ELECTROMAGNETIC COMPATIBILITY OF HIGH-VOLTAGE ELECTRICAL SYSTEMS

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ABSTRACT

Analysis of performance and reliability of electrical equipment of high-voltage electrical systems (hereinafter – HVES) confirms the need to improve evaluation methods and mathematical modeling of transients in power lines (hereinafter – PL), at substations, and in grounding and protective devices. One of the main problems, however, remains improvement of safety and quality of HVES functioning in accordance with their EMC in modes of overvoltage effects, including determination of evaluation criteria, scientific substantiation of deep forced restrictions of external and internal overvoltage of electrical equipment, optimization of PL protection and substations of the system from different levels of voltage, electromagnetic interference that could cause serious accidents.

Keywords: railway infrastructure, electrical power supply, electromagnetic compatibility, high-voltage electrical systems, lightning overvoltage, neutral of transformers.

Background. *The reliability and quality of power supply of rail sector are largely associated with development of high-voltage electrical systems (hereinafter – HVES) of electrical networks, which include power lines (hereinafter – PL) and substations (hereinafter – ES). HVES are independent technological systems, but they are also an integral part of higher level systems, and it is necessary to provide their effective and safe operation under a wide range of powerful electromagnetic influences. Among them it is possible to distinguish short-term pulse external and internal overvoltage, often becoming a cause of serious accidents. Therefore, an essential factor in improving performance of PL and ES has always been their electromagnetic compatibility (hereinafter – EMC) during overvoltage [1].*

Objective. *The objective of the authors is to consider issues of electromagnetic compatibility in high-voltage electrical systems.*

Methods. *The authors use general scientific and engineering methods, techniques of electrical engineering, mathematical methods.*

Results.

I.

The problem of EMC in providing protection against overvoltage of electrical equipment of HVES, PL, power transformers and instrument transformers of high-voltage and switching devices, reactors is of particular significance. The analysis shows that the share of EMC violations caused by overvoltage and specificity of electromagnetic processes in the general flow of electrical equipment failures exceeds 35–40%.

Solution of corresponding tasks imposes stringent requirements for development of protection circuits and protective devices, first of all of non-linear overvoltage limiters (hereinafter – OVL) and valve arresters. The purpose of protective devices in terms of EMC is that for short intervals that are typical of overvoltage, they create routes through which energy of electromagnetic effects, harmful for protected electrical installations, is drawn off them into the ground.

EMC violations often occur due to interference in the form of overvoltage while using the method of ungrounded neutral of a part of power transformers 110–220 kV or grounding them through a reactor or resistor to limit short-circuit currents.

The growth of short-circuit currents leads to an increase in dynamic effects on transformer windings, significant loading of operation of switching equipment, increase in dangerous effects of power lines on communication lines, and worsens the conditions of safety for the personnel of power systems and industrial plants.

Short-circuit current limitation is possible via separation of power systems (networks), when power lines in a normal mode are turned off and in case of need are turned on by automation system. However, this method for limitation of short circuit currents is relatively rare because it reduces the reliability of power supply.

In networks of 110–220 kV, which are most prevalent in Russia, a method of ungrounded neutral system of a part of power transformers or a method of grounding them through a reactor or resistor are used to limit short-circuit currents. This leads to an increase in resistance of zero sequence of a network in relation to short-circuit point and, consequently, to reduction of single phase short-circuit currents.

This fact is essential for operation and design of networks, since in adverse combination of resistance of direct, reverse and zero sequences currents of single-phase short-circuit can be 15–20% higher than the current of a three-phase analog. In networks 110–220 kV single-phase short circuit represents generally more than 75% of all short circuits. Reduction of single-phase short-circuit currents, it is necessary to bear in mind, significantly reduces requirements for grounding devices and equipment for protection of communication lines [2, 3].

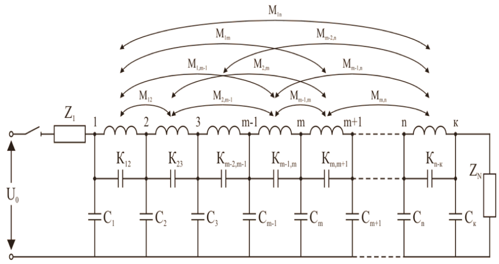
However, if ungrounded neutral of power transformers is used, it is necessary to give it appropriate insulation strength by necessary means of protection against overvoltage. In addition, in case of damage of isolation transformer can continue to work practically in a mode with grounded neutral, which ultimately affects only ratio of reactive resistance of direct and zero sequence for the current network of a network. It is impossible to identify neutral insulation damage during operation. Generally, it is found during preventive tests.

To calculate voltages in the neutral of a transformer at impulse action it is proposed to replace it with simple L–C circuit, and to study processes with a method of symmetrical components. The voltage in the neutral corresponds to the voltage at circuit capacity. It is shown [2], that voltage value depends on oscillation period of the circuit L–C, instead of specific values L and C.

Direct measurement of lightning overvoltage in the power transformer neutral during arrival of storm waves through the PL is very difficult. Firstly, this is due to complex technical problems in creating registrars of lightning overvoltage. Secondly, for measurement of lightning overvoltage in the neutral it is necessary to connect voltage dividers to it, which can significantly distort the transition process. Therefore, usually the study of lightning overvoltage is performed by an analytical calculation or using a physical model.

II.

Lightning overvoltage at the power transformer neutral arises on arrival of waves through one, two or three phases. The form of a wave, acting on linear ends, depends on whether valve arresters from linear end of a transformer



Pic. 1. The equivalent circuit of the transformer.

come into effect or not.

If the waves arrive with the same amplitude through the three phases of a transformer which windings are star-connected with isolated neutral, wave process within all three phases is almost identical.

If an overvoltage wave arrives through one phase of winding, this wave is refracted in neutral and enters two other phases, grounded through wave resistance of the line (substation bus bars). The impact of voltage can be represented in harmonic spectrum, which contains harmonics of direct, reverse and zero sequence. Voltage caused by harmonics of direct and reverse sequence is zero. Thus, for calculation of overvoltage in the neutral of the transformer it is necessary to take into account only harmonics of zero sequence.

In single-phase (e. g., phase «C») exposure:

$$\dot{E}_A = 0; \quad \dot{E}_B = 0; \quad \dot{E}_C = \dot{E};$$

$$\dot{E}_{A0} = \dot{E}_{B0} = \dot{E}_{C0} = \frac{1}{3}\cdot\left(\dot{E}_A + \dot{E}_B + \dot{E}_C\right) = \frac{1}{3}\dot{E}. \qquad (1)$$

That is, voltage in the neutral is determined by three voltages $\dot{E}_{A0}$, $\dot{E}_{B0}$, $\dot{E}_{C0}$ with amplitude equal to 1/3 of amplitude $\dot{E}$, acting through one phase of the wave.

Similarly, voltage in the neutral can be found when a wave falls through two phases (for example, «A» and «B»):

$$\dot{E}_A = \dot{E}; \quad \dot{E}_B = \dot{E}; \quad \dot{E}_C = 0;$$

$$\dot{E}_{A0} = \dot{E}_{B0} = \dot{E}_{C0} = \frac{1}{3}\cdot\left(\dot{E}_A + \dot{E}_B + \dot{E}_C\right) = \frac{2}{3}\dot{E}. \qquad (2)$$

In general, the voltage in the neutral is determined by single-phase circuit in case of arrival to transformer of a wave which amplitude is equal to $K_н \cdot U_o$, where $K_н$ coefficient is equal to 1/3, 2/3, 1, when a wave of overvoltage arrives, respectively, to one, two and three phases.

It follows that under asymmetric effects on the three-phase transformer's winding transients in all three phases can be regarded as symmetric, replacing a three-phase transformer with a single phase one, using the equivalent circuit shown in Pic. 1, in which for the sake of clarity only a portion of mutual inductance relations is shown. Calculation of equivalent circuit parameters contains a number of simplifying assumptions. The main of them is that elements of the equivalent circuit are linearly dependent on frequency.

The result of the study of lightning overvoltage is a formula for determining their maximum values in the ungrounded neutral of power transformer 110–220 kV class: $U_{max} = n/3 \cdot U_0 \cdot f \cdot (\tau_в / T)$, where U_0 is wave amplitude in the line entrance, n is a number of phases in which the wave arrives at the same time.

Studies show that the amplitude of voltage at isolated neutral of the power transformer is primarily determined by the amplitude of arriving storm wave and VAC arrester installed at the substation. In addition, it is subject to the same functional dependence of the wavelength, which existed before actuation of the valve arrester.

Emergence at the substation of waves with parameters, which are dangerous for insulation, is possible in three cases: in three phases under the effect of induced overvoltages; with overlapping of two phases of the lines from lightning stroke in the top of the support or wire; the same with overlapping of three phases of the line.

Table 1

The specific number of dangerous overvoltage for insulation of the neutral on arrival at the substation of waves of induced overvoltage

$U_н$, kV	Material of supports	Type of protective device								
		RVS			RVMG			OVL		
		number of outgoing lines			number of outgoing lines			number of outgoing lines		
		1	2	3	1	2	3	1	2	3
110	metal	26	3,4	0,45	9,26	1,08	0,01	1,5	0,01	0,01
	reinforced concrete	48	7,0	0,9	30,7	4,1	0,45	7	0,2	0,01
	wood	26	3,4	0,45	9,26	1,08	0,01	1,5	0,01	0,01
220	metal	13	1,8	0,22	5,4	0,4	0,01	1,0	0,01	0,01
	reinforced concrete	8	0,6	0,01	0,15	0,01	0,45	0,01	0,01	0,01

When lightning strikes near the line, propagation of overvoltage waves develops through it in both directions. Instantaneous values of overvoltage depend on the value of lightning current, average height of the suspension of the phase conductor, the distance from the line to the point of impact, reverse lightning speed, divided by the speed of light and time.

$$U_u(t) = \frac{60 \cdot I_l \cdot h_c}{b} \cdot \left\{ \frac{\beta}{\beta^2 \cdot c^2 \cdot t^2 / b^2 - 1} \cdot \left[\frac{c \cdot t}{b} - \frac{1}{\sqrt{\beta^2 \cdot c^2 \cdot t^2 / b^2 + 1 - \beta^2}} \right] + \frac{b}{\sqrt{\beta^2 \cdot c^2 \cdot t^2 / b^2 + 1 - \beta^2}} \right\}, \qquad (3)$$

where I_l is lighting current, kA; h_c is average height of suspension of phase conductor, m; b is distance from the line to the point of impact, m; β is speed of inverse lightning, divided by the speed of light; c is speed of light, m/ms; t is time, ms.

Probability of hitting and the point of impact of lightning into the danger area is defined as the double integral:

$$P_u = \iint\limits_s f(I_l, b)\, dI_l db.$$

The integration is performed approximately by the sites. We divide the entire area of «dangerous» parameters into rectangular elements, then $P_u = \sum_{i-1}^{m} \Delta P_i$, where m is a number of elements, into which the area is divided,

$$\Delta P_i = \iint\limits_s f(b) \cdot 0,04 \cdot e^{-0,04 \cdot I_l} db\, dI_l =$$

$$= 0,04 \cdot f(b) \int\limits_{I_i}^{I_{max}} e^{-0,04 \cdot I_l} dI_l \int\limits_{b_i}^{b_{i+1}} db =$$

$$= 0,04 \cdot f(b) \int\limits_{I_i}^{I_{max}} (b_{i+1} - b_i) \cdot e^{-0,04 \cdot I_l} dI_l = \qquad (4)$$

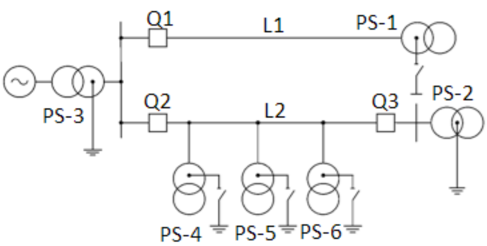
$$= \Delta b \cdot f(b) \cdot e^{-0,04 (I_{max} - I_i)}.$$

Calculation of probability of lightning striking and of the point of lightning strike in the danger zone by this method is not too difficult, especially with the use of modern personal computers. Knowing the probability $P_и$, it is possible to determine the number of lightning strikes per 100 storm hours and per 100 km of lines for

Table 2

Parameters of a calculation scheme for open-phase switching of power transformer with the line

Mode	E	C_1	C_2	C_3
Single-phase switching on (phase A)	U_F	C_A	C_{AB}	$C_C + C_B$
Two-phase switching on (phases A and B)	$0{,}5\cdot U_F$	$C_A + C_B$	$C_{AC} + C_{AB}$	C_C



Pic. 2. The most characteristic arrangement of transformers with ungrounded neutral in networks 110÷220 kV.

0,08 strikes per 1 km² of the Earth's surface in one lightning hour $n^* = 0{,}08\cdot 100\cdot 100\cdot b_{max}\cdot 2\cdot P_и = 1{,}6\cdot b_{max}\cdot P_и\cdot 10^3$. The results are summarized in Table 1.

Let's estimate probability of two-phase overvoltage for a line 110 kV on metal supports. It can occur after single-phase overvoltage with a proviso that lightning current continues to increase, that is, at the front of a current wave.

The lightning current I_l is equal to:

$$I_l = \frac{U_{\tau_f} - U_{op} - E_{av}\cdot h_c\cdot\left(1-K_{sc}\right)}{\left(1-K_{sc}\right)\cdot\left[\chi\cdot R_{зи} + \dfrac{\chi^2\cdot L_s + M_s}{\tau_f}\right]}, \qquad (5)$$

where I_l is lightning current; $U_{\tau f}$ is voltage of lightning chain overlapping at the time τf; U_{op} is operating voltage; E_{av} is average electric field strength along the length of support of power line; h_c is average height of suspension of electric conductor; K_{sc} is coupling coefficient of suspension strand-electric conductor; is coefficient of current drain into electric conductor; L_s is average inductance of support; M_s is mutual inductance between lightning current channel and support; τ_f is front time of lightning current waves.

Assuming that voltage-second characteristics of the insulation of the line are values τ_f and U_τ, it is possible to construct a curve of dangerous currents for two-phase overlapping of the line. Integrating it, we obtain the probability of two-phase overlapping in all possible range of amplitudes and steepness of lightning currents P_{2f}.

Then, the specific number of two-phase overlapping per 100 storm hours and 100 km of the line is:

$$n^* = \left(S\,h_{tr} + \frac{h_{tr}^2}{30}\right)\cdot P_{2f}. \qquad (6)$$

Substituting in the calculation initial data for the 110 kV line on metal supports, we get $n^* = 4{,}2\cdot 10^{-3}$. Of course, the probability of three-phase overlapping is even less, as to overlap the third string the greater lightning current is required. Therefore, when calculating the number of hazardous storm effects on the insulation of the neutral of the power transformer, two-phase and three-phase overlapping can be neglected, since their number is almost an order of magnitude less than the number of overlapping from induced overvoltage.

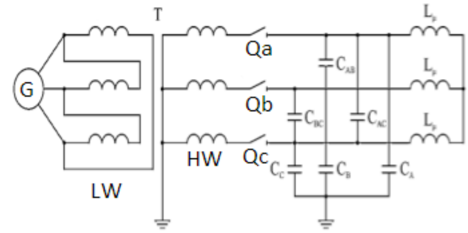
III.

Lightning overvoltage represents a danger for insulation of the neutral of power transformers 110–220 kV and therefore it is necessary to protect it with valve-type arresters or nonlinear voltage limiters. Increase in the number of outgoing lines reduces the voltage, but it remains to be dangerous for insulation.

In an isolated neutral of power transformers internal overvoltage may occur in transient and quasi-stationary modes. In symmetric modes of switching of network elements in the neutral appears moderate overvoltage. Basic overvoltage in it is caused by quasi-stationary modes of asymmetrical nature.

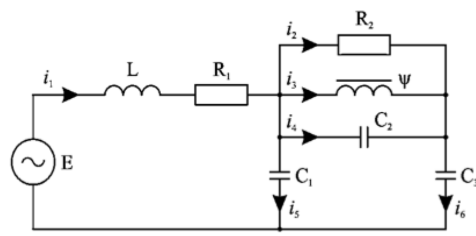
This overvoltage occurs during open-phase modes of turning off or turning on of transformers, due to ferroresonance, asymmetrical modes of turning off or turning on of lines, asymmetrical short circuits in the network with a partially ungrounded neutral.

Pic. 2 shows the most characteristic location of transformers with isolated neutral. For analysis of the values of overvoltage in open-phase switching on, this basic circuit can be transformed to the form shown in Pic. 3.



Pic. 3. The equivalent circuit for evaluation of overvoltage in open-phase inclusions of lines with transformer with isolated neutral.

With a slight error it can be assumed that two unswitched phases (single-phase switching) or one switched phase (two-phase switching) are almost symmetrical, and with average length of lines, which does not exceed 200 km, it is permissible to replace them with lumped capacitors. This allows to move to a calculation scheme shown in Pic. 4, with parameters from Table 2.



Pic. 4. Calculation scheme of open-phase modes.

In Table 2: C_A; C_B; C_C are phase capacitance to ground; C_{AB}; C_{Ac}; C_{CB} are phase to phase capacitance.

The initial equations:

$$E = L\frac{di_1}{dt} + R_1 i_1 + \frac{d\Psi}{dt} + \frac{1}{C_3}\int_0^t i_6\,dt\,;\ i_1 = i_2 + i_3 + i_4 + i_5;$$

$$E = L\frac{di_1}{dt} + R_1 i_1 + R_2 i_2 + \frac{1}{C_3}\int_0^t i_6\,dt\,;\ i_6 = i_2 + i_3 + i_4; \qquad (7)$$

$$E = L\frac{di_1}{dt} + R_1 i_1 + \frac{1}{C_5}\int_0^t i_5\,dt\,;\ i_3 = \Phi(\Psi);$$

$$E = L\frac{di_1}{dt} + R_1 i_1 + \frac{1}{C_2}\int_0^t i_4\,dt + \frac{1}{C_3}\int_0^t i_6\,dt\,;\ E = U_0\sin(\omega t + \alpha).$$

In order to proceed with computer calculations, a system of equations (6) is converted to the form:

$$\frac{di_1}{dt} = i_7\ ;\ \frac{di_2}{dt} = F(i_1, i_2, \Psi)\ ;\ \frac{d\Psi}{dt} = R_2 \cdot i_2\ ;$$

$$\frac{di_1}{dt} = \frac{\omega U_0}{L}\cos(\omega t + \alpha) - \frac{R_1}{L}\left(1 - (C_2 / C_3 + 1) \cdot R_2 / L\right) \cdot \cdot F(i_1, i_2, \Psi) - \frac{L_2 \Phi(\Psi)}{LC_3}, \quad (8)$$

where

$$F(i_1, i_2, \Psi) = \frac{1}{R_2 \cdot (1 + C_2 / C_1 + C_1 / C_3)} \begin{vmatrix} i_1 - i_2 & -i_2 + \Phi(\Psi) \\ C_1 & C_3 \end{vmatrix}.$$

Overvoltage in isolated neutrals of power transformers has been studied under conditions of three phase and open-phase switching, and of switching off of a line with idle transformers. The calculation results allow to state that the presence of active load on the transformer significantly affects a value of overvoltage in case of ferroresonance.

Conclusion.

1. In the networks 110–220 kV malfunction of normal operation of insulation of lines and electrical equipment of substations may occur due to lightning and internal overvoltage. This is due to non-compliance with electromagnetic compatibility in a high-voltage electric power system between insulation, overvoltage and main protection devices which are valve-type arresters.

2. In order to ensure coordination of insulation and electromagnetic compatibility effective protective devices – OVL – can be applied with success. However unreasonable choice and incorrect arrangement of those protective devices in operation lead to negative consequences. Therefore, predicting the characteristics and the proper operation of OVL of any voltage class is essential.

3. Lightning overvoltage is dangerous for insulation of the neutral of power transformers of 110–220 kV, so it is necessary to protect it with valve-type arresters or nonlinear OVL.

4. In open-phase switching of dead-end lines with idle transformers in the network ferroresonance may occur between nonlinear inductance of the transformer and capacitance on the ground of unswitched phases. Ferroresonance occurs when the following conditions are combined: all transformers connected to the line must have an isolated neutral, and switching of the line in the open-phase mode should take place with switching angle within the range of 0–10 degrees (either in two-phase switching mode one of the phases must have the same switching angle).

5. Overvoltage arising due to ferroresonance is dangerous for lightweight insulation of the neutral and results in failure of valve-type arresters. Switching of the active load (from 5 to 15%) first reduces ferroresonant overvoltage in the neutral, and further eliminates the occurrence of resonance.

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