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Method for Determining the Resonant Frequencies of Extra High Voltage Power Transmission Line

***Abstract**. The paper proposes a mathematical model for determining the resonant frequency of a 750 kV line relative to an unloaded transformer and studies the possibility of overvoltages in 750 kV lines at the 2nd harmonic. A resonant circuit has been compiled to determine the natural frequencies of an ultrahigh voltage power line to analyze the conditions for overvoltages at higher harmonic components. Analytical expressions are obtained to determine the degree of influence of the line parameters' value on the line's resonant frequency. The paper presents the relationship between the operating mode of an ultra-high voltage power line and an autotransformer (transformer) on the conditions for the existence of overvoltages. Analytical expressions for evaluating the influence of the degree of charging power compensation on the values of the mode parameters of the ultra-high voltage power transmission line are given.*

***Streszczenie.** W pracy zaproponowano model matematyczny wyznaczania częstotliwości rezonansowej linii 750 kV względem nieobciążonego transformatora oraz zbadano możliwość wystąpienia przepięć w liniach 750 kV na 2. harmonicznej. Opracowano obwód rezonansowy do wyznaczania częstotliwości drgań własnych linii elektroenergetycznej ultrawysokiego napięcia w celu analizy warunków przepięć przy składowych wyższych harmonicznych. Otrzymuje się wyrażenia analityczne w celu określenia stopnia wpływu wartości parametrów linii na częstotliwość rezonansową linii. W artykule przedstawiono zależność między trybem pracy linii najwyższych napięć a autotransformatorem (transformatorem) na warunki występowania przepięć. Podano wyrażenia analityczne do oceny wpływu stopnia kompensacji mocy ładowania na wartości parametrów modowych elektroenergetycznej linii przesyłowej najwyższych napięć. (**Metoda wyznaczania częstotliwości rezonansowych linii przesyłowej wysokiego napięcia**)*

Keywords: resonance overvoltages, nonsinusoidal mode, no-load autotransformer, resonant frequency.
Słowa kluczowe: przepięcia rezonansowe, tryb niesinusoidalny, autotransformator bez obciążenia, częstotliwość rezonansowa..

Introduction

One of the problems encountered during the operation of 750 kV transmission lines is resonant overvoltage. They can occur both at the fundamental frequency and at harmonic frequencies [1-3]. The potential occurrence of harmonic resonance requires the development of logical blocking algorithms for switching devices to ensure the correct sequence of operations during operational switching at 750kV substations. This can lead to a complication of the control system, an increase in its cost, and significant restrictions when performing commutations. Overvoltages in 750 kV lines at higher harmonics are the result of transient ferroresonance.

It can occur when switching unilaterally fed lines to a non-excited transformer (autotransformer). During switching, a free damped aperiodic component of the flux linkage appears in the magnetic circuit of the transformer, which leads to the appearance of harmonic components in the magnetization current. The latter, in turn, cause a voltage drop on the elements of the electrical circuit, which is equivalent to introducing a longitudinal emf into the circuit. appropriate frequency [4, 5]. If one of the natural frequencies of the transmission line is close to the emf frequency, then voltage resonance occurs at this frequency.

In 1986, start-up tests were carried out when the 750 kV power transmission line of the South Ukrainian NPP - Isakcha was put into operation. With an unloaded 750/400 kV autotransformer from the side of Isacchi and various options for connecting power transmission lines, the voltage increased by 20-45% of the original due to the appearance of the 2nd harmonic. Only at a load of 150-200 MW on the 400 kV side of the autotransformer, the connection of the power transmission line did not cause resonant overvoltages. During this transmission line's design, the occurrence of resonance at the 2nd harmonic was not sufficiently studied. This led to unforeseen problems in the operation of automation from excess voltage during start-up tests. Similar problems arose during the start-up tests of the 750 line. The construction of the substation 750/330 kV and outgoing lines 750 kV was caused by the need to improve the reliability and efficiency of the energy system of Ukraine. Since at the time of putting the substation under voltage, its 750/330 kV autotransformers carried the load only for the substation's own needs, it became necessary to assess the possibility of overvoltage on the 2nd harmonic [6-8]. The functions of extra high voltage transmission lines in integrated electrical power systems.

Mathematical model for estimation of natural frequency

Mathematical model for estimation of natural frequency A single-line equivalent circuit of an idle mode line with an unloaded transformer (autotransformer) is shown in Fig. 1.

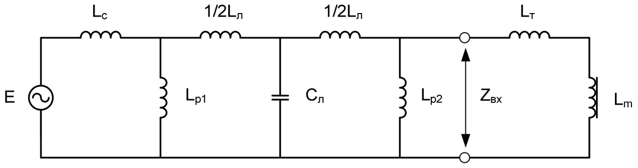

Fig. 1. Equivalent circuit of the line with unloaded transformer (autotransformer)

On this scheme E is e.m.f. system, L_S is system inductance, L_L is line longitudinal inductance, $\mathrm{C_L}$ is line transverse capacitance, L_{s1} is shunt reactor inductance at the beginning of the line, L_{s2} is shunt reactor inductance at the end of the line, L_T is transformer inductance, L_μ is transformer magnetic shunt inductance. As already noted, when switching the line to an unloaded transformer in its magnetic circuit (due to saturation), a current of the 2nd harmonic may occur. Representing the voltage drop of this current across the transformer resistance in the form of emf. 2nd harmonic $E_{(2)}$, we obtain a circuit for analyzing the possibility of resonance occurrence (Fig. 2). If the natural frequency.

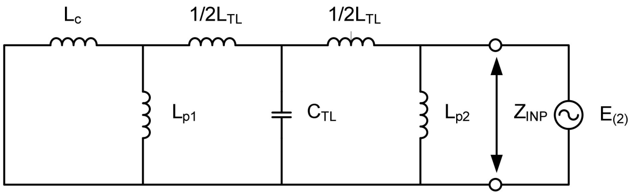

Fig. 2. Equivalent circuit of the line with voltage drop

Input resistance of the circuit relative to the transformer is close to the frequency of the 2nd harmonic, then resonance will occur, which will lead to overvoltage. Having performed a number of transformations of the circuit, which is shown in Fig. 1, we obtain an expression for the input resistance relative to the transformer terminals:

$$Z_{INP}=\frac{A\omega^4+B\omega^2}{D\omega^3+F\omega}, \tag{1}$$

where

$$\begin{cases} A=0.5(L_C+L_{P1})L_{TL}L_TL_{P2}+L_CL_{P1}L_TL_{P2}+\\ +0.25(L_C+L_{P1})L_{TL}^2L_TL_{P2}+\\ +0.5L_CL_{P1}L_{TL}(L_T+L_{P2});\\ B=-\dfrac{1}{C_{TL}}\begin{bmatrix}(L_C+L_{P1})L_TL_{P2}+\\ +L_{TL}(L_C+L_{P1})(L_T+L_{P2})+\\ +L_CL_{P1}(L_T+L_{P2})\end{bmatrix};\\ D=0.5(L_C+L_{P1})L_{TL}L_T+L_CL_{P1}L_{P2}+\\ +0,25(L_C+L_{P1})L_{TL}^2+0,5L_CL_{P1}L_{TL};\\ F=-\dfrac{1}{C_{TL}}\begin{bmatrix}(L_C+L_{P1})L_{P2}+\\ +L_{TL}(L_C+L_{P1})+L_CL_{P1}\end{bmatrix}. \end{cases} \tag{2}$$

Zeros Z_{INP} of the function occur at conditionally, and poles at

$$D\omega^3+F\omega=0\,. \tag{3}$$

The resonant frequency of interest to us is determined from the relationship:

$$\omega_0=\pm\sqrt{-\frac{B}{A}}. \tag{4}$$

$$\begin{aligned}A'&=0.5(L_C+L_{P1})L_{TL}L_{P2}+L_CL_{P1}L_{P2}+\\ &+0.25(L_C+L_{P1})L_{TL}^2L_{P2}+0.5L_CL_{P1}L_{TL};\end{aligned} \tag{5}$$

$$B'=-\frac{1}{C_{TL}}\left[(L_C+L_{P1})L_{P2}+L_{TL}(L_C+L_{P1})+L_CL_{P1}\right]; \tag{6}$$

$$\begin{aligned}A'&=0.5(L_C+L_{P1})L_LL_{P2}(1+0.5L_L)+\\ &+L_CL_{P1}(L_{P2}+0.5L_L);\end{aligned} \tag{7}$$

$$B'=-\frac{1}{C_L}\left[(L_C+L_{P1})(L_{P2}+L_L)+L_CL_{P1}\right]. \tag{8}$$

Resonant frequency analysis

The presence of resonance at the 2nd harmonic for the 750 kV line was established during start-up tests. Let's carry out calculations to determine the resonant frequency in accordance with the proposed model.

The line 750 kV before commissioning required a detailed analysis of the possibility of occurrence of resonant overvoltages due to the 2nd harmonic. Initial data for the line 750 kV: line length – 131 km; linear parameters of the line per 1 km: L_1 = 9.19992*10^{-4} H, L_0 = 3.1735*10^{-3} H, C_1 = 1.2567*10^{-8} F, C_0 = 7.4453*10^{-9} F; shunt reactor resistance X_{SR}=1880 Ohm; number of shunt reactors – 2. The introduction of a compensation reactor into the neutral of a group of shunt reactors may be required due to the conditions for limiting overvoltage in the pause of a single-phase automatic reclosing.

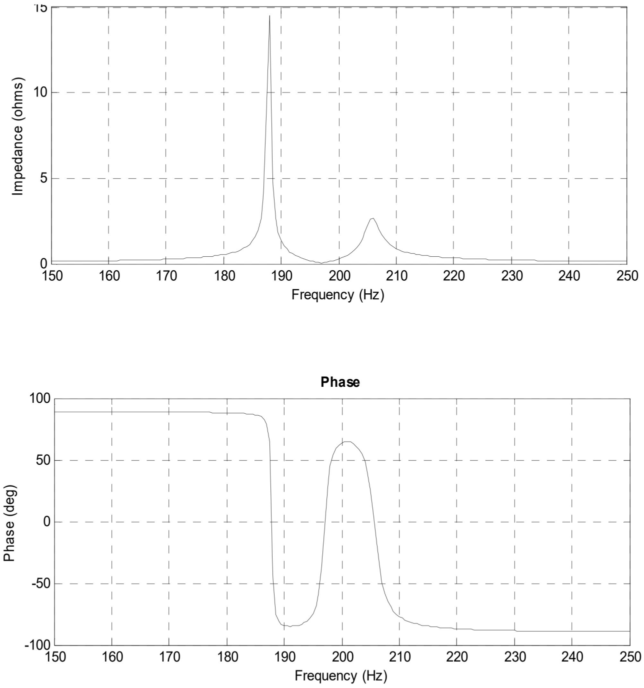

Fig. 3. Frequency response of the input impedance of the 750 kV Kyiv - Chernobyl line (powered from the Chernobyl side, system resistance 141.053 Ohm)

The results of the calculations that were carried out according to (3) are presented in Table 1. Comparison of the calculation results with the results of modeling the input resistance in Matlab shows some discrepancy. So for the option of powering the line from the Chernobyl nuclear power plant, the system resistance is 141.053 Ohm and two groups of shunt reactors, the resonant frequency was 195.226 Hz. The simulation results in Matlab are shown in Fig. 3. As we can see, the frequency.

$$\omega_0=\pm\sqrt{-\frac{B}{A}}. \tag{4}$$

$$\begin{aligned}A'&=0.5(L_C+L_{P1})L_{TL}L_{P2}+L_CL_{P1}L_{P2}+\\ &+0.25(L_C+L_{P1})L_{TL}^2L_{P2}+0.5L_CL_{P1}L_{TL};\end{aligned} \tag{5}$$

$$B'=-\frac{1}{C_{TL}}\left[(L_C+L_{P1})L_{P2}+L_{TL}(L_C+L_{P1})+L_CL_{P1}\right]; \tag{6}$$

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Influence phase asymmetry on power transfer capability of extra high voltage line

Creation of a reliable and efficient system of transmission and distribution of electricity is one of the most important tasks of the energy industry. 750 kV networks play a special role in this process. They serve to create intra-system and inter-system links that ensure the transmission of large powers over long distances in normal and emergency modes. As you know, 750 kV lines have a large charging capacity. Thus, a 750 kV line 400 km long at rated voltage generates reactive power of about 900 MVAr. In the minimum load mode, especially when the line is switched on unilaterally, the reception of reactive power into the system may be unacceptable.

One of the factors that determine the admissibility of this mode is the voltage level. The reactive power drain in idle mode should not cause the voltage to exceed the highest operating value. For 750 kV lines, the permissible excess of the rated voltage is 5%, that is, the maximum operating linear voltage is 787.5 kV (phase - 454.66 kV). Calculation of the mode of EHV lines is carried out according to the formulas:

$$\dot{U}_1 = \dot{U}_2 ch\left(\sqrt{\underline{Z}\underline{Y}}\right) + \dot{I}_2 \underline{Z}_B sh\left(\sqrt{\underline{Z}\underline{Y}}\right)$$
$$\dot{I}_1 = \dot{U}_2 \frac{sh\left(\sqrt{\underline{Z}\underline{Y}}\right)}{\underline{Z}_B} + \dot{I}_2 ch\left(\sqrt{\underline{Z}\underline{Y}}\right) \tag{9}$$

where $\underline{Z}$ is the longitudinal resistance of the line; $\underline{Y}$ is transverse conductivity of the line; $\underline{Z}_{TL} = \sqrt{\underline{Z}/\underline{Y}}$ is line impedance. The voltage and current at the intermediate points of the line can be determined as follows:

$$\dot{U}_{1x} = \dot{U}_2 ch(\dot{\gamma} l_x) + \dot{I}_2 \underline{Z}_B sh(\dot{\gamma} l_x)$$
$$\dot{I}_{1x} = \dot{U}_2 \frac{sh(\dot{\gamma} l_x)}{\underline{Z}_{TL}} + \dot{I}_2 ch(\dot{\gamma} l_x) \tag{10}$$

where l_x is the distance from the end of the line, $\dot{\gamma} = \sqrt{\underline{Z}_0 \underline{Y}_0}$ - wave propagation coefficient, $\underline{Z}_0$ and $\underline{Y}_0$ are linear longitudinal resistance and transverse conductivity of the line.

The most unfavorable from the point of view of voltage increase is the idle mode of the extra-high voltage (EHV) line. A feature of this mode is a large excess of reactive power generated by the EHV line. In idle mode, the reactive power generated by the line capacitance is practically not compensated by its losses in the line inductance. This position can be confirmed as follows. Since in the idle mode the current $\dot{I}_2 = 0$, then expression (2) will take the form:

$$\dot{U}_{1x} = \dot{U}_2 ch(\dot{\gamma} l_x)$$
$$\dot{I}_{1x} = \dot{U}_2 \frac{sh(\dot{\gamma} l_x)}{\underline{Z}_{TL}}, \tag{11}$$

Then the value of losses of reactive power ΔQ_x and charging power Q_{ch} in the section of length $\Delta l \to 0$, located at a distance l_x from the end of the line, can be determined by the formulas:

$$\Delta Q_x = \dot{I}_{1x}^2 x_0 \Delta l$$
$$Q_{\text{з}x} = \dot{U}_{1x}^2 b_0 \Delta l \tag{12}$$
,

where x_0 is the linear longitudinal reactance of the line; b_0 - linear transverse capacitive conductivity of the line. A small Δl value allows us to assume a constant value of current and voltage in this section.

As we noted, the current at the end of the EHV line in idle mode is zero. Consequently, and reactive power losses at the end of the line $\Delta Q_l = 0$. At the same time, charging power at the end of the line $Q_{\text{з}l} \neq 0$. That is, the validity of the inequality is confirmed $|Q_{\text{з}l}| > |\Delta Q_l|$.

Then the value of losses of reactive power and charging power in the section of length , located at a distance from the end of the line, can be determined by the formulas: , (four) where is the linear longitudinal reactance of the line; - linear transverse capacitive conductivity of the line. A small value allows us to assume a constant value of current and voltage in this section. As we noted, the current at the end of the EHV line in idle mode is zero. Consequently, and reactive power losses at the end of the line. At the same time, charging power at the end of the line. That is, the validity of the inequality is confirmed. For an arbitrary section of the line, expression (12), taking into account (11), can be written as follows:

$$\Delta Q_x = \left[\dot{U}_2 \frac{sh(\dot{\gamma} l_x)}{\underline{Z}_B}\right]^2 x_0 \Delta l$$
$$Q_{ch} = \left[\dot{U}_2 ch(\dot{\gamma} l_x)\right]^2 b_0 \Delta l \tag{13}$$
.

According to (13), we determine the module of the power ratio:

$$\left|\frac{Q_{ch}}{\Delta Q_x}\right| = \left|\underline{Z}_B^2 cth^2(\dot{\gamma} l_x) \frac{b_0}{x_0}\right|. \tag{14}$$

The active components $\underline{Z}$ and $\underline{Y}$ are quite small. Therefore, we can accept that $\underline{Z}_{TL} \approx \sqrt{x_0/b_0}$. Then (14) will take the form:

$$\left|\frac{Q_{ch}}{\Delta Q_x}\right| = \left|cth^2(\dot{\gamma} l_x)\right|. \tag{15}$$

The expression for determining the losses of active power of the section of the EHV line at idle, by analogy with (15), will look like:

$$\Delta P_x = \left[\dot{U}_2 \frac{sh(\dot{\gamma} l_x)}{\underline{Z}_B}\right]^2 r_0 \Delta l, \tag{16}$$

where r_0 is the linear longitudinal active resistance of the line. The mode parameters of the EHV line 400 km long, made with wire 5AC-400 (r_0=0.015 Ohm/km, x_0=0.286 Ohm/km, b_0=4.13*10^{-6} Sm/km) at rated supply voltage, are presented in Table 1.

Table 1. Results of calculation parametres

Distance from the start of the line, km	0	100	200	300	399
U_x, kV	433,0	452,3	466,22	474,61	477,46
Q_{ch}, kVar/км	774,5	844,91	897,71	930,42	941,5
ΔQ_x, kVar/km	166,54	96,32	43,67	11,05	0,001
$\lvert Q_{ch}/\Delta Q_x \rvert$	4,637	8,75	20,5	83,99	846610
ΔP_x, W/km	8758,87	5065,94	2296,52	580,97	0,06

The charging power Q_{ch} exceeds the reactive power ΔQ_x losses along the entire length of the line. The value of the ratio of charging power and reactive power losses $|Q_{ch}/\Delta Q_x|$ increases from the beginning to the end of the line. This is explained by the fact that in the idle mode, the entire charging power of the EHV line flows to the beginning of the line. As already noted, the current at the end of the line in idle mode does not flow, therefore $|Q_{ch}/\Delta Q_x| \to \infty$. Active power losses vary ΔP_x along the line similarly to reactive ones.

If the rated voltage is applied at the beginning of the line, then, starting from a distance of 115.5 km from the beginning, the voltage on the line will exceed the maximum operating voltage of 454.66 kV (Fig. 4). And at the end of the line it will reach 477.458 kV. This indicates that this line cannot operate in idle mode without devices for transverse charging power compensation. there is no 2nd harmonic voltage.

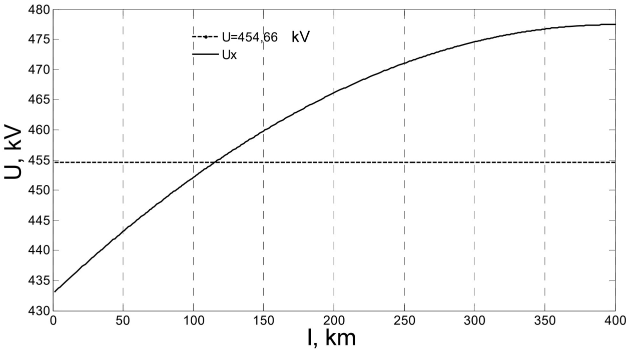

Fig.4. Phase voltage distribution along the 750 kV line at no load. kV. Thus, the increase in voltage at the end of the line was more than 10% compared to the beginning.

Conclusions

The paper proposes a mathematical model and calculation expressions for estimating the resonant frequency of the input impedance of a line connected to a power source on the one hand, in order to analyze the possibility of resonance occurrence. on the 2nd harmonic in the line 750 kV, which was observed during the commissioning of the line, the resonant frequencies of the input impedance of the line 750 kV in various modes were far from 100 Hz.

Therefore, we can conclude that there is no danger of overvoltage in this line due to the appearance of the voltage component of the 2nd harmonic.

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