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THERMAL STABILITY OF OVERHEAD POWER TRANSMISSION LINES UNDER GROWING SHORT-CIRCUIT CURRENT LEVELS

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Since early 2000s, an increase in the levels of short-circuit (SC) currents has been observed within the electric power systems of the Russian Federation, including 110 and 220 kV networks. This problem is especially important in the regions with high density of electric power plants and relatively short distances between network nodes. As the level of short-circuit currents increases, the issues of thermal and electrodynamic stability of the electrical equipment, and first of all, equipment which has completed its standard service life, become of primary importance. The paper discusses the issues of thermal stability of the overhead power transmission lines (OPTL), offers analysis of the calculation results related to wire heating by SC currents in more than 1000 OPTL operating at 35 – 220 kV of voltage, and provides recommendations for ensuring thermal stability of OPTL.

Keywords: thermal stability; overhead power transmission lines (OPTL); short-circuit current.

The OPTL thermal stability calculation consists of determining the heating temperature (ϑ_{sc}) of the wire by the time of short-circuit clearing and comparing this temperature with the maximum allowable heating temperature during SC ($\vartheta_{sc\ alw}$). A conductor satisfies the thermal stability condition if the following inequality holds true:

$$\vartheta_{sc} \le \vartheta_{sc\ alw}. \tag{1}$$

The maximum allowable heating temperature of the wires during SC has been specified by GOST R 52736 [1] and Electrical installation code (PUE) [2]. For example, for the aluminum portion of steel-aluminum wires, this temperature is equal to 200°C.

When calculating thermal stability of the wires, the following assumptions are usually made: the process of heating of the wires is considered adiabatic during SC lasting less than 1 sec, the current density and temperature are assumed to be uniform in the cross-section of the aluminum portion of steel-aluminum wires, and temperature dependences of heat capacity and active resistance of the conductor materials are assumed to be linear. In addition, in steel-aluminum wires, the heat transfer between the steel and aluminum portions of the wire, as well as magnetic losses in the steel core are neglected.

The calculated SC duration t_{sc} (sec) can be determined as follows:

$$t_{sc} = t_{sig} + t_{prot} + t_{clear}, \tag{2}$$

where t_{sig} is the time required to form a signal to disconnect the switch (time setting of relay protection actuation), sec; t_{prot} is the intrinsic actuation time of the relay protection, sec; and t_{clear} is the total switch clearance time, sec.

In the presence of automatic circuit reclosers (ACR), according to [1], the total thermal effect of the SC current is considered if the reclosing fails, and the calculated duration of SC is determined as a sum of durations of the first and second SC. According to [1], a decrease in the wire temperature during the reclosing dead time is neglected.

The calculation of the wire temperature by the time of short circuit clearance comes down to solving the equation of heat balance under adiabatic heating of the wires made of a uniform material (aluminum, copper and their alloys) or the conducting aluminum portion of steel-aluminum wires, which can be written as follows:

$$i^2 R_\vartheta dt = c_\vartheta m d\vartheta, \tag{3}$$

where i is the instant SC current value, A; R_ϑ is the active resistance of the wire at temperature ϑ, Ω; c_ϑ is the specific heat capacity of the material at temperature ϑ, J/(kg · K); and m is the mass of conducting portion of the wire, kg.

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Within the heating temperature range of 300 to 400°C, both the active resistance and specific heat capacity can be presented as follows:

$$R_\vartheta = R_0(1 + \alpha\vartheta); \tag{4}$$

$$c_\vartheta = c_0(1 + \beta\vartheta); \tag{5}$$

where R_0 is the wire resistance to direct current at 0°C, Ω; α is the temperature coefficient of electric resistance, 1/°C; c_0 is the specific heat capacity of the material at 0°C, J/(kg · °C); and β is the temperature coefficient of heat capacity, 1/°C.

The values of α, c_0 and β for various wire materials are provided, for example, in [3] and constitute: for aluminum — $\alpha = 0.00403$, $c_0 = 886$ and $\beta = 0.000534$; for copper — $\alpha = 0.00396$, $c_0 = 384$ and $\beta = 0.000271$; for steel — $\alpha = 0.00600$, $c_0 = 437$ and $\beta = 0.001076$. The values of wire resistance to direct current are assumed based on the wire manufacturers' data, or, if such data are unavailable, are taken from GOST 839 [4].

The resistance of the conducting portion of the wire can be conveniently presented as:

$$R_0 = \frac{\rho_0 l}{S}, \tag{6}$$

where ρ_0 is the specific electric resistance of the conducting portion of the wire at 0°C, Ω · mm²/m; l is the length of the wire, m; and S is the cross-sectional area of the conducting portion of the wire, mm².

The mass of the conducting portion of the wire (kg) is equal to:

$$m = \lambda/S, \tag{7}$$

where λ is the density of the material of the conducting portion of the wire, kg/(m · mm²).

For the split-phase OPTL, cross-section S is assumed to be equal to the total cross-section of the phase conductors.

If the OPTL reveal defects associated with wear or damage of the conducting portion of the wires, the wire resistance shall be increased directly proportionally to the wear of the cross-sectional area. If no reliable data about the wear is available, it is safe to assume (according to [5]) that for steel-aluminum wires with the service life of more than 35 years, the cross-sectional area of the conducting portion of the wire is 17% less than the nominal value.

After transformations, differential equation (3) can be rewritten as follows:

$$\frac{B_\mathrm{c}}{S^2} = A(\vartheta_\mathrm{f}) - A(\vartheta_\mathrm{i}), \tag{8}$$

where $B_\mathrm{c} = \int_0^{t_\mathrm{sc}} i^2 dt$ is the Joule integral, which determines the degree of thermal effect of SC current, A² · sec; ϑ_f and ϑ_i are the final and initial heating temperatures of the wire, °C; $A(\vartheta_\mathrm{f})$ and $A(\vartheta_\mathrm{i})$ are the values of the function, which is determined by the physical properties of the material of the conducting portion of the wire:

$$A(\theta) = \frac{c_0 \lambda l}{\rho_0}\left(\frac{\beta\theta}{\alpha} + \frac{\ln(\alpha\theta + 1)(\alpha - \beta)}{\alpha^2}\right). \tag{9}$$

For 35 – 220 kV electrical networks, the calculation of the Joule integral without considering a change in the periodic component of SC current results in the following formula [1]:

$$B_\mathrm{c} = I_\mathrm{p0}^2\left[t_\mathrm{sc} + T_\mathrm{a}\left(1 - e\left(-\frac{2t_\mathrm{sc}}{T_\mathrm{a}}\right)\right)\right], \tag{10}$$

where I_p0 is the effective value of the periodic component of SC current at the initial moment of time at the OPTL reference point, A; T_a is the time constant of the aperiodic component of SC current, sec.

The initial temperature ϑ_i is determined based on the solution of the equation of heat balance of the wire under the operating steady-state condition preceding SC. In this case, the following factors are taken into account: heating of the wire by operating currents, heating from solar radiation, radiation heat flux, as well as heat flux caused by mixed convection (free/forced in case of calm weather of light breeze) or just forced convection (if wind speeds exceed 3 – 5 m/sec). The solution of the equation of heat balance for wires and other similar conductors is provided in [5, 6].

Considering "safety margin," the initial temperature of the wire can be assumed equal to a continuous heating temperature, for example, 70°C for steel-aluminum wires.

Based on the considered solution, a study of thermal stability was conducted on more than 1000 lines operating at 35, 110 and 220 kV. For this purpose, an OPTL database was created and calculation model of the studied network was developed.

The database includes the following parameters: OPTL wire brands, year of OPTL commissioning and reconstruction, length of the lines, support-based OPTL diagrams, types of OPTL disconnect switches, total clearance time, operating time of the main and reserve protections.

The network model was developed using Neplan software based on the actual calculation scheme of the 35 – 750 kV network. The inter-system connections are accounted for in the calculation scheme by the equivalents of the networks of the neighboring regions. By using the software, the values of electric currents during SC occurring at the beginning and at the end of all OPTL were calculated, and the effective values of the periodic components of one-, two-, and three-phase SC currents as well as time constants of aperiodic components of SC currents were determined.

To establish the thermal stability of the wires, the maximum values of single- or three-phase SC currents were chosen in the first or last span of the dual-fed OPTL, or at the beginning of the single-fed line. These values were entered into the database. In case of a change in the OPTL wire cross-section, the calculations were done for each section of the line. This provided the possibility to assess thermal stability of the design spans (typically, end spans).

A program for calculating the final heating temperature of the wires during SC was developed, which allows calculating a large number of lines from the database. Calculations of thermal stability during a single SC, reclosing failure, or activation of a circuit breaker failure protection device were performed. Earlier, to determine the initial wire temperature, a procedure and program were developed to calculate the heating of the OPTL wires considering free/forced convection heat transfer, solar radiation and other factors according to the recommendations provided in [3]. However, considering the analysis of the scheme and network operation modes, the major volume of thermal stability calculations was carried out at the initial temperature equal to the continuous heating temperature, i.e., 70°C. In case of the problem lines (in terms of thermal stability), the initial temperature was revised by taking into account the maximum possible operating load, highest ambient temperature and maximum solar radiation.

The analysis of the database parameters of the studied 220 kV OPTL demonstrated the following: the database includes the parameters of 148 lines; about 90% of these lines utilize steel-aluminum wire with 400 mm^2 cross-section (hereinafter, the cross-section of the conducting portion of the wire is specified); the smallest cross-section of the utilized steel-aluminum wires is also equal to 400 mm^2; the OPTL clearance is mainly performed by the gas-insulated switches of various types, such as: ELK-14, VGBU-220, 8DN9-6, etc., while several lines are cleared using U-220 switches. The database also includes 737 OPTLs operating at 110 kV: more than 78% of the lines utilize steel-aluminum wire with 150 mm^2 cross-section, 15% — 120 mm^2; one line has spans with steel-aluminum wires of 70 mm^2 cross-section; three lines are entirely composed of or have spans made of steel-aluminum wires with 95 mm^2 cross-section; about one third of the OPTL are cleared by gas-insulated switches of various types, and the rest — by oil switches, such as: MKP-110M, U-110, VMT-110, etc.; many single-fed lines are equipped with short-circuit throwing switches at the tail stations. The database also contains parameters of 336 OPTL operating at 35 kV: almost 37% of the lines utilize steel-aluminum wire of 70 mm^2 cross-section, 29% — 95 mm^2 and 33% — 120 mm^2; an insignificant portion of these lines utilizes the wire with 150 mm^2 cross-section; the smallest cross-section of the utilized steel-aluminum wires is 50 mm^2; the spans of 45 (13%) lines are made of the wire with such cross-section; the lines are cleared by oil and vacuum switches of various types.

The SC current calculation results have confirmed that the maximum currents and, therefore, the greatest thermal exposures are experienced by the 110 and 220 kV OPTL,

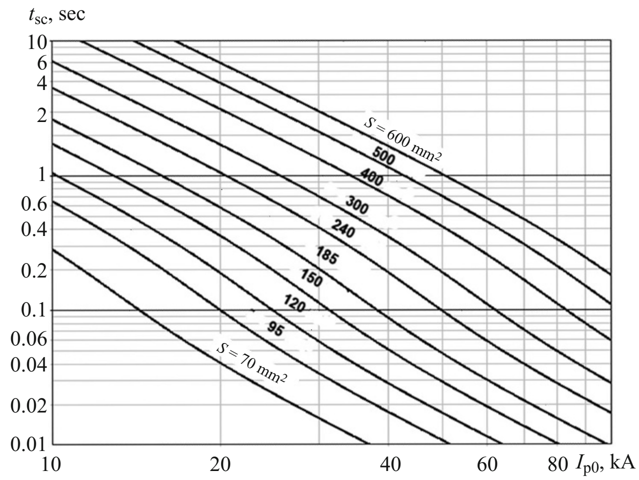

Fig. 1. Maximum allowable SC durations and currents based on thermal stability requirement for steel-aluminum wires.

which are electrically close to large power plants and substations under the voltage of 500 and 750 kV. On the 110 kV lines, in a number of cases, a single-phase SC current exceeds that of the three-phase SC by 10% or less. The maximum values of the SC currents are as follows: 220 kV OPTL — 57.5 kA, 110 kV OPTL — 44 kA, 35 kV OPTL — 8 kA.

It should be noted that on 97.2% of the 110 kV lines, the SC currents do not exceed 35 kA (constitute no more than 80% of the maximum current). About 1.5% of the 110 kV lines experience SC currents in the range of 80 – 90% of the maximum value, and less than 1.3% of the OPTL experience higher current values (up to 100%).

When calculating the OPTL thermal stability, SC duration was determined based on Eq. (2). The intrinsic microprocessor protection time was assumed to be equal to 50 msec. Depending on the switch type, the total clearance time varied from 35 to 80 msec. Since the main means of protection of all surveyed OPTL were of differential types, for calculation purposes, the time setting was assumed to be equal to zero, or 0.5 sec if the circuit breaker failure protection was active.

Thus, the SC duration was as follows: under normal operation of the protections and switches — 85 to 130 msec; in case of automatic reclosing, the total SC duration doubles and constitutes 260 msec for selected lines; in case of the circuit breaker failure protection activation — from 0.585 to 0.63 sec.

The calculations of the heating temperature of the wires were conducted during SC at the beginning (and also, at the end, in case of a dual power supply) of all lines with active main and reserve protections. For the ease of analysis of the results, nomograms of the dependence of the allowable short circuit duration on the effective value of periodic SC current component were plotted for wires of various cross-sections. As an example, Fig. 1 shows a nomogram for steel-alumi-

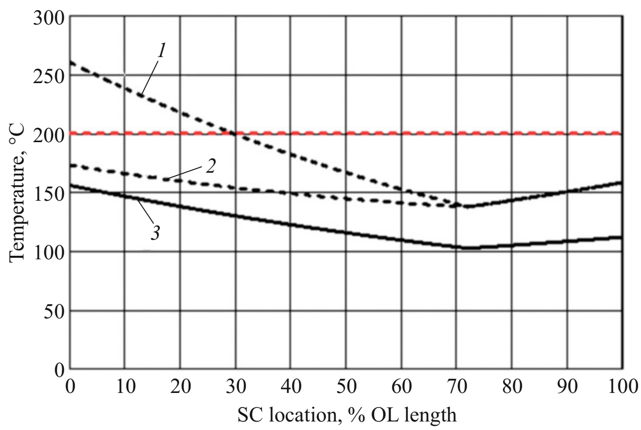

Fig. 2. Maximum calculated wire temperature of the 110 kV dual-fed OPTL as a function of SC location: *1*, ACR failure; *2*, ACR failure with reclosing from the side of a less powerful source; *3*, no ACR.

num wires obtained at the time constant of aperiodic component of SC current equal to 0.1 sec.

As can be seen from the provided nomograms, for the wires with 400 mm^2 cross-section (minimum allowable for 220 kV OPTL) and SC lasting for 130 msec (i.e., in case of successful automatic reclosing and operation of the main protection), the allowable value of SC current (based on thermal stability requirement) constitutes 72 kA, which exceeds the maximum calculated value of 57.5 kA. Moreover, in case of the circuit breaker failure protection activation and SC lasting for 0.585 sec, all lines remain thermally stable at this level of SC currents.

The 110 kV OPTL wires having cross-section of 70 and 95 mm^2 (even under successful reclosing) are in the risk zone in terms of the thermal stability requirements, since their allowable currents are equal to 13 and 18 kA, respectively, which is much less than the maximum rated SC current value of 44 kA. For the most common wire cross-section of 120 mm^2, the allowable current is equal to 22 kA, which is also less than the maximum rated value. The calculation analysis has shown that more than half of the 110 kV lines do not have sufficient reserves in terms of the thermal stability requirements, and do not allow for any further increase in SC currents.

Upon reclosing, 58 lines operating at 110 kV do not comply with the thermal stability requirements if the reclosing is done using a more powerful source.

According to [1], switch failure and circuit breaker failure protection activation with the time delay of 0.5 sec do not represent the design case for OPTL testing for thermal stability. However, the vast majority of 110 kV lines do not pass such testing, and moreover, the calculated temperatures of the main spans of about 100 OPTL exceed the melting point of aluminum (660°C) upon switch failure or the circuit breaker failure protection activation. Upon activation of the reserve protection, it is also advisable to carry out an additional inspection to ensure maintenance of the structural integrity of the line. The criterion of such inspection could be the aluminum hot working temperature of 450°C.

It should be noted that when the calculated wire temperatures exceed 300 – 400°C, equations (4) and (5) are not quite accurate. Specifically, when the temperature of aluminum wire approaches 600 – 650°C, the resistance value calculated using Eq. (4) will be lower than the actual one by approximately 10%, and the heat capacity value calculated using Eq. (5) — by 4%. To improve the accuracy of calculations, a nonlinear approximation of the temperature dependences of heat capacity and active resistance should be used. Hence, if the calculated temperature falls into the range from 400 to 650°C, it should be noted that when using equations (4) and (5), the actual wire temperature will exceed the calculated value by approximately 5%.

The level of SC currents in the 35 kV OPTL is insignificant. All 35 kV OPTL meet the thermal stability requirements in case of automatic reclosing failure, or circuit breaker failure protection activation. Therefore, the issue of thermal stability of the OPTL wires is more relevant for the 110 kV networks.

It should be noted that SC currents at the beginning and at the end of the line may be very different even in case of a dual power supply. The wire temperature reaches its maximum values when short-circuit occurs at the main spans of the OPTL from the side of a more powerful source. Figure 2 provides graphs illustrating the relationship between the maximum calculated temperature of the wire and the distance from the SC location along one of the 110 kV OPTL.

The maximum allowable temperature of 200°C during ACR failure will only be exceeded if SC occurs within first 30% of the OPTL length (curve *1*). However, in case of reclosing from the side of a less powerful source (if ACR failed), the wire temperature will not exceed the maximum allowable value of 200°C (curve *2*).

The conducted studies have shown the following:

1. Due to an increase in the level of SC currents and variations in network configuration, it is imperative to strictly comply with the requirements of industry standards and PUE related to testing of thermal stability of OPTL wires, as well as switchgear busbars predominantly operating at 110 kV. When testing thermal stability of the lines that have been in service for a considerable period of time, the degree of wear of the wires should be taken into consideration.

2. For 35 and 220 kV OPTL, the thermal stability conditions are usually satisfied with sufficient margin.

3. All inspected 110 kV lines are in compliance with the thermal stability requirements in case of a single exposure to SC current.

4. In case of ACR failure, 7.9% of the inspected 110 kV dual-fed lines do not meet the thermal stability requirements upon reclosing from the side of a more powerful source. On the other hand, when reclosing from the side of a less powerful source, all OPTL remain thermally stable.

5. For 0.6% of 110 kV single-fed OPTL, the rated SC current constitutes about 90% of the maximum allowable value in terms of the thermal stability requirement (if ACR fails).

6. In case of the circuit breaker failure protection activation and maximum rated SC current, the wire temperature of the considerable number of lines exceeds 450°C (i.e., hot-working temperature of aluminum), and in some cases — 650°C (melting temperature of aluminum).

Thus, in addition to the typical measures to ensure thermal stability of the OPTL, such as: restriction of SC current levels by subdividing the network and installing current-limiting reactors, as well as reducing the SC duration by implementing modern high-voltage switches with the minimal short circuit clearance time, the following solutions are possible:

1) automatic reclosing from the side of a substation with the lowest level of SC currents for the single-fed lines;

2) OPTL reconstruction with an increase in wire cross-section on the main spans of the thermally unstable lines; discontinuing of ACR usage or significant increase in the reclosing dead time;

3) restriction of the OPTL load in order to decrease the maximum temperature of the wires under the normal operating conditions, and hence, the initial and final temperature during SC.

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