Types of overvoltages in 10-35 kV distribution networks and modern methods and means of their limitation

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Abstract. The basis for the transmission of electrical energy from sources to receivers are overhead power lines 10–35 kV. In these networks, an isolated transmission line or transmission line, grounded through resistors or using arc-quenching reactors, is used. The Republic of Mari El uses networks with isolated transmission line, the total length of which is more than 7000 km. When operating distribution networks, their insulation is affected by a number of internal factors such as long-term operating voltage and voltage fluctuations, short-term overvoltages associated with arc closures, wire breaks, and insulation overlaps. These networks are located on an open area, so they are exposed to lightning overvoltages, temperature, wind loads (mechanical forces), precipitation (snow, humidity). Overvoltages occurring in electrical systems are one of the main factors that significantly affect the reliability of power supply. Despite the short-term effects, overvoltages are characterized by a high multiplicity with respect to the long-term operating voltage, the impact on all electrically connected elements of the system, regardless of the place of occurrence. Overvoltage is the main cause of defects and accelerated aging of structural components. Currently, 90 % of 10-35 kV overhead lines are made on the basis of the use of reinforced concrete structures of supports that require grounding devices, depending on the value of the soil resistivity. High-speed vacuum circuit breakers are used as switching devices in modern distribution networks of 10–35 kV. The specific properties of vacuum as an arc-quenching medium contribute to the transients in their switching, which require scientific understanding.

1. Introduction
Currently, according to GOST 1516.3-96 [1], the maximum voltage of electrical equipment is set, coinciding with the upper limit of the long-term permissible voltage in the electrical network. The values of the highest operating voltages for the network with different nominal voltage $U_{\text{nom}}$ are given in Table 1.

The following characteristics are used to estimate the magnitude of overvoltages: multiplicity, repeatability, curve shape and network coverage.

Multiplicity is the ratio of the maximum value of the $U_{\text{max}}$ voltage to the amplitude of the maximum operating voltage for a given insulation structure (Figure 1): $K = U_{\text{max}} / U_{\text{ov}} (U_{\text{op}})$. However, in measurements or calculations to determine the multiplicity, $U_{\text{max}}$ is usually referred not to the magnitude, but to the actual amplitude of the operating voltage that occurs immediately before the appearance of the overvoltage or established after it. This definition of K does not contradict the above definition, since it is assumed that the value of $U_{\text{max}}$ is proportional to the operating voltage, and when the voltage rises to the highest operating voltage, the magnitude of the multiplicity does not change.
Table 1. Nominal and maximum voltage of electrical equipment [kV]

| Voltage class of equipment | Maximum operating voltage of electrical equipment | Rated voltage of electric network | The maximum permissible operating voltage in the electrical network |
|-----------------------------|--------------------------------------------------|---------------------------------|---------------------------------------------------------------|
| 10                          | 12.0                                             | 10.0                            | 11.5                                                          |
|                             |                                                  | 11.0                            | 12.0                                                          |
| 15                          | 17.5                                             | 15.0                            | 17.5                                                          |
|                             |                                                  | 15.75                           | 17.5                                                          |
| 20                          | 24.0                                             | 20.0                            | 23.0                                                          |
|                             |                                                  | 22.0                            | 24.0                                                          |
| 35                          | 40.5                                             | 35.0                            | 40.5                                                          |

Figure 1. Waveform of overvoltage

Repeatability is determined by the expected number of cases of overvoltage in a given period of time, for example, per year.

The shape of the overvoltage curve is determined by the length of the front, the duration and number of pulses and the duration of the existence of the overvoltage.

Network coverage is number of insulation structures that are simultaneously affected by a given overvoltage [2–4].

All of these overvoltage parameters are usually random and have statistical characteristics.

Depending on the location of the application, different types of overvoltages can be distinguished: phase, inter-phase, intra-phase, between contacts.

Phase overvoltages are of the most practical importance. They act on the isolation of live parts of electrical equipment from the ground or grounded structures. A phase voltage is normally applied to this insulation. However, in networks with isolated transmission line, it should be borne in mind that in the process of finding a ground fault (lasting from minutes to several hours), a line voltage can be applied to the phase isolation.

Phase-to-phase overvoltages are considered when choosing phase-to-phase isolation, for example, distances between wires of different phases on lines and substations, windings of different phases of transformers, machines, reactors. The operating voltage for these types of isolation is line voltage [5–7].

Intra-phase overvoltages occur between different current-carrying elements of the same phase, for example, between adjacent turns or coils of the transformer winding, as well as between the transmission line and the ground.
2. Research Method

Depending on the cause of "generating" there are two groups of overvoltages: external and internal, which develop due to the energy of generators connected to the network or reactive elements (L, C), as well as due to various resonant processes, accidents and switching elements network, including re-ignition of the electric arc.

The classification of external overvoltages is shown in Figure 2.

![Figure 2. Classification of external overvoltages](image)

External overvoltages in high-voltage electrical networks occur when a direct lightning strike in the elements of the electrical network (supports, cable, wire). At high current values (50 kA and above), a direct lightning strike leads to overlapping and destruction of insulation. Inducted overvoltages are the result of mutual magnetic (inductive) and electrical (capacitive) connection of the lightning channel with current-carrying and grounded elements of the electric network. They have a significantly moderate value in comparison with overvoltages when striking current-carrying and grounded parts of the electrical installation. The induced overvoltages are dangerous for the insulation of networks of 10–35 kV.

Overvoltage pulses can also affect the insulation of substations located at a considerable distance from the impact site on the line, as they propagate along the line for considerable distances with little attenuation. These are called surge of the incoming waves. They can be a danger to substation electrical equipment, which has lower electrical strength reserves compared to linear insulation. For economic reasons, cable protection is not used on 10-35 kV air lines, so when insulation is overlapped and when induced overvoltages, a significant part of them is distributed along the air lines. In addition to this, the overvoltages arising at the substation, as a rule, exceed the voltage of the incoming wave due to wave processes at the busbar and in electrical equipment. Being distributed on windings of cars and transformers, waves can influence their main and turn isolation, and passing through the transformer they influence the isolation of the electric equipment connected to their other windings.

The share of failures caused by internal overvoltages in 10-35 kV distribution networks with isolated transmission lines is 80 % of all types of failures. The largest number of failures is due to overvoltages with arcing ground faults. The following group of internal overvoltages is associated with switching in distribution networks: switching on and off inductive and capacitive elements, resetting loads. In a separate group includes over-voltage, caused by abnormal modes in the distribution network: the offset of the transmission line, load dump, short circuit protection.

The classification of internal overvoltages is shown in Figure 3.

![Figure 3. Classification of internal overvoltages](image)

3. Results and Discussion

To protect against atmospheric overvoltages, cable and rod lightning protectors, as well as protective devices such as nonlinear overvoltage arresters, valve arresters, long spark gaps in combination with high-voltage surge arrester (long-spark arresters) are used.

Protection of approaches of overhead power lines of transmission of 10–35 kV to substations is carried out with use of long spark gaps of type LSA (Figure 4). Their feature is a phase-by-phase installation to the approaches of the substation on three spans of one set of LSA. The disadvantage of using LSA is the increased requirements for grounding devices for each set in a phase-by-phase installation, which leads to significant material costs.
Figure 3. Classification of internal overvoltages

High-voltage surge arrester with spark gap (Figures 5, 6) is used on the traverse of straight sections of the line to protect against induced lightning overvoltages.

Figure 4. The image of a LSA

Figure 5. A high-voltage surge arrester with spark gap

Arrester RMKE-20-IV-UHL1 refers to multi-chamber dischargers screen type. It protects overhead power lines of three-phase AC voltage classes with uninsulated and shielded wires from direct lightning strikes as well as indirect shocks that cause induced lightning overvoltages. Arresters of RMKE-20 type are installed on any types of supports and insulation.

Figure 7 shows the main types of grounding used in electric networks of 10–35 kV. The device of lightning grounding is not usually made, and grounding devices of working and protective grounding are used.

However, the values of their resistance are significant and range from 0.5 to 4 Ohms for industrial frequency currents, and their values depend on the resistance of the soil. For effective work of means of protection of networks against external overvoltages it is necessary to connect protective devices to the grounding devices having impulse resistance of grounding less than 0.5 Ohm.

Lightning protection groundings are designed to protect against direct lightning strikes on the electrical installation, incoming waves on power lines, and induced overvoltages in case of lightning strikes on grounded structures or trees near electrical installations. For reliable operation of the
protective devices listed above, it is necessary to provide grounding devices, which should ensure a low value of impulse resistances.

Figure 6. A high-voltage surge arrester with spark gap

Figure 7. Grounding in electrical installations

The reduction of impulse resistance of grounding is achieved by increasing the number of horizontal and vertical electrodes. The length of the vertical electrodes laid in the ground should be greater than the depth of soil freezing. The ground freezing For the Volga-Vyatka region is 1.95 m.

The grounding device which is executed with observance of requirements to its design shall have activity impulse resistance no more than 0.05 Ohm during a thunderstorm.

The impulse resistance of the grounding conductor $R_{im}/R_i$ at lightning current flow $I_m/I_i$ and the spreading resistance of the industrial frequency $R_{im}$ are related by the ratio [2]:

$$R_{im}/R_i = \alpha_{im/i} R_{im}/(\eta_{im/i} n),$$

where $\alpha_{im/i}$ is the impulse coefficient of the grounding conductor; $R_i$ is the resistance of the grounding during the flow of current of industrial frequency; $\eta_{im/i}$ is the impulse coefficient of use of grounding devices; $n$ is the number of vertical groundings.

The resistance of the grounding conductor of the substation in the form of a grid, which consists of vertical electrodes connected by horizontal stripes, is calculated by the empirical Equation (2):

$$R = \rho_{cal} \left( A L + \frac{1}{S} \right),$$

where $L$ is the total length of all horizontal grounding electrodes (strips); $n$ and $l$ are number and length of vertical electrodes; $S$ is the area occupied by the grounding conductor; $\rho_{cal}$ is the resistivity of the soil; $A$ is the coefficient determined by the value of $l/\sqrt{S}$ according to Table 2:

| $l/\sqrt{S}$ | 0   | 0.05 | 0.1  | 0.2  | 0.5  |
|-------------|-----|------|------|------|------|
| $A$         | 0.44| 0.40 | 0.37 | 0.33 | 0.26 |
The approximate values of the impulse coefficient $\alpha/i$ for grounding conductors in the form of grids are determined by the formula (3) or by the graph shown in Figure 8. For broaching groundings ($\sqrt{S} > 10$ m) the pulse coefficient can be estimated by the approximate formula:

$$\alpha_i = \frac{1500\sqrt{S}}{\sqrt{(\rho_{cal} + 320)(I_m + 45)}}, \quad (3)$$

where $S$ is the transformer substation area, [m$^2$]; $\rho_{cal}$ is the calculated value of soil resistivity, [Ohm-m]; $I_m$ is the lightning current, [kA].

Figure 8. Values of impulse coefficient for grounding devices in the form of grids for calculated values of soil resistivity, where $\rho_{cal} = 100…600$ [Ohm-m]

- Zone 1–2: the lightning current $I_m/l = 10$ kA
- Zone 3–4: the lightning current $I_m/l = 100$ kA

The calculated value of $\rho_{cal}$ is determined by:

$$\rho_{cal} = k \cdot \rho_{izm}, \quad (4)$$

where $k$ is the coefficient of seasonality ($C = 1.2…4.5$), depends on the soil moisture; $\rho_{izm}$ is measured value of soil resistivity.

4. Conclusion

10–35 kV overhead lines are subject to external and internal overvoltages, which have their own classification depending on the source of overvoltages. To ensure reliable power supply and overvoltage protection, cable and rod lightning rods are used, as well as protective devices: nonlinear overvoltage limiters, valve arresters, long spark gaps. The performance of protective devices is influenced by the parameters of grounding devices.

References

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