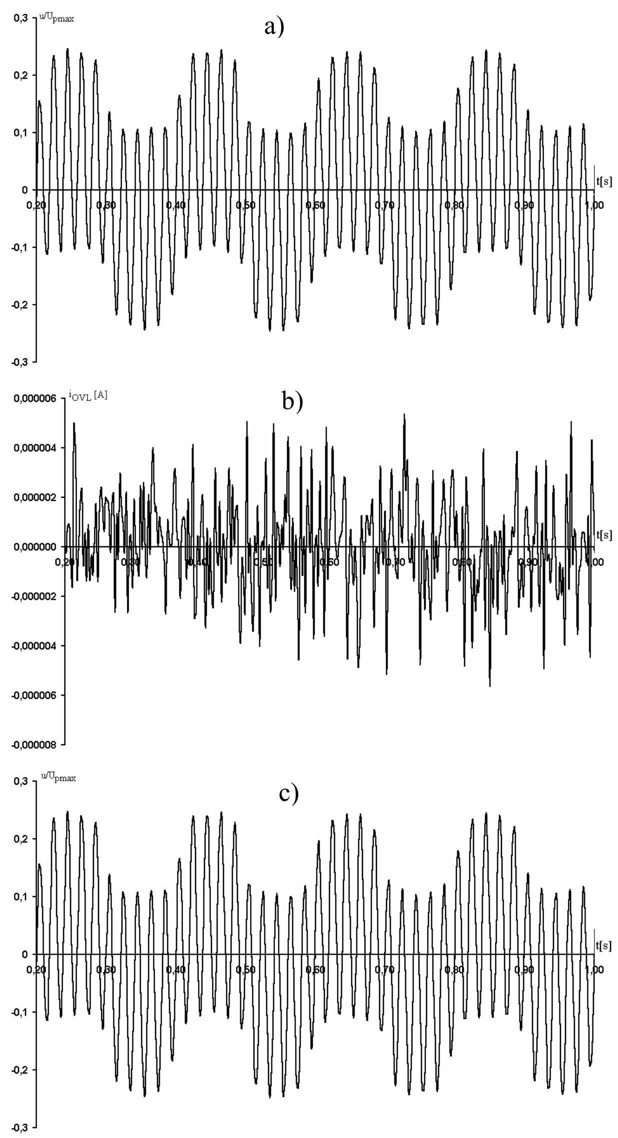

Figure 5. Ferroresonance process at energization of the autotransformer 330/220 kV without OVL (TL length is 72 km): a) voltage at the disconnected phase; b) phase current through OVL; c) voltage at the end of line

One can see that ferroresonance overvoltages on disconnected phases are not higher than $1.8\,U_{p\max}$ (Figure 4a). Process becomes steady, when the voltage on disconnected phase is higher than OVL actuation voltage. Currents flowing through OVL have certain form and are repeated regularly (Figure 4b). This operating condition is dangerous for OVL, because after certain quantity such kind of repetitions will lead to the collapse of OVL. Appearance of such pulses allows to combine application of protection devices against electrical transmission line open-phase operating conditions with application of OVL facilitating choice of protection action characteristics in case of appearance ferroresonance phenomena. The voltage at the end of line has stable form (Figure 4c).

Performed studies show that an increase of the autotransformer power and line length does not influence neither to form nor to the quantity of peaks in one period of voltage variation in case of presence of OVL.

As one can see from Figure 4, durations of ferroresonance processes starting with certain time shift on dependence from length of TL do not change the form of current curves in case of presence of VOL and their steady amplitudes are observed since OVL actuation, i.e. since ferroresonance appearance.

IV. CONCLUSION

Calculation formulae for some characteristic node points, necessary for numerical experiments of the open-phase operation of the transmission line and its protection ways are obtained. The obtained formulae allow in the framework of unique algorithm to perform computer simulation of the ferroresonance overvoltages from the phases spread, in case of line energization, broken wire, also simultaneously to take into account an actuation of OVL in multi-wire ETL.

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