ISSUES OF CHOOSING THE CROSS-SECTION OF 6-500 kV CABLE SCREENS

Mikhail Dmitriev, PhD
info@voltplace.com

The article is intended to draw attention to the fact that if there is significant uncertainty in the key source data when designing cable lines, then it makes no sense to use complex thorough methods of calculating and selecting cables – it is quite acceptable to replace them with simplified ones. One example is the choice of the screen cross section of single-core high-voltage cables.

When choosing a screen, the "exact" complex methodology of IEC 60949-2009 [1] is used, which allows, by modeling cable cooling, to refine the cross-section of the screen by 10-20% compared to what simple formulas give. However, both calculation methods use unreasonable values of the short-circuit current and its clearance time, which can change the screen cross-section up to 2-3 times compared to what is really necessary – against this background, the struggle for 10-20% related to accounting/non-accounting for cooling seems pointless at the moment.

Keywords: cable line, single-core cable, cross-linked polyethylene, screen cross-section, short-circuit, non-adiabatic process.

1. Introduction

Modern cable lines (CL) of high voltage 6-500 kV are built mainly by single-core cables, in the design of which there are conductive screens (usually made of copper wires). If the cable insulation is damaged, the short-circuit current (SC) from the cable core passes into its screen and then into the groundings located at the ends of the CL route (Figure 1).

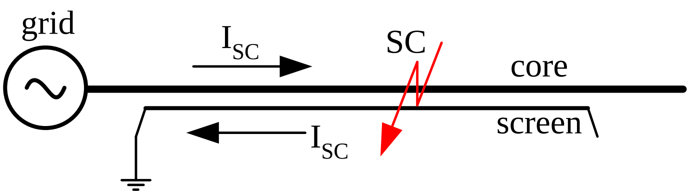

Fig.1. Short-circuit "core-screen" of a single-core cable.

The short-circuit currents pass through the screen and heats it to temperatures that can be dangerous for the insulation of cross-linked polyethylene (XLPE) adjacent to the screen. It is usually assumed that for XLPE insulation, the maximum permissible temperature for the time of short-circuit is 350°C. The selection of the screen cross-section F_S of a single-core cable is made from the condition of excluding overheating of the screen above the specified temperature.

A reasonable choice of the screen cross-section F_S will ensure that there is no dangerous overheating of the screen along the CL route and the XLPE insulation adjacent to it, that is, minimizes the consequences of short-circuit. If the screen cross-section F_S is selected incorrectly, in the case of a short-circuit, not only the repair of the original short-circuit place will be required, but also the complete replacement of those sections of the CL route on which, due to the passage of short-circuit currents, the screen overheated and the destruction of the XLPE insulation occurred.

Considering the above, there should be no doubt that the choice of the screen cross-section F_S for the short-circuit current I_{SC} and the clearance time t_{SC} is the most important part of the project documentation. It is also known as the "thermal stability checking".

At short-circuit, the temperature of the cable screen can be found by calculating the thermal balance, taking into account the process of cable screen heating due to short-circuit current and the process of cooling it due to heat removal into the XLPE insulation adjacent to the screen and the cable outer sheath. Since the time t_{SC} of the passage of the short-circuit current and heating of the screen is very limited (up to 3-4 s), the cooling processes do not have time to sufficiently affect the temperature, and therefore they are often not taken into account at all. Such heating of the screen, which does not take into account cooling, is called "adiabatic". On the contrary, if cooling is taken into account, the process of heating the screen is called "non-adiabatic". Let's compare these processes.

2. Adiabatic heating

The assumption of adiabatic heating of the screen makes it possible to simplify the choice of F_S, reducing it to the elementary formula justified in the book [1]:

$$F_S \geq I_{SC} \cdot \frac{\sqrt{t_{SC}}}{K_S} \qquad (1)$$

where F_S is the screen cross section (mm^2),
I_{SC} is short-circuit current (kA),
t_{SC} is short-circuit clearance time (s),
K_S is the proportionality coefficient.

If the screen temperature is 80°C before the short-circuit in normal mode (slightly less than the core temperature of 90°C, which is long-term permissible for XLPE insulation), then according to calculations [1] for a copper screen, $K_S = 0.174$ is valid.

Formula (1) for the case of adiabatic heating is given not only in the book [1], but also in the catalogs of most cable plants. It can also be obtained, for example, from IEC 60949-2009 [2], based on the expressions given there (paragraph 3 in IEC) and physical properties of materials (Table 1 in IEC). The difference between IEC and the book [1] is only in the system of designations used:

– the IEC screen section is S (instead of F_S);
– the IEC short-circuit current is I_{AD} (instead of I_{SC}).

Regardless of the designations system, the formula (1) for selecting the screen cross-section during adiabatic heating of screens is confirmed by various researchers and is very simple and convenient in everyday calculations.

3. Non-adiabatic heating

Of course, one can only welcome the work aimed at clarifying the selection of the screen cross-section F_S. At the same time, such work could be divided into two areas of research that do not depend on each other:

– clarification of the formula $F_S = f(I_{SC}, t_{SC})$ itself;
– clarification of the values I_{SC} and t_{SC} included in the calculations.

Clarification of the above formula $F_S = f(I_{SC}, t_{SC})$ is possible if we take into account the non-adiabatic nature of the process of heating the cable screen with a short-circuit current, that is, take into account that some heat has time to be transferred from the screen to the adjacent XLPE insulation and cable outer sheath. This calculation method is proposed in IEC 60949-2009 [2] and usually allows you to justify the admissibility of reducing the screen cross-section by 10-20% compared to the value of F_S calculated by the well-known simple formula (1) for the adiabatic process.

It is important to note that the methodology IEC [2] for taking into account the non-adiabatic process is based on a set of empirical correction coefficients that were obtained during a limited number of experimental studies and therefore cannot cause sufficient confidence, as stated directly in IEC. In addition, the results of calculations significantly depend on the initial data, which, as a rule, are still unknown at the CL design stage:

– diameter of each screen wire;
– number of screen wires;
– the gap between the wires;
– presence/absence of gap filling;
– materials in contact with screen wires;
– the presence of tapes superimposed spirally on top of the screen wires.

Taking into account all the above considerations, the methodology for calculations of the non-adiabatic process and the choice of the screen cross-section according to IEC [2] is more like a kind of divination than a calculation. Even if the CL designer somehow managed to accurately guess the numerous design features of the cable, which will eventually be purchased during the construction of the CL, and even if the designer correctly interpreted the rather confusingly stated provisions [2], then, at best, we are talking about the possibility of clarifying (reducing) the screen cross-section F_S by only 10-20%.

Is it worth spending time and efforts on the controversial accounting of the non-adiabatic process, which makes it possible to clarify the cross-section by 10-20%? Or is it better to start clarifying the choice of the screen cross-section F_S by sorting out the values of the short-circuit current I_{SC} and its clearance time t_{SC}, which are embedded in the calculations and are able to change the F_S section by 2-3 times at once?

Obviously, the clarification of the short-circuit current and the clearance time should be done first, but for many years of mass use of single-core cables with XLPE insulation, this work has not been carried out. Next, we will describe the problem in more detail.

4. The periodic component of the short-circuit current

To select the screen cross-section F_S by formula (1) or by any other method, reliable information is needed about the magnitude of the periodic component of the short-circuit current. We are talking about the following short-circuit currents:

- in 6-35 kV grid with an isolated (compensated) neutral, a double short-circuit current is required, calculated as $\sqrt{3}/2 = 0.87$ of the three-phase short-circuit current;
- in 110-500 kV grid with a grounded neutral, a single-phase short-circuit current is required.

Over the past 15 years, in a number of publications of the author, including in the book [1], attention has been paid to methods for calculating the longitudinal active-inductive impedances of cables, taking into account the screen cross-section F_S, its material and the bonding/grounding scheme. Despite this, in all regulatory documents (for example, [3]), as well as cable catalogs, still there are formulas that do not take into account the influence of screens. As a result, the real inductive impedance of the CL may be less than the calculated values [3], and therefore, the real short-circuit currents in cable networks will be greater than expected.

For example, according to [4], the use of correct longitudinal impedances of the short-circuit led to the fact that the value of the periodic component of the short-circuit current turned out to be higher than the initially assumed value obtained according to regulatory documents:

- by 15-20% for three-phase short-circuit;
- by 30-35% for single-phase short-circuit.

The short-circuit current is included in the numerator of the formula (1), and the screen cross-section is proportional to it. Therefore, an increase in the short-circuit current by 35% means that the final cross-section of the screen F_S will also grow by 35% (1.35 times). Thus, due to incorrect calculation of CL parameters and short-circuit currents of cable networks, at present, when designing CL, the cross-section of cable screens F_S is most likely selected less than the actual required values.

5. The aperiodic component of the short-circuit current

In general, the short-circuit current contains not only a periodic component, but also an aperiodic one. Both of these components cause heating of the cable cores/screens, and also, for example, determine the electrodynamic forces that arise between adjacent cables.

Regulatory documents and cable catalogs take into account both components in the calculations of the forces between cables necessary for the selection of cable clamp types, however, they propose to calculate the screen cross-section F_S by the periodic component only, omitting the aperiodic one, which is an error.

It is shown in [5, 6] that the aperiodic component of the short-circuit current is capable of noticeably increasing the screen temperature and, of course, should be taken into account when choosing F_S, for which the formula (1) can be adjusted by adding the coefficient K_A:

$$F_S \geq I_{SC} \cdot \frac{\sqrt{K_A \cdot t_{SC}}}{K_S} \tag{2}$$

The aperiodic coefficient K_A has a strict mathematical justification. It is calculated by a convenient expression given in [5, 6], and it can be $K_A = 1.0 \div 2.5$. For example, for a CL adjacent to an electric power station, with a clearance time equal to $t_{SC} = 0.4$ s, the value $K_A = 1.725$ is true (see Table 3 of [5]), which gives $\sqrt{K_A} = 1.31$.

It can be seen that in the considered example, taking into account the aperiodic component of the short-circuit current will lead to the need to increase the screen cross-section F_S by 31% (1.31 times) compared with the cross-section that would be found by formula (1).

6. Short-circuit clearance time

The catalogues of cable factories provide examples of using formula (1) for the case $t_{SC} = 1$ s. This is done not because this is the real time of switching off the short-circuit, but solely for the convenience of extracting the square root. However, sometimes they forget about this and mistakenly design the CL at the time $t_{SC} = 1$ s.

The real short-circuit clearance time t_{SC} consists of the following components:

– the response time of the relay protection (main or backup);
– operating time of the switch;
– the duration of the switch failure backup device.

In practice, the response time of the main and backup protections differs by an order. If the response time of the main protection can be, say, only 0.1 s, then the backup is up to 3-4 s. It is obvious that clear rules are needed that would allow, depending on the degree of responsibility of the CL, to choose the protection time and calculate the total time t_{SC} of the passage of the short-circuit current required to select F_S. The absence of these rules has been repeatedly stated [1, 5, 6], but regulatory documents still do not contain sufficient explanations about the definition of t_{SC}.

Let's assume that when designing the CL and choosing the screen cross-section F_S, it was decided that the time t_{SC} is determined not by the main protection, but by the backup, accounting for which, for example, led to a 3-fold increase in t_{SC}. Then in formula (1) instead of $\sqrt{t_{SC}}$ we get $\sqrt{3t_{SC}} = 1.73 \cdot \sqrt{t_{SC}}$.

It can be seen that in the considered example, the absence of regulated rules for choosing the short-circuit clearance time will lead to the need to increase the screen cross-section F_S by 73% (1.73 times) compared to the cross-section that was selected for the main protection.

7. Automatic reclosure accounting

The technical policy of electric grid companies prohibits automatic reclosure (AR) for CL. However, for mixed cable and overhead lines (ML) in our country, the AR cycle, as a rule, is still allowed. This means that for ML with short-circuit on the cable section (insertion, entry, tap) the short-circuit current will pass twice through the core and the screen of the damaged cable, increasing the heating and the required screen cross-section. That is why they are trying to introduce selective AR for ML [1, 6], when the AR is launched in the event of a short-circuit in the air section of the ML and is prohibited in case of a short-circuit on the cable section of the ML.

If AR is used on ML, but its selectivity is not ensured, then the choice of the screen cross-section of the cable section should take into account the risk of repeated passage of the short-circuit current, which can be done according to the formula (3):

$$F_S \geq I_{SC} \cdot \frac{\sqrt{K_{A1} \cdot t_{SC1} + K_{A2} \cdot t_{SC2}}}{K_S} \quad (3)$$

where t_{SC1} and t_{SC2} are the times of the first and second short-circuit passages; K_{A1} and K_{A2} are aperiodic coefficients for the first and second short-circuits.

If we assume that both clearance time t_{SC} and aperiodic components (coefficients K_A) coincide for two short-circuits, then taking into account $\sqrt{2} = 1.41$, we get:

$$F_S \geq 1.41 \cdot I_{SC} \cdot \frac{\sqrt{K_A \cdot t_{SC}}}{K_S}$$

It can be seen that in the considered example, the use of AR, which is not selective, led to the need to increase the cross-section of the screen F_S by 41% (1.41 times) compared with the cross-section that would have been selected with selective AR.

8. Conclusions

To select the screen section F_S, IEC 60949-2009 was introduced, which is believed to be "accurate" because it takes into account the cooling process of the screen and allows us to justify the possibility of reducing the screen section by 10-20% compared to the simplest formula (1), which does not take into account cooling.

The article showed that the cable screen cross-section F_S, although it depends on the accounting/non-accounting of cooling, but in fact it depends much more on the accuracy of taking into account:

- the magnitude of the periodic component of the short-circuit current;
- presence and attenuation of the aperiodic component of the short-circuit current;
- short-circuit clearance time;
- features of the AR.

Each of the four listed factors, independently of the others, is able to increase the screen cross-section F_S by 30-70% (1.3-1.7 times), and the total effect can increase the cross-section F_S by 2-3 times. For this reason, the situation seems really dangerous when the methodology for taking into account the listed factors is still missing in industry regulations, and the determination of short-circuit currents and times is carried out subjectively, based on the private personal opinion of each individual specialist.

Instead of paying attention to the importance of the problems of correctly accounting for all sources of screen heating (short-circuit current and its clearance time), which can significantly increase F_S, designers are required to thoroughly account for screen cooling in accordance with the ambiguous IEC 60949-2009, the main result of which is the justification of the possibility of reducing the F_S cross-section by 10-20% using unproven system of empirical coefficients depending on little-known design features of the cable.

According to the author of the article, at present the problem of choosing the screen cross-section F_S is not in accounting/not-accounting for barely noticeable cooling, but in the absence of legalized rules for setting key input data – the short-circuit current I_{SC} and time t_{SC}, which determine the screen heating and can increase the cross-section F_S by 2-3 times. Prior to the development of such rules, there is no point in fighting for 10-20% related to accounting/non-accounting of cooling. Thus, we can recommend:

– initiate the development of the standard "Checking the cross-section of cable screens according to the conditions of thermal resistance and non-combustibility", where to solve all the problems described in this article and studies by other authors;
– before the new standard appears, allow the use of simple formulas (1-3) instead of the IEC 60949-2009 methodology.

References

1. IEC 60949-2009 "Calculation of thermally permissible short-circuit currents taking into account non-adiabatic heating".
2. "High voltage cable lines"/M.V. Dmitriev. –St. Petersburg: Polytech-press, 2021. -688p.
3. STO 56947007-29.060.20.071-2011 "110-500 kV power cable lines. Conditions of creation. Norms and requirements" (as amended on 28.09.2021).
4. Dmitriev M.V. "Short-circuit currents in electrical networks containing modern 6-500 kV cable lines" // "Electric power. transmission and distribution", №3(78), 2023, pp.62-66.
5. Dmitriev M.V. "Screens of single-core cables 6-500 kV. Selection of the cross section taking into account the aperiodic component of the short-circuit current" // "Electrical Engineering News", №4(88), 2014, pp.34-37.
6. Alekseev V.G., Dementiev Yu.A., Smekalov V.V., etc. "Features of the choice of 110-500 kV cables for cable and cable-overhead lines" // " Electric power. transmission and distribution", №1(40), 2017, pp.84-92.