Steady State Effects of Design Properties and Environmental Conditions on Underground Power Cable Ampacity

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Abstract

The steady state analysis of the cables under selected design and installation conditions provide information to ensure that the cables remain within allowable operating temperature limits. Manufacturers share the ampacity levels and derating factors under certain conditions for the cables that they produced, depending on the standards. However, the diversity of conditions can increase in the real applications. In this study, ampacity comparisons have been carried out for a different design and environmental characteristics of an underground cable system. The selected parameters have been analyzed for steady-state conditions within certain ranges. Characteristic ampacity trend curves corresponding to the relevant parameter changes have been generated with iterative solutions.

1. Introduction

Power cable design and application processes have experienced a serious development over the decades [1]. Today, power cable industry produces a wide variety insulated cables that can be used in different conditions [1,2]. In the design process, productions are optimized according to certain standards and boundary conditions to ensure transmission/distribution security and to consume the expected service period of related cables [3-4]. This process can be divided into two sections: the first is cable itself design and the second is cable environment conditions. Choosing the right form which will be installed in local area and the right cable designs require significant expertise.

The field experts need to try different possibilities. It is reasonable to do steady-state analysis according to the different ranges of the cable parameters (on the manufacturer side) and environment conditions (on the operator side). When all these analysis are carried out, the current carrying capacity (Ampacity) is the most important parameter that should never be changed on the demand side. Since, the desired ampacity is determined by the electric energy requirement of the relevant zone. The derating factors should be calculated by considering cable installation form and environmental conditions [5,6]. The manufacturers offer several derating factors for different installation conditions. However, geographical differences significantly change the environmental properties such as soil characteristics and climate [7-8]. For this reason, a new analysis process is usually required depending on the selected installation conditions and the characteristics of the geographical area.

The useful lifetime of the underground cable is adversely affected by its operating temperature depending on the load [9]. Therefore the ampacity of cable is limited by the maximum allowable temperature under constant current (100% load factor) on steady state conditions [10,11]. The produced heat on conductor due to electrical losses needs to be transferred through thermal resistances of cable parts and other installation stages to the earth. As internal heat sources, conductor I^2R losses, metallic shielding or sheaths losses (for medium voltage and upper), dielectric losses (for higher voltages), and as external heat sources, mutual heating from other cables or nearby heat source should be considered [12]. Non-metallic parts of the cable, non-metallic conduits, duct banks, air gaps, backfill, concrete and soil are defined as thermal resistances. All these thermal resistances affect the level of the cable's temperature and its ampacity [13]. It should be noted that all parts of the cable have a thermal capacitance which can store the heat produced in cable. Especially, thermal capacities of insulation parts affect the temperature distribution and changes as a function of time [11,14]. This situation is manifested in transient states such as step load changes, generally. Even if the load current changes suddenly, the temperature does not change suddenly due to the thermal capacity. It is known that thermal capacitances are no effect in steady state conditions [11]. Therefore, they have not been evaluated within the scope of this study.

The aim of this study is to show how the cables' design parameters and environmental conditions affect the ampacity on a steady state operation. The parameters examined are evaluated separately and within certain limits. Thus, there has been demonstrated how the ampacity changes within the given ranges for each parameter.

2. The Steady State Thermal Model

The thermal equivalent circuit model is preferred for many years as a solution of buried cable systems. Two proper ladder networks based on thermal-electrical analogy is presented for transient and steady state conditions in the literature [11,14]. In the steady state model, the equivalent thermal circuit contains only thermal resistances and heat sources as shown in Fig. 1. Where the electrical voltages refer to the temperatures, the current supplies refer to the cable losses and the ohmic resistances refer to the thermal resistances.

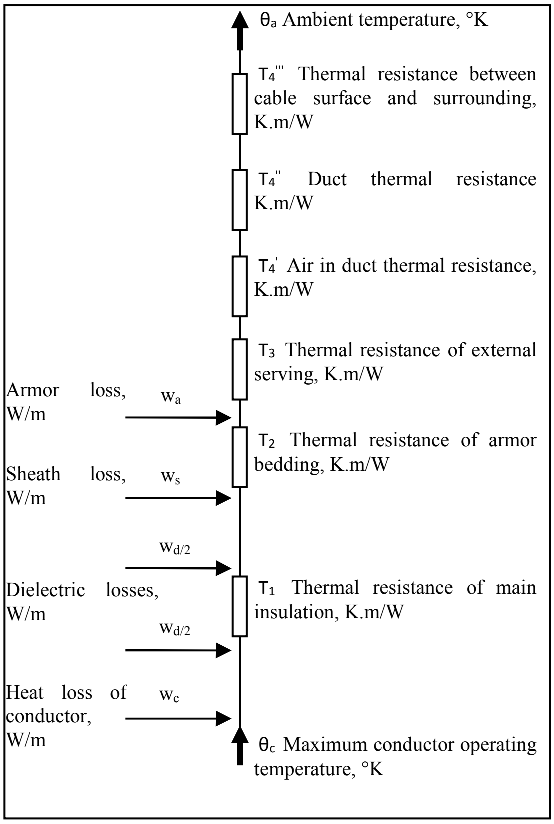


Fig. 1. Thermal equivalent circuit model for the steady state conditions

In steady state operation, total joule loss except dielectric loss (w_d) is defined as $w_I = (w_c + w_s + w_a)$ and also it is written $w_I = w_c(1+\lambda_1+\lambda_2)$. Where, λ_1 is called the sheath loss factor and λ_2 is called the armor loss factor, respectively. The number of installed cables is defined as (n). In the steady state condition, the following equation that gives the temperature difference between the conductor and the ambient temperature can be written by;

$$\begin{aligned}\theta_c - \theta_a = \left(w_c + \tfrac{1}{2}w_d\right)T_1 + [w_c(1+\lambda_1) + w_d]nT_2 \\ + [w_c(1+\lambda_1+\lambda_2) + w_d]n(T_3+T_4)\end{aligned} \tag{1}$$

The expression (I^2R_{ac}) is written here instead of w_c and the ampacity of the cable can be calculated as follows;

$$I = \sqrt{\frac{\Delta\theta - w_d[1/2\,T_1 + n(T_2+T_3+T_4)]}{R_{ac}T_1 + nR_{ac}(1+\lambda_1)T_2 + nR_{ac}(1+\lambda_1+\lambda_2)(T_3+T_4)}} \tag{2}$$

The thermal resistances T_1, T_2 and T_3 are calculated in a similar way for single core cables. Where, d_c is conductor diameter (mm), t_i, t_2, and t_3 are the main insulation thickness (mm), the jacket thickness (mm) and the serving thickness (mm), respectively. And ρ, ρ_2 and ρ_3 are the main insulation thermal resistivity (K.m/W), the jacket thermal resistivity (K.m/W) and the serving thermal resistivity (K.m/W), respectively. D_s is the external diameter of the sheath (mm) and D_a is external diameter of armor (mm).

$$T_1 = \frac{\rho}{2\pi} ln\left(1 + \frac{2t_i}{d_c}\right) \tag{3}$$

$$T_2 = \frac{\rho_2}{2\pi} ln\left(1 + \frac{2t_2}{D_s}\right) \tag{4}$$

$$T_3 = \frac{\rho_3}{2\pi} ln\left(1 + \frac{2t_3}{D_a}\right) \tag{5}$$

The external thermal resistance (T_4) varies according to the cable installation conditions. The thermal equation (6) is used only for direct buried cables in a flat configuration while the other thermal equations (7) to (12) are used for the cables installed as flat configuration in backfills/concrete and duct banks.

$$T_4 = \frac{\rho_s}{2\pi} ln\left\{\left(u + \sqrt{u^2-1}\right)\left[1 + \left(\frac{2L}{s}\right)^2\right]\right\} \tag{6}$$

Where, T_4' is the medium thermal resistance between the cable surface and the duct internal surface (K m/W), T_4'' is the thermal resistance of the duct material (K m/W), $T_4'''^{N}$ is the external thermal resistance (K m/W) for only concrete/backfill - none of the soil, $T_4'''^{c}$ is the correction of the thermal resistance (K.m/W), and T_4''' is the corrected external thermal resistance (K.m/W), respectively. Where, ρs, ρ_d and ρ_c are the thermal resistivity of soil (K.m/W), the thermal resistivity of duct (K.m/W), the thermal resistivity of the backfill or concrete (K.m/W), respectively. The coefficients U, V and Y are selected according to IEC-60287 standard facility conditions [10]. Where, θ_m is mean temperature of the duct filling medium (°C), D_e is the external diameters of cable (mm), D_d is the internal diameters of duct (mm), t_d is the thickness of the duct material (mm), L is the depth of burial of the cable (mm), s is the distance between cables (mm), The parameter, u is defined as (L_b/r_b). Here, L_b is the distance between the soil surface and the center of backfill (mm), r_b is the equivalent radius of the backfill envelope (mm).

$$T_4' = \frac{U}{1 + 0.1(V + Y\theta_m)D_e} \tag{7}$$

$$T_4'' = \frac{\rho_d}{2\pi} ln\left(1 + \frac{2t_d}{D_d}\right) \tag{8}$$

$$T_4'''^{N} = \frac{\rho_c}{2\pi} ln\left\{\left(u + \sqrt{u^2-1}\right)\left[1 + \left(\frac{2L}{s}\right)^2\right]\right\} \tag{9}$$

$$T_4'''^{c} = \frac{n}{2\pi}(\rho_s - \rho_c)\ln\left(u + \sqrt{u^2-1}\right) \tag{10}$$

$$T_4''' = T_4'''^{N} + T_4'''^{c} \tag{11}$$

$$T_4 = T_4' + T_4'' + T_4''' \tag{12}$$

3. The Steady State Calculations

In practice, many different types of cables and installations are available. Since it is not possible to show them all, the steady-state analysis has been carried out through an example in this study in accordance with the standard IEC 60287 [10]. Unlike the literature, the solutions will be presented for selected ranges of the parameters related to the cable and its surrounding medium. The standpoint suggested in this study is feasible for other cables (such as 154kV, 400kV, 230kV) and installation configurations (such as direct buried or in backfill with duct bank).

3.1 Design Properties and Environment Conditions of the Selected Underground Cable System

An XLPE insulated cable (10kV) which is frequently used in practice is preferred as reference [11,15]. The cable and the environment properties are given in Table 1 and Fig. 2.

Table 1. Installation properties

Cable properties	**Unit**	**Values**
Operating voltage	V	10 000
Frequency	Hz	50
Conductor	-	Copper
Max. cond. temp. for XLPE	ºC	90
Thermal resistivity of insulation	K.m/W	3.5
Dielectric loss	Watt	-
Jacket thermal resistivity	K.m/W	6
Environment properties	**Unit**	**Values**
Depth of burial of cables	mm	1000
Spacing between conductors	mm	72
Soil thermal resistivity	K.m/W	1
Ambient temperature	ºC	15

Reference cable and environment properties are taken from the book of Anders, G. [12]. (A.1 - Model Cable No. 1)

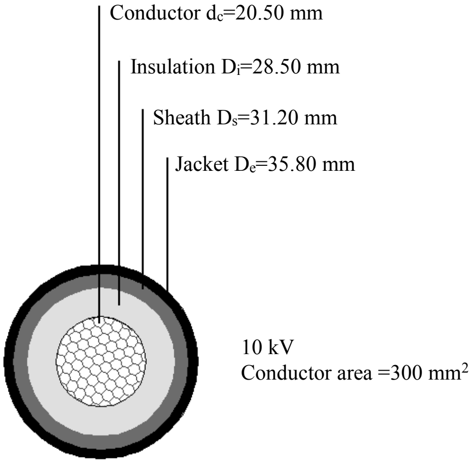


Fig. 2. Sample cable cross-section

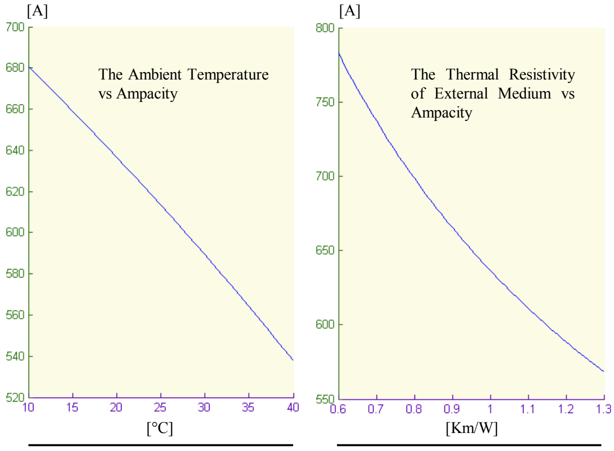
The steady state calculation has been performed within a certain ranges by selecting some of the values of the parameters in the Table 1. In addition, some design features of the cable have been analyzed. All of these selected parameters have been showed Table 2. Iterative solutions have been carried out to see the trend corresponding to range of the parameters. While the ranges of the examined parameters are set, certain rules or standards are not followed. Since the purpose of the study is to determine how the ampacity changes depending on the type and range of parameters. These changes have been presented graphically.

Table 2. Selected parameter ranges and types

Selected parameters	**Analyzed ranges / types**
Ambient temperature	(10 ↔ 40) °C
Thermal resistivity of soil	(0.6↔ 1.3) K.m/W
Distance between conductors	(40 ↔ 120) mm
Depth of buried cable	(200 ↔ 1600) mm
Insulation types	XLPE, PE, EPR, PPL
Conductor types	Copper, Aluminum

3.2 Graphical Representation of the Results

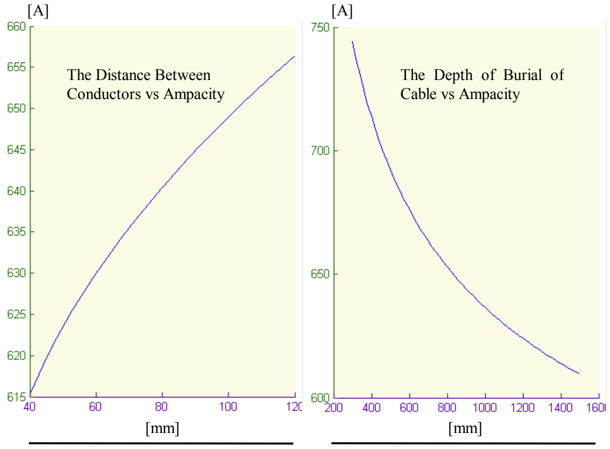
The Fig. 3 is related to the environmental properties. It is known that the cable ampacity is greatly affected by the variations of soil thermal resistivity and ambient temperature. The ampacity varies nonlinearly for selected ranges of both parameters but they are characteristically different from each other. In Fig. 3(a), the trend is an exponentially decreasing function, while the trend is a logarithmically decreasing function in Fig. 3(b). Manufacturers assume the ambient temperatures are constant in their calculations. However, especially seasonal effects cause the ambient temperature changes. Similarly, the thermal resistivity of the soil may be different according to various geographical regions and it is very important, especially for the systems directly buried in the soil.



(a) (b)

Fig. 3. Ampacity vs environment properties

In Fig. 4, the effect of the distance between conductors and the depth of the buried cables, on the ampacity has been investigated for the center cable which is the worst case cable in terms of thermal stress. In both cases, the ampacity changes logarithmically. However, the direction of the ampacity trend is positive in Fig. 4(a), while it is negative in Fig. 4(b).



(a) (b)

Fig. 4. Ampacity vs installation conditions

In Fig. 5, the effects on the ampacity of the main insulation materials used in the cable are presented comparatively. When this investigation is carried out, thicknesses (as 2-10 mm) are taken into account to make the comparison better. The ampacity changes are nonlinear for all insulation types. But the PPL gives the worst response with the increase of insulation thickness, among other insulation types. The XLPE and PE insulations give better results than EPR and PPL insulations. The ampacity curves of XLPE and PE insulations overlap for this cable. Because the dielectric losses are not included in the calculation for medium voltage cables. It is known that the thermal resistivity and thermal capacity of the XLPE and PE insulation materials are the same but their dielectric constants and loss factors which is used for dielectric loss factor calculation may differ from each other according to the cable types. In terms of ampacity, there is a fixed ratio of about 0.8 between aluminum and copper, predictably.

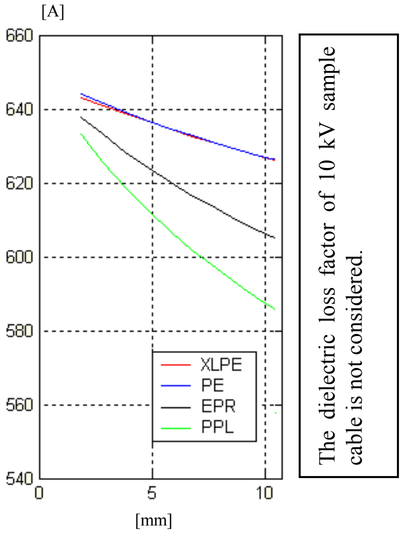


Fig. 5. Ampacity vs main insulation types

4. Conclusions

Manufacturers design their products according to the standards. They provide some suggestions on how to install the cables and give derating factors according to installation conditions. But some different conditions can be faced in applications. It should be very well evaluated which cable design and installation type should be preferred for different environmental and climatic conditions. It is important to know how and in what range these parameters affect the ampacity of the cable. It will be useful to evaluate the obtained results. Analyzing the parameter ranges at a certain range is helps to determine the trend of the ampacity.

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