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The Calculations of Conductive Noise and Heating of the Screen in a Control Cable

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Abstract—Lighting strokes and short circuits (SCs) are the main sources of conductive noise that propagates along control cables and can lead to the failure of microprocessor equipment in the protection and control systems of electric power substations. Two-sided grounding of the screen of a control cable substantially reduces the pulse and high-frequency conductive noise level, but leads to heating of the screen under short-circuit conditions. The existing standards determine the conductive noise and screen heating as a function of screen voltage that is suitable for a single cable. A more general case that takes into account the cable magnetic coupling with other conductors when current is used as a calculation parameter has been considered. The conductive noise at the first pulse of lightning current is determined using the transfer impedance "screen—cable core" or 3D cable model in the general case. To calculate the heating, the formula of *GOST* (State Standard) *28895-91*, which is rejected in modern standards because of the assumption that short-circuit current is invariable (in fact, the current decreases with heating of the screen), has been used. Using this formula in a step algorithm leads to correct results. The cable magnetic coupling with other conductors is expressed as insertion impedance that increases the screen impedance and decreases the current and screen heating. A numerical experiment for a typical cable has shown that conductive noise and heating of the screen of the cable can be substantially reduced because of the parallel laying of conductors. It has been concluded that, to decrease the conductive noise and heating of the screen of a control cable, it is necessary to decrease the screen current.

Keywords: control cable, conductive noise, screen heating, transfer impedance, insertion impedance, step algorithm

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Lighting strokes, short circuits, and high-voltage equipment switching are sources of electromagnetic and conductive noise, which can lead to failure, damage, or false triggering of microprocessor equipment in the protection and control systems of electric-power substations.

Two-sided grounding of the screen of a control cable leads to a substantial decrease in the conductive high-frequency and pulse noise of a general type (cable core–screen) at the cable output. The conductive noise level can be determined by the voltage between points of screen grounding U, which is decreased by k times [1]

$$U_c = U/k, \quad (1)$$

where k is the screening (attenuation) coefficient.

Coefficient k is affected by the screen parameters, as well as by the point of current injection, points of screen grounding, characteristics of grounding device (GD), trace of cable routing, and presence of parallel conductors and is a function of the frequency or time at pulse processes. Therefore, Eq. (1) is associated with an error at normative $k = 6–10$ [1], while the design solutions under a decrease in the conductive noise, which are based on Eq. (1), may be insufficiently grounded.

Another, more general, approach to determining conductive noise is associated with using the screen current as a parameter $U_c = Z_t lI$, where l is the cable length and Z_t is the transfer impedance (coupling resistance) "screen–cable core," which is numerically equal to the screen voltage at a length of 1 m under flowing of a screen current of 1 A [2]. This approach has not been accepted in the Russian regulatory standards.

Two-sided grounding of the screen of a control cable entails a second problems for designers, to calculating heating of the screen under short-circuit conditions.

The conventional technique to calculate heating of a cable screen is determined by *GOST* (State Standard) *28895-91*,

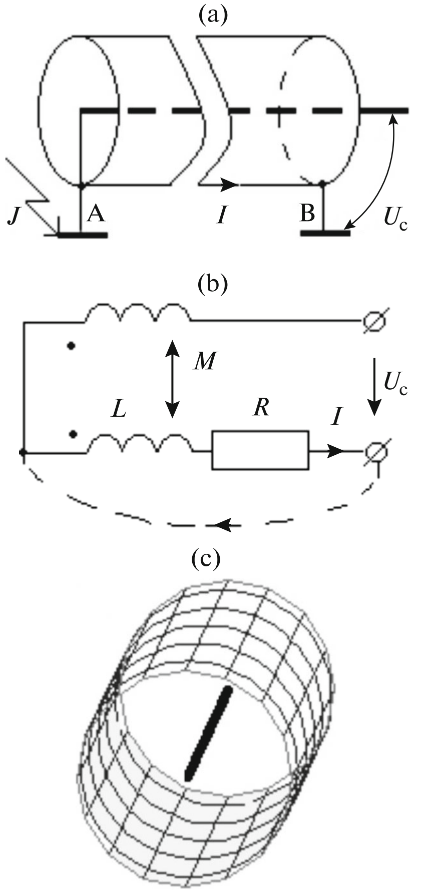

Fig. 1. (a) Physical model of a cable, (b) *RL* equivalent circuit, and (c) 3D model.

$$\theta_f = (\theta_i + \beta)\exp\left(\frac{I^2\tau}{\varepsilon(\tau)^2 S^2 K^2}\right) - \beta, \qquad K^2 = \frac{\sigma(\beta + 20)}{\rho_{20}}, \tag{2}$$

where θ_i and θ_f are the initial and final temperature, β is the parameter inversely proportional to the temperature coefficient of conductor resistance at 0°C, I is the short-circuit current, τ is the short-circuit duration, $\varepsilon(\tau)$ is the coefficient that describes the heat removal to neighboring elements, S is the sectional area of the screen, σ is the specific thermal capacity of the screen at 20°C, and ρ_{20} is the specific resistance of the screen at 20°C.

Equation (2) was obtained under the assumption that the short-circuit current is constant. Therefore, it leads to overestimated heating of the screen, since, in fact, the screen current decreases thanks to an increase in the screen resistance with increasing temperature. That drawback was eliminated in [3], in which, when deriving the equation of heating, the condition of current invariability was changed by the actual condition of invariability of screen voltage,

$$\theta_f = \sqrt{(\theta_i + \beta)^2 + \frac{2U^2\tau(\beta + 20)}{\varepsilon(\tau)^2 L^3 \sigma \rho_{20}}} - \beta, \tag{3}$$

where U is the voltage between points of screen grounding and L is the cable length.

A simplified version of Eq. (3) was used in the State Standard [4]:

$$\Delta\theta = 7\left(U/L\right)^{1.5}\sqrt{\tau}. \tag{4}$$

Thus, the modern approach to the calculations of conductive noise and heating of the screen of a control cable is based on the using screen voltage instead of current, which have been enshrined in regulatory standards. Substitution of voltage for current in the calculation expressions seems to be of little effect and may even have some advantages; however, it is valid for a single cable only if the magnetic coupling with GD conductors, voltage equalizing buses (VEBs), and neighboring cables and is not taken into account. It is easy to take these factors into account using screen currents instead of voltages as calculation parameters.

A typical task that needs to be performed by an engineer in the course of design is to reduce the conductive noise and heating. However, if it is identified with the problem of decreasing the screen voltage (according to the calculation expressions), optimal technical solutions can hardly be found. E.g., according to [4], it is recommended to lay a cable into a tube to reduce heating if the efficiency of the solution has been confirmed by calculations. When the cable is lain into a tube, the screen voltage slightly decreases at a GD dense net; therefore, this technical solution, which has the ability to substantially decrease the current and heating of the screen, will not be carried out.

This paper considers methods of calculations of conductive noise and heating of the screen of a control cable using the screen current as a calculation parameter.

Current pulse injection (at point A, Fig. 1a) leads to a drastic increase in the GD potential with respect to the potential of point B at a distance from a source. Without screen grounding, conductive noise $U = U_A - U_B$ will be applied to the input of a microprocessor device and can be higher than the admissible values. Two-sided grounding of the screen will lead to current flow through the screen I, a current that provides a decrease in the noise as low as U_c, i.e., by $k = U/U_c$ times.

In an important particular case, to calculate the conductive noise at the first pulse of a lightning current (equivalent frequency of 25 kHz), the capacitive coupling can be neglected and the *RL* circuit can be used (Fig. 1b).

Then, the core–screen voltage at the cable output is

$$U_c = RI + j\omega(L - M)I = Z_t lI,$$

where I is the screen current, R is the active screen resistance, L is the screen inductance, M is the mutual inductance between a core and screen, Z_t is the transfer impedance of a cable, and l is the cable length.

In the first approximation, $M = L$. Then,

$$U_c = R_0 lI,$$

where $R_0 = 0.018\ \Omega/\text{m}$ is the linear resistance of a copper screen of KBBGE cable at the given equivalent sectional area of a screen $S = 1\ \text{mm}^2$ [4]. This R_0 value is in agreement with measurements for cables with a diameter of 10–15 mm [3].

Thus, to calculate the conductive noise at the first pulse of a lightning current, it is sufficient to determine the current of a cable screen. The model of a screen with the shape of a thin-walled tube or rod with a diameter equal to the cable-screen diameter and linear resistance R_0 is suitable for these purposes, which allows one to calculate the conductive noise using any program for GD calculation.

To calculate the conductive noise at the second and subsequent pulses of lightning current (with a pulse front of 0.25 μs) or under the action of a high-frequency component of a short-circuit current (at frequencies of 1 MHz or higher), it is necessary to take into account the capacitive coupling between the screen and GD conductors, screen, and cable core. A 3D mesh model of a cable can be used for this purpose (Fig. 1c), a model that also allows one to calculate the conductive noise using GD calculation programs. There are some difficulties in the computing process (the small sizes of the cross section of a cable in comparison with its length require a substantial increase in the number of calculation elements), but they are not of critical importance, as has been shown in the program used for modeling grounding devices [5].

As an example, let us determine the core–screen noise at the output of a control cable placed at a height of 0.5 m above ground with a screen diameter of 10 mm, length of 100 m, and linear resistance $R_0 = 0.018\ \Omega/\text{m}$ upon injection of a lightning current pulse of 100 kA with a linear front of 10 μs into a cable (Fig. 2). The GD net is made up of steel rods with a diameter of 20 mm placed at a depth of 0.5 m under soil with specific resistance $\rho = 100\ \Omega$ m.

Calculations using 3D cable models are considered to be exact (Fig. 2, curve *1*). The cable behaves as an active-inductive circuit and makes smoother higher harmonics of the screen current that determines the conductive noise according to Eq. (5). The form of curve *2* (Fig. 2) calculated by Eq. (1) substantially differs from that of curve *1*; furthermore, the noise is lowered in most of the time interval. The actual attenuation coefficient determined at maximum is equal to $k = 13$, which is higher than the typical values ($k = 6$–10) thanks to the influence of GD and the point of current injection (at the cable head). A change in the point of current injection, improper grounding, and incorrect cable tracing decreases this coefficient. The results will also change at different conductivities of grounds and cable length. As has already been noted, the magnitude of coefficient k can hardly be generalized.

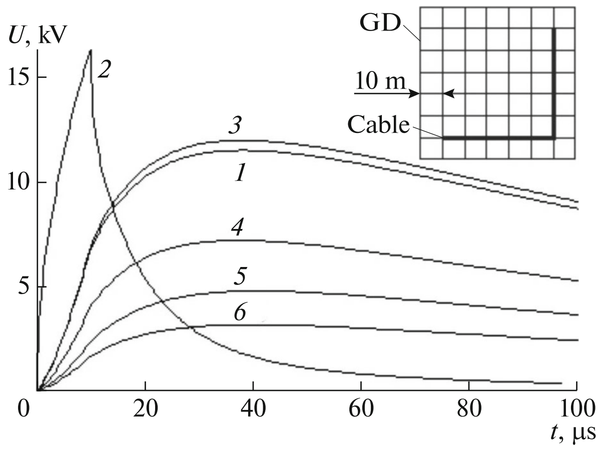

Fig. 2. Calculations of conductive noise: (*1*) using 3D cable model, (*2*) by Eq. (1) at $k = 10$, (*3*) by Eq. (5), with additional conductors: (*4*) VEB at distance of 0.1 m from the cable, (*5*) double VEB, (*6*) double VEB and GD with a step of 5 m instead of 10 m.

The results of calculations by Eq. (5) (Fig. 2, curve *3*) almost coincide with the exact solution of this and another problem. Equation (5) can be recommended to calculate the noise under the action of first pulse of lightning current.

A steel bus with a cross section of 50 × 5 mm^2 (VEB), which is laid at a distance of 0.1 m from the cable, shunts the screen current (using the galvanic and magnetic coupling) and decreases the noise by 1.6 times (Fig. 2, curve *4*). The second bus (at the opposite side from the cable) decreases the noise by another 1.5 times (Fig. 2, curve *5*). Thus, the use of voltage equalizing buses is an effective way to limit conductive noise. The control cables laid in the cable channel side by side act similarly. Note that the numerical values change with changing distance and position of the VEB with respect to the cable.

Let us reinforce the GD by halving the grid step, which will lead to an additional decrease in the noise by 1.5 times. Furthermore, the GD-input resistance (pulse) will decrease by 1.16 times (from 1.86 to 1.6 Ω); therefore, a decrease in the noise is again caused by the shunting action of GD conductors.

When solving the problem using the existing technique (1), the integration of two voltage equalizing busses decreases the screen voltage by 1.5% only, while reinforcing the grounding device decreases it by another 16%; i.e., the screen voltage in Eq. (1) changes slightly. The decrease in the noise is here caused by an increase in the attenuation coefficient because of the incorporation of the VEB. However, this coefficient is

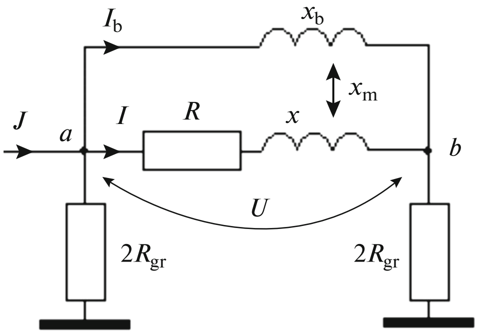

Fig. 3. Equivalent circuit for a cable with two-sided grounding of the screen and with a bus.

specific for each problem and can hardly be predetermined with sufficient accuracy.

Thus, Eq. (5) provides a more exact solution than does Eq. (1) for calculations of the conductive noise that occurs at the first pulse of the lightning current.

Let us consider the equivalent circuit of a cable with two-sided grounding of the screen parallel to which a steel bus is laid (Fig. 3).

The screen voltage is

$$U = RI + jxI + jx_m I_b \approx R + jx_m I_b/l = (R + \Delta z)I,$$

$$\Delta z = \Delta R + j\Delta x,$$

where I and I_b are the screen and bus currents, R and x are the active resistance and reactance of a screen ($R > x$), x_m is the mutual inductive impedance between the screen and bus, and Δz is the insertion impedance of a screen. In a particular case, at $\varphi_b = 0$ and $x = 0$ (Fig. 3), the bus current lags in phase from the screen current by $\pi/2$ and the insertion impedance is pure active resistance $\Delta z = \text{D}R$ and $\Delta x = 0$.

In the general case, the insertion impedance is affected in a complicated manner by all the longitudinal and flowing currents of grounding devices. Therefore, it can be numerically determined

$$\Delta z = U/I - R = \Delta R + j\Delta x,$$

where U and I are the cable voltage and current (complex values).

Thus, an increase in the screen resistance taking into account the insertion impedance leads to a decrease in the current and heating of the screen. To increase the insertion impedance, it will be necessary to decrease the resistance of parallel conductors (by increasing the cross section or number of busses) and enhance the magnetic coupling (by decreasing the distance between conductors and cable or laying the cable in a tube).

To calculate heating of the screen taking into account the magnetic coupling with other conductors, we should deal with currents as in Eq. (2). Let us show that, in this equation, the error associated with the assumption of current invariability during short circuit can be eliminated if the step algorithm is applied.

Let us divide a time interval by n equal steps with length h in such a way that the current can be taken as constant within a step. Then, the use of expression (2) will be justified. The heating temperature at the end of the nth step is

$$\theta_{n+1} = (\theta_n + \beta)\exp\left(\frac{I_n^2 h}{\left(\varepsilon_{n+1}(\tau)^2 SK\right)^2}\right) - \beta, \qquad (6a)$$
$$\theta_0 = 20°\text{C},$$

where all the variables are described in Eq. (2) and $\varepsilon_{n+1} = \varepsilon(t_{n+1})$.

Let us take into account the change in the active resistance of a conductor with change in the temperature:

$$R(0) = R_0\left(1 + \frac{\theta}{\beta}\right) = R_{20}\frac{\beta}{\beta + 20}\left(1 + \frac{\theta}{\beta}\right) = R_{20}\frac{\beta + \theta}{\beta + 2\theta},$$

where R_0 and R_{20} are the resistance at 0 and 20°C and $\beta = 234.5$°C for copper. Let us assume that the insertion impedance is unaffected by the temperature.

Then, if the screen voltages of the n and $(n + 1)$th step are equal, the current of the $(n + 1)$th step is equal to

$$I_{n+1} = \frac{z_n}{z_{n+1}} I_n = \frac{\left|R_{20}\dfrac{\beta + \theta_n}{\beta + 2\theta} + \Delta z\right|}{\left|R_{20}\dfrac{\beta + \theta_{n+1}}{\beta + 2\theta} + \Delta z\right|} I_n I_0 = I(0). \qquad (6b)$$

For a single cable ($\Delta z = 0$), we can obtain

$$I_{n+1} = \frac{\beta + \theta_n}{\beta + \theta_{n+1}} I_n. \qquad (6c)$$

As an example, let us calculate heating of a KBBGE cable with a length of 100 m with a copper screen with a cross section of 1 mm^2 ($R_{20} = 1.78\ \Omega$) at initial current $I = 250$ A; the process is taken to be adiabatic ($\varepsilon = 1$). The screen voltage $U = R_{20}I = 445$ V is taken to be constant during a short circuit. During the calculations using step algorithm (6a), (6c), the screen is heated up to 244°C for 1 s, which completely coincides with the calculations according to Eq. (3) here and in other cases. Thus, the solution according to Eqs. (6) is valid.

Then, let us calculate heating of the screen taking into account the magnetic coupling of a cable. Let a cable be laid along a GD (Fig. 2), an SC current be injected at the point of cable grounding and equal to 20 kA, and the SC duration be 1 s. Let us consider four cases: a cable interacting with GD conductors, then with the addition of a voltage-equalizing bus is added, addition of another VEB, and, finally, a halving of the GD cell size similarly to as in the problem in Fig. 2. For each case, let us calculate the current, voltage, and heating temperature of the cable screen; the results of calculations are listed in Table 1.

Table 1. Calculations of cable heating temperature

No.	Version (Fig. 2)	U, V/phase	I, A/phase	R_{20}, Ohm	Δz, Ohm	Heating temperature, °C	
						by Eq. (3)	by Eq. (6)
1	Cable, GD	551/52'	271/45'	1.78	0.24 + j0.25	328	291
2	Cable, GD, VEB	454/55'	189/41'	1.78	0.55 + j0.58	251	181
3	Cable, GD, two VEB	400/58'	144/39'	1.78	0.85 + j0.9	210	122
4	Cable, GD, two VEB, size of GD cell is 5	293/59'	98/38'	1.78	1.01 + j1.07	134	69

It follows from Table 1 that Eq. (3) obtained for a single cable taking into account just intrinsic resistance leads to the overestimated heating. In fact, the screen resistance is higher by magnitude of insertion impedance Δz; therefore, the screen current and heating are lower. The higher the number of parallel conductors, the greater the difference between the results of calculations according to Eqs. (3) and (6).

Thus, the existing calculation expressions obtained for a single cable overestimate heating of the screen to one extent or another.

CONCLUSIONS

The calculations of conductive noise and heating of the screen of a control cable in short-circuit conditions should be carried out taking into account the magnetic coupling between the cable and other conductors.

To calculate the conductive noise at first pulse of lightning currents, Eq. (5) is recommended; in the general case, a 3D cable model should be used.

To calculate heating, step algorithm (6) that allows one to take into account a decrease in the current during the heating and magnetic coupling of the cable can be used.

To reduce the conductive noise and heating of the screen of a control cable, the screen current should be decreased, which can be achieved by means of laying the parallel conductors in an GD, voltage-equalizing buses, or laying the cable in metallic tubes, troughs, etc.

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