CABLE LINE CURRENT-CARRYING CAPACITY WHEN LAYING IN PIPES

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Over the past decades, there have been significant changes in cable networks associated with the emergence of modern high-tech polymer materials. So, the main insulation of high-voltage 6-500 kV cables became of cross-linked polyethylene (XLPE) instead of old-type oil-soaked paper. In addition, during pipe laying of cables, pipes made of polymer composition appeared instead of asbestos and steel. Taking into account the above, it is necessary to pay attention to a number of significant errors associated with an incorrect understanding of the impact of new pipes on the processes in cables.

Keywords: cable line, single-core cable, three-core cable, cross-linked polyethylene (XLPE), cable pipe, polymer pipe, current capacity.

1. INTRODUCTION

The successful experience of using polymer materials in the cable industry has led to the adjustment of approaches to the design, construction, operation of cable lines (CL). In particular, one of the key features of new CLs can be called an increase in the number of sections of the CL route on which cables are laid not in the open ground, but in the ground in polymer pipes – CLs are already known, where up to 90% of the entire line route is located in the pipes.

Polymer pipes allow you to lay an expensive cable underground with high quality. They bend well, do not have an abrasive effect on cables, do not heat up due to the influence of the alternating magnetic field of the cables laid in them. These pipes are resistant to mechanical influences, corrosion and aggressive environment, are securely connected to each other by butt welding, thereby allowing the formation of extended sealed pipe sections up to several hundred meters long, corresponding to the distance between adjacent cable joints.

Polymer pipes can be placed in the ground in an open way (in trenches) or in various closed ways, among which the most famous is the broaching of pipes in underground channels prepared by horizontal directional drilling (HDD). In these cases, pipes can protect the cable from external influences, reduce the amount of excavation work when laying new cables and their subsequent repair or replacement.

The requirements for polymer pipes for laying high-voltage CL are described in various industry standards. According to these requirements, cable pipes must have a whole list of important characteristics, including, for example:

- the ability to maintain properties throughout the service life of the cable (heat resistance under prolonged exposure to the temperature of the laid cables equal to 90°C or more);
- resistance of the inner layer to the spread of open flame (category FV-0);
- the possibility of cable testing and cable fault locating (CFL) of laid cables (polymer pipes must be transparent for the CL testing and locating current, that is, having the function of CFL).

Despite the fact that the regulatory documents correctly reflect many of the main issues of laying cables in polymer pipes, there is still no correct information about the nature of the influence of pipes on the current carrying capacity of CL. For example, it is mistakenly assumed that laying cables in pipes reduces the long-term permissible current by 10% compared to laying cables without pipes (that is, the correction factor for pipes is $K_P = 0.9$). Let's explain why this is not true.

2. LAYING IN PIPES OF 6-35 kV CABLE LINES

CLs of 6-35 kV rated voltages are laid in pipes in such a way that all three phases are placed in one common pipe – this is shown in Fig.1 on the example of a three-core cable (a) and a three-phase group of single-core cables (b).

Fig.1. 6-35 kV cable line laid in polymer pipes:
(a) – three-core cable; (b) – three single-core cables.

Alternating load current, passing through the cable core, with its magnetic field can cause alternating current induced in a two-side grounded screens (first of all, this happens for single-core cables). Therefore, in the general case, the cable has two most significant sources of heat generation at once – these are the losses of active power in the core P_C and the screen P_S. The heat released in the cable is diverted into the ground, meeting on its way the thermal resistance of the insulation R_{INS} and the outer sheath R_{OSH} of the cable, the air in the pipe R_{AIR} and its walls R_P, as well as the thermal resistance of the ground itself R_G. The resulting thermal scheme is shown in Fig.2(a), where T_C, T_S, T_G are the temperatures of the core, screen, ground.

The power loss in the core $P_C = {I_C}^2 \cdot R_C$ is determined by the current in the core I_C and its active resistance R_C, depending on the cross-section of the core F_C and the core material (copper, aluminum). With the help of a thermal equivalent circuit for any given cross-section of the core F_C (taking into account its material), it is possible to determine the current of the core I_C, at which the core temperature reaches the value $T_C = 90°\text{C}$ that is a long time permissible for XLPE insulation. The current I_C found in this way in the core is a long-term permissible current CL (current carrying capacity), which we denote as I_{CC}.

Obviously, if the same CL is laid in the ground in pipes or in the ground without pipes, then due to the different cooling conditions of the cables in the two cases indicated, different long-term permissible currents (current carrying capacities) will be obtained – respectively, $I_{CC(P)}$ and I_{CC}. The ratio of such currents is called the correction factor for laying in pipes:

$$\frac{I_{CC(P)}}{I_{CC}} = K_P$$

where $I_{CC(P)}$ is the permissible current of CL in pipes, Fig.2(a);
I_{CC} is the permissible current of the CL without pipes, fig.2(b).

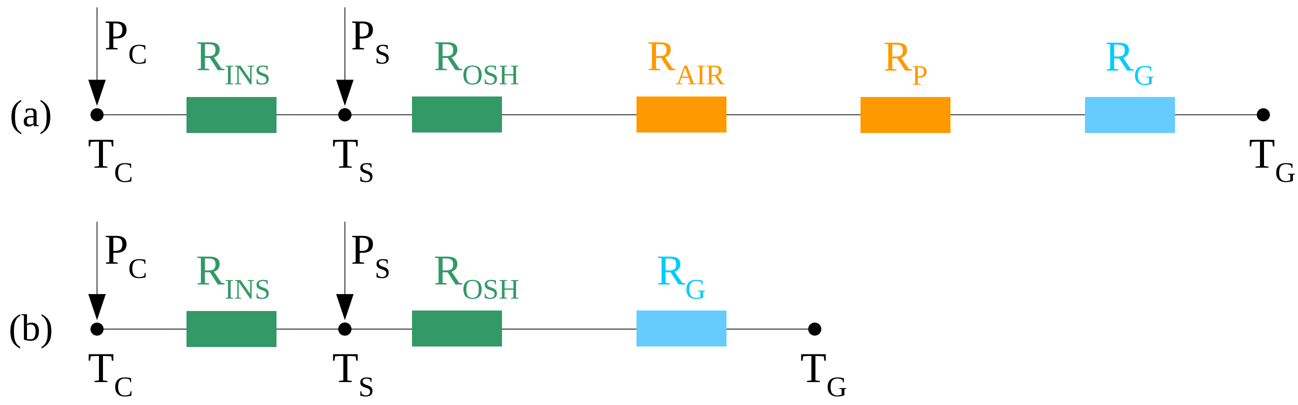

Fig.2. Thermal equivalent of CL:
(a) – laying in the ground in pipes; (b) – laying in the ground without pipes.

Comparing the schemes of Fig.2(a) and Fig.2(b), it seems that pipes complicate the cooling process of cables, since two additional thermal resistances R_{AIR} and R_P appear at once in the thermal circuit during pipe laying. For this reason, it is assumed that the long-term permissible CL currents that meet the condition $T_C = 90°\text{C}$ are necessarily in the ratio $I_{CC(P)} < I_{CC}$, that is, $K_P < 1$ is always true. Moreover, regulatory documents often even specify a specific universal value $K_P = 0.9$.

For example, if, when laying in the ground, the CL have a current capacity $I_{CC} = 1000$ A, then in the case of laying in pipes, the current will decrease to $I_{CC(P)} = K_P \cdot I_{CC} = 900$ A. Thus, in order to ensure the initial current of 1000 A, the CL designer will have to look for ways to reduce the temperature of the cables and will go to increase the core cross-section F_C, which will cause the total cost of CL to rise. These arguments are common for many projects, but they are based on the erroneous assumption that $K_P = 0.9$ is true. In fact, the influence of pipes on the long-term permissible current of CL is complex, and in some cases, pipes not only do not reduce the permissible current, but even, on the contrary, increase it.

The difference between the scheme of Fig.2(a) and Fig.2(b) is not only in the presence of R_{AIR} and R_P, but also in the different value of R_G, since in the first case ($R_{G(a)}$) the pipe contacts the ground, and in the second case ($R_{G(b)}$) – the cable itself. Using the example of a three-core cable per 1 m length, we can write:

$$R_{AIR} = 3 \cdot \frac{\rho_{AIR}}{2\pi} \cdot ln\left(\frac{D_{IN}}{d}\right),$$

$$R_P = 3 \cdot \frac{\rho_P}{2\pi} \cdot ln\left(\frac{D}{D_{IN}}\right),$$

$$R_{G(a)} = 3 \cdot \frac{\rho_G}{2\pi} \cdot ln\left(\frac{4h_G}{D}\right), \qquad R_{G(b)} = 3 \cdot \frac{\rho_G}{2\pi} \cdot ln\left(\frac{4h_G}{d}\right),$$

where ρ_{AIR}, ρ_P, ρ_G are the specific thermal resistances of air (taking into account its convection), pipe and ground;
d is the outer diameter of the cable;
D and D_{IN} are outer and inner diameters of the pipe;
h_G – depth of cables in the ground (not less than 0.7 m for 6-20 kV, not less than 1.0 m for 35 kV).

In the case of pipes, the thermal resistance $R_{AIR} + R_P + R_{G(a)}$ interferes with the cooling of cables, and in the case without pipes, the thermal resistance $R_{G(b)}$. Since the diameters of the pipe D and cable d are correlated as $D > d$, then according to the formulas $R_{G(a)} < R_{G(b)}$ is always true, and then there is no understanding in advance what the inequality sign $R_{AIR} + R_P + R_{G(a)} \lesseqgtr R_{G(b)}$

should be, that is, there is no clarity in which of the circuits (with or without pipes) the total thermal resistance will be less and, consequently, the long-term permissible current of the CL is greater.

If $R_{AIR} + R_P + R_{G(a)} > R_{G(b)}$, then the laying in the pipes complicates the cooling of cables (due to the influence of air in the pipe and its side wall), and then $K_P = I_{CC(P)}/I_{CC} < 1$.

If $R_{AIR} + R_P + R_{G(a)} < R_{G(b)}$, then the laying in the pipes simplifies the cooling of cables (due to the large contact area of the pipe with the ground), and then $K_P = I_{CC(P)}/I_{CC} > 1$.

It is obvious that the influence of pipes on the CL permissible current is determined by the same factors as the values of thermal resistances R_{AIR}, R_P, $R_{G(a)}$, $R_{G(b)}$. In particular, the influence of pipes will depend on the specific thermal resistance of the ground ρ_G and the pipe ρ_P, on the depth of the laying h_G, on the diameters of the pipe D and D_{IN}, on the diameter of the cable d.

For example, even with the standard value $D_{IN}/d = 1.5$, typical for laying cables in pipes, and the specific thermal resistance of modern polymer pipes $\rho_P = 2\ m \cdot K/Wt$, coefficient K_P will be determined by the properties of the ground ρ_G and the depth of the laying h_G, that is, it cannot have the same constant value $K_P = 0.9$, In particular, with increased ρ_G and h_G, characteristic of laying cables in pipes by the HDD method, the coefficient K_P can reach 1.0 or even more.

3. LAYING IN PIPES OF 110-500 kV CABLE LINES

For CL of rated voltages of 110-500 kV, the influence of pipes on the permissible current is even more difficult, since only single-core cables are used in these networks, and each phase is placed in its own separate pipe (Fig.3).

(a) (b)

Fig.3. 110-500 kV cable line laid in polymer pipes:
(a) – single-core cable; (b) – three single-core cables.

It is recommended to lay single-core cables in a closed triangle, since this ensures a high degree of compensation of the magnetic fields of the alternating currents of the three phases, that is, the magnetic field of the CL and its effect on people and neighboring lines decreases, thereby increasing the electrical safety of the CL.

If, instead of laying three phases in a closed triangle, it is decided to place three phases in three pipes, then when determining the long-term permissible current of the CL, it is necessary to take into account not only the rather complex influence of pipes, which was considered earlier on the example of 6-35 kV CL, but also the simple fact that phase-by-phase laying of cables in pipes increases the distance between phases (from the value $s = d$, corresponding to the diameter of the cable, up to $s = D$, corresponding to the diameter of the pipe), improving the cooling of cables and ensuring an increase in the permissible current of the CL.

The process of accounting of pipes for 110-500 kV CL assumes that two correction factors should be applied at once:

$$\frac{I_{CC(P)}}{I_{CC}} = K_S \cdot K_P \ ,$$

where $K_S > 1$ – takes into account the improvement of cable cooling when changing the laying of three phases in a closed triangle $s = d$ to laying in an open triangle $s = D$ (Fig.3(b));
$K_P \lesseqgtr 1$ – takes into account the influence of the pipe itself (as was considered earlier for 6-35 kV).

The process of transition from laying single-core cables in a closed triangle to phase-by-phase laying in pipes is schematically demonstrated in Fig.4, where it is clear why two coefficients should be applied at once – both K_S and K_P.

The experience of modeling CL processes obtained with help of computer programs allowed us to establish that many 110-500 kV CL have $K_S \cdot K_P = 1.05 \div 1.15$. Thus, the phase-by-phase laying of cables in polymer pipes leads to an increase in the long-term permissible CL current (current carrying capacity) by value of (5÷15)%, which means $I_{CC(P)} = (1.05 \div 1.15) \cdot I_{CC}$.

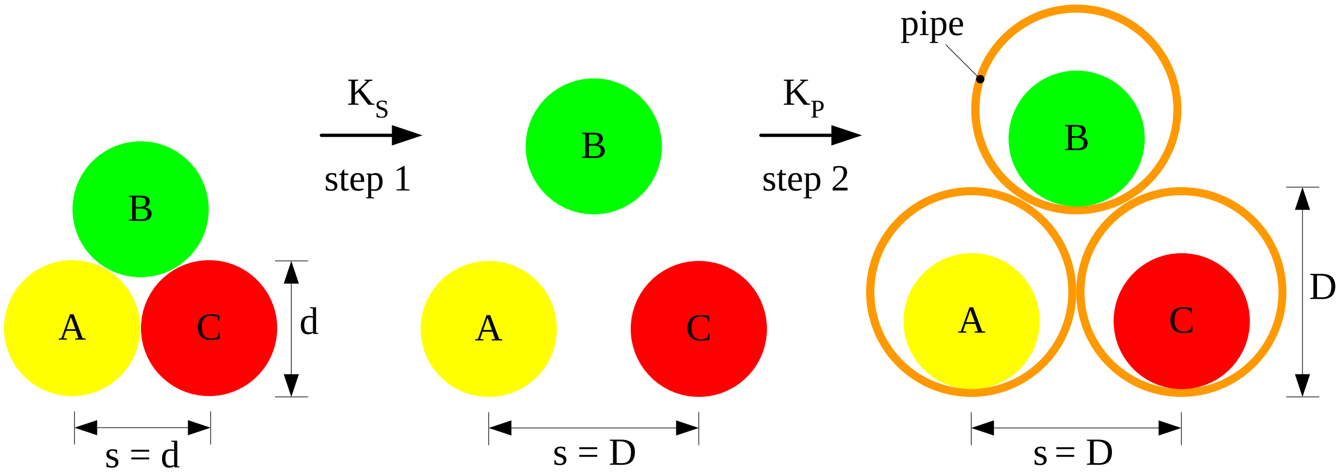

Fig.4. Step-by-step transition from laying cables in a closed triangle to laying in three pipes.

4. DIFFERENCES BETWEEN THE OLD AND NEW CABLE LINE GENERATIONS

The correction factor $K_P = 0.9$, which takes into account the influence of pipes on the permissible CL current, first appeared in regulatory documents at a time when cable networks had the following features:

– in pipes filled with air, mainly only 6-35 kV CL of three-core design were laid; it means that all phases were placed in the pipe at the same time, and phase-by-phase laying was not used;
– the pipes were laid in an open way on the trench bottom at a depth of no more than 1.5 m, since other methods were little known (in particular, there were no cases of HDD method, which, as a rule, is characterized by an increased specific thermal resistance of the ground ρ_G around the CL, associated with a significant depth of laying h_G up to 20 m);
– the pipes were mainly made of asbestos, which in fact was a heat insulator and had a significant specific thermal resistance, reaching the value $\rho_P = 10 \ m \cdot K/Wt$, which is 5 times more than resistance $\rho_P = 2 \ m \cdot K/Wt$ of modern polymer pipes.

The coefficient $K_P = 0.9$ quite correctly described the influence of pipes on the permissible current of the "old" CL, however, this coefficient does not take into account at all that significant changes have taken place in cable networks over the past 20 years – the design of cables, the methods of laying them, and the materials of pipe products have changed. It should not be surprising that the coefficient $K_P = 0.9$ no longer reflects the true thermal processes of the CL.

5. CONCLUSIONS

The placement of cables in pipes has become one of the most common ways of laying CL of all voltage classes. The influence of pipes on the long-term permissible current of CL is diverse, and it cannot be described by introducing a universal correction factor $K_P = 0.9$. In a whole series of cases, the pipe laying not only does not reduce the permissible CL current, but even, on the contrary, increases it, which is especially noticeable with phase-by-phase laying of cables in pipes.

In order to correctly calculate the influence of polymer pipes on the CL permissible current and not to overestimate the core cross-section F_C of cables, it is necessary to carry out thermal calculations of CL not through a system of simplified correction coefficients, but with the help of accurate scientifically based methods that take into account all influencing factors and implemented in various specialized computer programs.