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THE INFLUENCE OF DAILY LOAD PROFILE ON THE HEATING OF SINGLE-CORE XLPE CABLES BURRIED IN THE GROUND

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Abstract. *This paper presents and discusses the results of the transient heating analysis of single core cables laid directly in the ground. In order to analyze transient heating of cables a daily load diagram with three levels, which can be described by two parameters is used. These parameters are duration of high level loading and load factor. In order to analyze daily temperature variation of the cable the ratio of high level current loading to rated current of the cable is also required. Parameters that affect results are varied in analysis: thermal conductivity and diffusivity of soil, the distance between adjacent cables, temperature of referent soil, cross-bonding of metal sheets, etc. The results of analysis are ranges of conductor temperature variation, i.e. daily minimum and maximum temperature of the conductor for different laying and ambient conditions. The presented results can be used in estimation of cable overloading capability as well as for estimation of aging of cables exposed to cyclic loading.*

Key words: *single-core cable, transient heating, load diagram*

1. INTRODUCTION

Nowadays, application of XLPE power cables is very common, both in MV networks and HV networks [1, 2]. Development and application of this type of cables is particularly evident in the last thirty years. Cross-linked polyethylene has a low dielectric losses factor ($tg\delta=3\cdot10^{-4}$ on 20 °C, f=50 Hz), high electric permittivity, and its relative permittivity (ε_r=2.3÷2.5) is lower than it is in other materials. Considering thermal characteristics, cross-linked polyethylene has a lower value of thermal resistivity (3÷3.5 Km/W) than other insulation materials. Besides, this material allows permissible conductor tempera-

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ture of 90°C in normal operation and 130°C in emergency operation. The drawback of insulation made from this material is poor resistance to mechanical damage.

For a long time, calculating the current ampacity of power cables is an interesting topic for many researchers [3-9]. Current ampacity given by manufacturers is determined according to standard [10] and assumes a constant daily load, i.e. loading factor is equal to unity. Daily load diagrams are not constant, so cable load, in periods when it has maximum value, can be greater than ampacity given by manufacturers. Standard IEC60853-1 [11] gives a procedure for assessment of ampacity of cables up to 30 kV of nominal voltage, when exposed to influence of cyclic daily load and where the thermal capacity of insulation can be neglected. This procedure enables determination of overload capacity (in percent) with respect to current rating that corresponds to known daily load cycle without using the computer. Standard IEC60853-2 [12] considers power cables with nominal voltage above 30 kV, and also gives simple procedure for determination cyclic rating factor of these cables. Unlike the IEC60853-1, in this case thermal capacity of cables is not neglected, but well known equivalent circuit with two loops is used for calculations. Of course, standard IEC60853-2 can also be applied on cables with nominal voltage under 30 kV, but the idea of existence of standard IEC60853-1 is to simplify the calculation. On the other side, difference in obtained results for considered cables is negligible.

This paper presents and discusses results of analysis which deals with transient heating of single core cables directly buried in the ground. In order to analyze transient heating of cables, a daily load cycle with three load levels is used and its form can be defined with two parameters. During the analysis, parameters that affect the result were varied (thermal conductivity and thermal diffusivity, distance between adjacent cables etc.) and temperature range of conductor is determined, i.e. minimum and maximum temperature of conductor.

2. Current Rating of the Cable

The permissible cable current rating of an a.c. cable can be derived from the expression for temperature rise above ambient temperature. During determination of this current, beside constructive characteristics of cable, environmental conditions around the cable must also be taken into account. For cables buried in the ground it is needed to consider partial drying of soil around the cable [3]. However, if cable bedding is used, it can be said that partial drying of the soil is avoided and

$$I = \sqrt{\frac{\Delta\theta - W_d[0.5\mathrm{T}_1 + n(T_2 + T_3 + T_4)]}{RT_1 + nR(1+\lambda_1)\mathrm{T}_2 + nR(1+\lambda_1+\lambda_2)(T_3+T_4)}}\,, \tag{1}$$

where $\Delta\theta$ is the conductor temperature rise above the ambient temperature, n is the number of load-carrying conductors, R is the alternating current resistance per unit length at maximum operating temperature, T_1 is the thermal resistance per unit length between one conductor and the sheath, T_2 is the thermal resistance per unit length of the bedding between sheath and armor, T_3 is the thermal resistance per unit length of the external serving of the cable, T_4 is the thermal resistance per unit length between the cable surface and the soil, λ_1 is the ratio of losses in the metal sheath to total loses in all conductors in the cable, λ_2 is the ratio of losses in the armoring to total loses in all conductors in the cable, and W_d are dielectric losses per unit length per phase.

Power loss in the sheath (λ_1) consists of losses caused by circulating currents (λ'_1) and eddy currents (λ''_1):

$$\lambda_1 = \lambda_1' + \lambda_2'' \ . \tag{2}$$

For single-core cables with sheaths bonded at both ends of an electrical section, only the loss due to circulating currents in the sheaths need be considered. External thermal resistance, for a cable (labeled with *k*) laid in the group of *m* buried cables (not touching and unequally loaded), can be determined as:

$$T_4 = \frac{\rho_T}{2\pi}\left[\ln(\mathrm{u}+\sqrt{u^2-1}) + \sum_{\substack{i=1\\ i\neq k}}^{m} \chi_i \ln\frac{d'_{ik}}{d_{ik}}\right] , \tag{3}$$

where ρ_T is thermal resistivity of soil, u=2L/D_e, L is laying depth of cable in the ground and, D_e is external diameter of the cable, d_{ik} is distance between considered and i^{th} cable, d_{ik}' is distance between considered cable and image of i^{th} cable, χ_i is power loss ratio between i^{th} and considered cable.

For the middle cable in the group of three cables laid in a horizontal plane, equally spaced apart, and having approximately equal losses expression (3) becomes:

$$T_4 = \frac{\rho_T}{2\pi}\left[\ln(u+\sqrt{u^2-1}) + \ln\left[1+\left(\frac{2L}{s_1}\right)^2\right]\right] , \tag{4}$$

where s_1 is the axial separation between two adjacent cables.

This expression can be used for the cable line consisting of three single-core cables laid in a horizontal plain when transposition of metal sheaths is carried out. If cross bonding of metal sheaths is not carried out and/or the sheaths are bonded at all joints, losses in the sheaths of single-core cables are unequal. For calculation of the external thermal resistance in this case the following expression should be used:

$$T_4 = \frac{\rho_T}{2\pi}\left\{\ln(u+\sqrt{u^2-1}) + \frac{1+0.5(\lambda_{11}'+\lambda_{12}')}{1+\lambda_{1m}'}\ln\left[1+\left(\frac{2L}{s_1}\right)^2\right]\right\} , \tag{5}$$

where λ'_{11} and λ'_{12} are sheath loss factors for outer cables in the group, and λ'_{1m} is sheath loss factor for the middle cable of the group.

3. Transient Heating of Cables

Transient heating analysis of power cables is quite a complicated task. The basics of this analysis can be found in paper [3], and systematized through standards IEC60853 in which the main attention is directed towards determining cyclic overloading factor and emergency current rating of cables. For determination of conductor temperature rise above ambient temperature caused by current loading in moment *t* after the beginning of loading, the following expression is used [2, 12]:

$$\theta(t) = \theta_c(t) + \alpha(t)\theta_e(t) \quad , \tag{6}$$

where $\theta_c(t)$ is transient temperature rise of conductor above cable surface in moment t, $\theta_e(t)$ is temperature difference between outer surface of cable and ambient (temperature rise of cable surface above ambient) in moment t, $\alpha(t)$ is attainment factor for the transient temperature rise between the conductor and the outer surface of the cable.

Transient temperature rise of the conductor above the surface of the cable (i.e. temperature rise of conductor above cable surface) in moment t is given by relation:

$$\theta_c(t) = W_c\left[T_a(1-\mathrm{e}^{-at}) + T_b(1-\mathrm{e}^{-bt})\right] \ . \tag{7}$$

In previous relation W_c denotes power loss per unit length in cable conductor, T_a and T_b denotes corresponding thermal resistances, while a and b are corresponding constants. Thermal resistances (T_a, T_b) as well as constants a and b, depend on the cable construction. Procedure for their calculation is presented in detail in [2, 6, 7, 12]. Attainment factor $\alpha(t)$ represents ratio between temperature rises $\theta_c(t)$ and $\theta_c(\infty)$ which corresponds to steady state, i.e.:

$$\alpha(t) = \frac{\theta_c(t)}{\theta_c(\infty)} = \frac{\theta_c(t)}{W_c(T_a+T_b)} \ . \tag{8}$$

Temperature rise of cable above ambient temperature (temperature difference between external surface of cable and ambient) in moment t, $\theta_e(t)$, can be determined by relation [2, 11, 12]:

$$\theta_e(t) = \frac{W_I\rho_T}{4\pi}\left\{-Ei\left(\frac{-D_e^2}{16t\delta}\right) + Ei\left(\frac{-L^2}{t\delta}\right) + \sum_{i=1}^{m}\chi_i\left[-Ei\left(\frac{-d_{ik}^2}{4t\delta}\right) + Ei\left(\frac{-d'^2_{ik}}{4t\delta}\right)\right]\right\} \ . \tag{9}$$

where W_i is total Joule power loss in the cable per unit length, δ is thermal diffusivity of soil, $-Ei(-x)$ is exponential integral function. Thermal diffusivity of soil depends on thermal resistance of soil and its values are given in [2, 7, 12] while exponential integral is calculated relatively simply using certain polynomials [13].

To determine conductor temperature, temperature rise from relation (6) needs to be added with temperature of referent soil and temperature rise caused by dielectric losses. In case of variable loading, a superposition principle is applied and every load change is modeled as switching on new load whose losses are equal to difference of losses between new and previous load, whereby relation (6) is applied for every step function.

4. Heating of Cables Exposed to Cyclic Loading

Overload capacity of cable exposed to cyclic loading, according to standard IEC60853, is given by cyclic rating factor. Cyclic rating factor is defined as ratio of permissible peak value of current during a daily (24 h) cycle I_{max} to rated current for corresponding laying conditions:

$$M = \frac{I_{\max}}{I_R} \ . \quad (10)$$

Calculation of this factor is based upon transient heating analysis of power cables, but to enable classic way of calculation (without using the computer) analysis is simplified and conducted under certain assumptions. It is assumed that maximum temperature of the cable should be equal to rated temperature and that it is sufficient to accept only variable loads for a period of 6 hours prior to the maximum temperature. For the previous period, load is constant, and power losses can be represented with sufficient accuracy by using an average loss value during cycle. If it is unknown in which moment occurs maximum temperature, for referent moment is taken the last one in which the current load was maximal. Electrical resistance of conductor is also considered as constant and equal to resistance for rated temperature. Under these assumptions, cyclic loading factor is determined as:

$$M = \frac{1}{\left(\mu\left(1-\frac{\theta_R(6)}{\theta_R(\infty)}\right)+\sum_{t=0}^{5}\left(\frac{\theta_R(t+1)}{\theta_R(\infty)}-\frac{\theta_R(t)}{\theta_R(\infty)}\right)\right)^{1/2}} \ , \quad (11)$$

where μ is loss-load factor and:

$$\frac{\theta_R(t)}{\theta_R(\infty)} = \alpha(t)(1-\mathrm{k}-\beta(t)\,\mathrm{k}) \ , \quad (12)$$

where k is the ratio of cable external surface temperature rise above ambient to conductor temperature rise above ambient under steady conditions, and $\beta(t)$ attainment factor for cable surface.

In the case of group of unequally loaded cables attainment factor $\beta(t)$ is:

$$\beta(t) = \frac{-Ei\left(-\frac{D_e^2}{16t\delta}\right)+Ei\left(-\frac{L^2}{t\delta}\right)+\sum_{i=1}^{m}\chi_i\left[-Ei\left(-\frac{d_{ik}^2}{4t\delta}\right)+Ei\left(-\frac{d'^2_{ik}}{4t\delta}\right)\right]}{2[\ln(u+\sqrt{u^2-1})+\sum_{\substack{i=1\\ i\neq k}}^{m}\chi_i\ln(d'_{ik}/d_{ik})]} \ , \quad (13)$$

while:

$$k = \frac{W_I T_4}{W_c(T_a+T_b)+W_I T_4} \ . \quad (14)$$

A daily profile with three levels (low, medium and high levels) is used for analysis of daily load profile impact on the temperature of the cable exposed to cyclic loading. The profile consists of four intervals with constant loading. Duration of low and high levels are equivalent ($t_{\min}$=$t_{\max}$), whilst value of medium level is an average of low and high levels. The daily load profile like this can be described with only two parameters. Medium level loading appears twice during the day, and the duration of each of these intervals is equal to supplement of $t_{\max}$ to 12 hours. Due to the way of forming daily load profile it is obvious that the mean value of the load during the day is equal to the medium level value, i.e. that load factor *m* is equal to the ratio of medium level and high level load. Fig. 1 shows three levels load profile with 0.7 load factor and 7 hours duration of high load interval. In addition to these two parameters, for the analysis of temperature variation of the cable exposed to this daily load profile it is necessary to know the ratio of maximum load and rated load for the given laying conditions (overload factor).

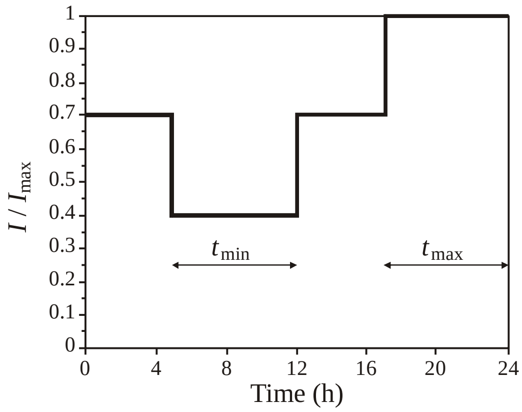


Fig. 1 Daily load diagram with three levels t_{max}=7h and m=0.7

5. TEST EXAMPLE

The analyses have been performed for single-core 110 kV cables with XLPE insulation and 630 mm^2, 800 mm^2, 1000 mm^2, 1200 mm^2 and 1400 mm^2 cross section area aluminum conductors [14]. The analyses include steady-state as well as transient heating for different values of load profile parameters and different laying conditions. It has been considered three single-core cables in flat formation and 1 m laying depth, temperature of referent soil 10°C and 20°C, and maximum allowed steady-state temperature of conductor 90°C. The cases with cross-bonding of metal sheaths and without cross-bonding of metal sheaths are included in the analyses. Five different values of load factor are used (m=0.9, m=0.8, m=0.7, m=0.6 and m=0.5), and eleven values of duration of high load interval (1 to 11 hours). In addition, three different values of distance between adjacent cables ($a=D_e$, $a=D_e$+70mm and a=250mm), three values of overload factor (I_{max}/I_R=1.1; I_{max}/I_R=1.2; I_{max}/I_R=1.3) and three different values of thermal resistivity of the soil (ρ_T=0.7 Km/W, ρ_T=1 Km/W and ρ_T=1.5 Km/W) are considered. Thermal diffusivities of soil corresponding to these thermal resistivity are $0.6\cdot10^{-6}$ m^2/s, $0.5\cdot10^{-6}$ m^2/s and $0.4\cdot10^{-6}$ m^2/s respectively. Thermal resistivity of cross-linked polyethylene is 3.5 Km/W, thermal capacity of cross-linked polyethylene $2.4\cdot10^6$ J/(m^{3}K) and thermal capacities of aluminum and copper are $2.5\cdot10^6$ J/(m^{3}K) and $3.45\cdot10^6$ J/(m^{3}K), respectively.

Fig. 2 shows daily temperature variation for cable with 1000 mm^2 cross-section area aluminum conductor exposed to load profile like the one shown in Fig. 1, i.e. for 7 h duration of high load interval and different values of load factor. The temperature of the referent ground is 20°C, thermal resistivity of soil is 1 Km/W, distance between adjacent cables $a=D_e$+70mm, and overload factor 1.2. Metal sheaths of cables are cross-bonded.

Rated current for this laying conditions according to manufacturer's catalogue is 950 A, while calculation gives value of 952.7 A. It can be seen from Fig. 2 that for load factor equal to 0.7 conductor temperature is always lower than 90°C, while for load factor 0,8 temperature varies between 82°C and 98°C.

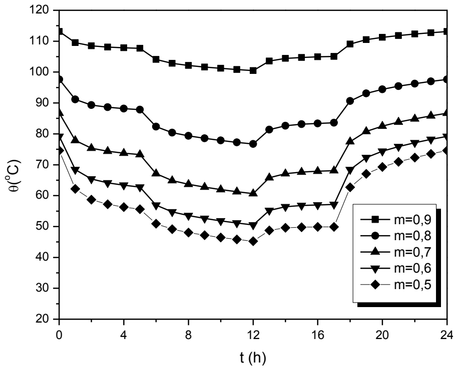
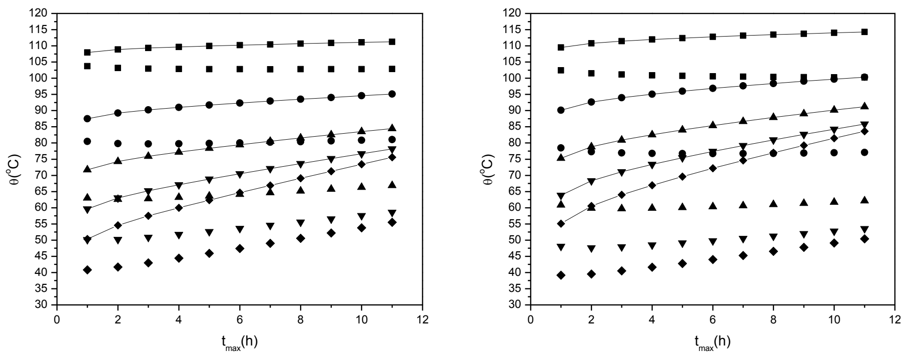


Fig. 2 Daily temperature variation for three levels load profile (I_{max}/I_R=1.2, t_{max}=7h, ρ_T=1 Km/W, θ_a=70°C, $a=D_e+70mm$)

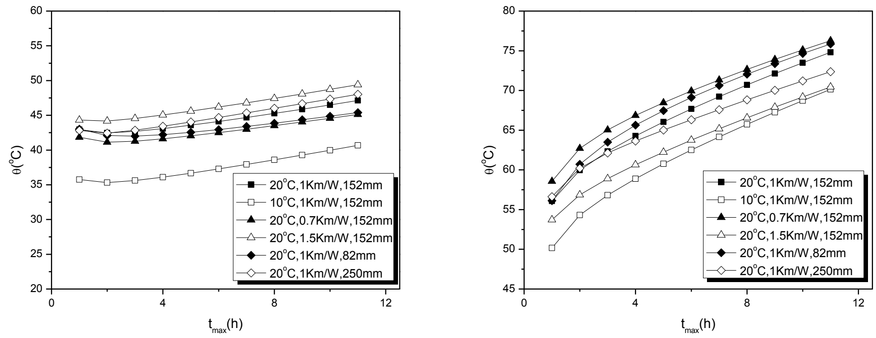
Fig. 3.a and Fig. 3.b show maximum and minimum daily temperature of the conductor (1000mm^2) as a function of duration of high load interval for referent ambient conditions and overload factor 1.2. Fig. 3.a refers to the case without cross-bonding of metal sheaths, while Fig. 3.b refers to the case with cross-bonding. The maximum temperatures are drawn using line and symbols, whereas for minimum temperatures only symbols are used. Different symbols correspond to different values of load factor as on the Fig. 2. The graphs shown in Fig. 3.a and Fig. 3.b are very similar, however it can be noticed that daily variations of temperature are slightly pronounced on the case of cross-bonded metal sheets (maximum temperatures are slightly higher, while minimum temperature are slightly lower). Rated current of cable for the case without cross-bonding of metal sheets is 720 A according to manufacturer's catalogue, while calculation gives value 723.4 A.



a) b)

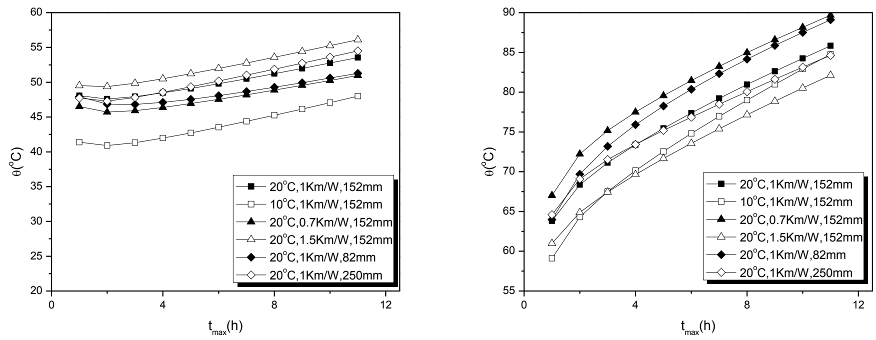
Fig. 3 Maximum and minimum temperature for I_{max}/I_R=1.2
a) without cross-bonding, b) with cross-bonding

Fig. 4 to Fig. 6 gives maximum and minimum daily temperatures of 1000 mm^2 conductor for different laying and ambient conditions and load factor 0.6. Fig. 4a shows minimum daily temperatures, as well as Fig. 5a and Fig. 6.a. Fig 4.b, Fig 5.b and Fig 6.b show maximum daily temperatures. As can be seen from these figures, the range of minimum temperature variation is significantly narrower than the range of maximum temperatures. The range of daily temperature variation (between minimum and maximum temperature) increases with increasing of overload factor for identical laying conditions. It can be seen from figures that for defined laying conditions and load factor, minimum temperature almost do not depend on daily diagram profile, while soil temperature have dominant effect. Decreasing of referent ground temperature for 10°C (from 20°C to 10°C) leads to decreasing of conductor temperature about 7°C. Otherwise, for referent ground temperature 20°C, overload factor 1.2 and different values of thermal resistivity of soil and distances between adjacent cables, it can be adopted minimum temperature value 52°C regardless of the laying conditions. This conclusion is carried out under assumption that duration of high level loading is up to six hour. Duration of maximum load level in power system of Serbia is up to three hours, so that minimum temperature for specified values of ground temperature and overload factor is smaller than this estimated value.



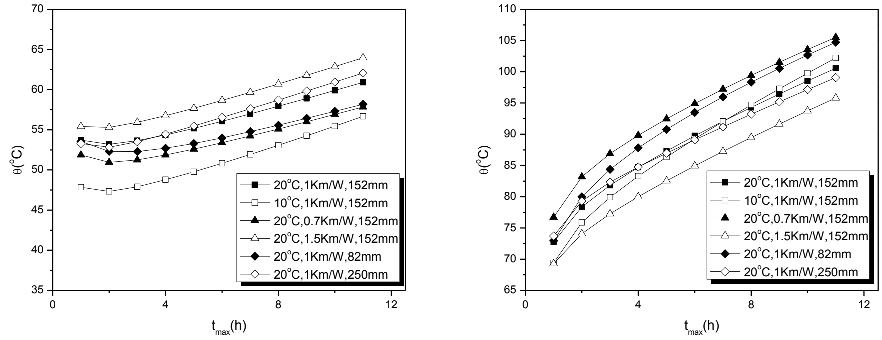
a) b)

Fig. 4 Maximum and minimum daily temperature for m=0.6, I_{max}/I_R=1.1
a) minimum temperature, b) maximum temperature



a) b)

Fig. 5 Maximum and minimum daily temperature for m=0.6, I_{max}/I_R=1.2
a) minimum temperature, b) maximum temperature

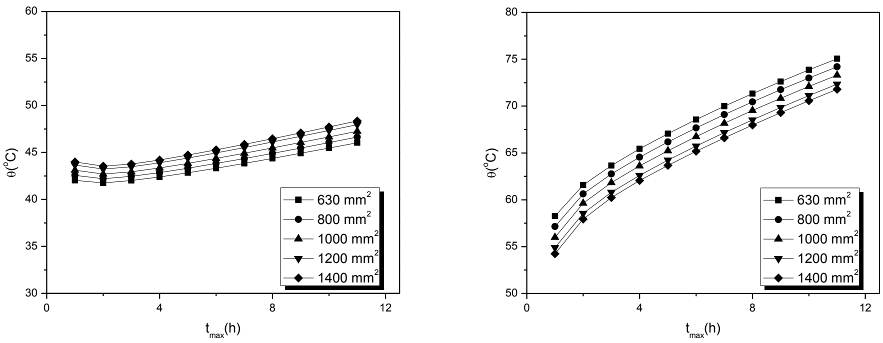


a) b)

Fig. 6 Maximum and minimum daily temperature for m=0.6, I_{max}/I_R=1.3
a) minimum temperature, b) maximum temperature

Maximum daily temperatures shown in Fig. 5.b are smaller than 90°C for all laying condition and all durations of high load level interval. Therefore, cyclic rating factor is larger than 1.2 for load factor 0.6 and all laying and ambient conditions as well as all durations of high load level. From Fig. 6.b can be seen that cyclic rating factor is 1.3 for 20°C referent ground temperature, and distance between adjacent cables 70 mm ($a=D_e$+70mm), thermal resistivity of the soil 0.7 Km/W and duration of high load level interval of 4 hours. For other conditions shown in Fig 6.b cyclic rating factor is 1.3 for duration of high load level larger the 4 hours (about 4.6 hour for $a=D_e$ and ρ_T=1 km/W; about 6 hours for $a=D_e$+70mm and ρ_T=1 km/W).

Fig. 7 and Fig. 8 show minimum and maximum conductor temperature for cables of different cross-section area. Temperature of referent ground is 20°C, distance between adjacent cables 70 mm ($a=D_e$+70mm) and load factor 0.6. The figures show that daily variation of conductor temperature is more pronounced. It can be noticed that minimum daily temperature for each following larger cross-section is 0.5°C to 1°C lower, while the maximum temperature is 1°C to 1.5°C higher.



a) b)

Fig. 7 Maximum and minimum daily temperature for m=0.6, θ_g=20°C, I_{max}/I_R=1.1
a) minimum temperature, b) maximum temperature

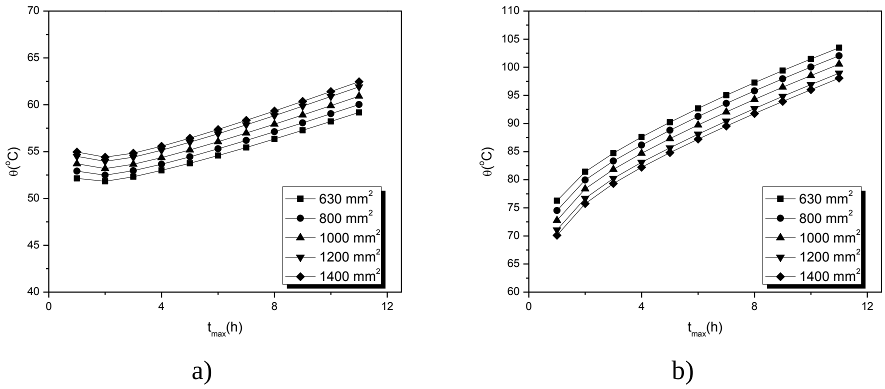


Fig. 8 Maximum and minimum daily temperature for m=0.6, θ_g=20°C, I_{max}/I_R=1.3
a) minimum temperature, b) maximum temperature

6. CONCLUSION

This paper presents results of transient heating analysis of buried single-core XLPE cables exposed to different daily load profiles. In order to analyze transient heating of cables a daily load diagram with three levels, which can be described by two parameters, is used. International standards give simple methodology for calculation of cyclic rating factor of cables under assumption that maximum temperature does not exceed rated temperature. On the other hand, calculation of daily variation of cable temperature is not so simple task. The results presented in paper include 110 kV cables with different cross-section area of aluminum conductor, for different laying and ambient conditions, as well as for different parameters of load profile. The calculation results are graphically illustrated and discussed. It is shown that the minimum temperature is in a very narrow range for cables of different cross-section areas as well as different laying conditions. The presented diagrams can be used in the analysis of thermal aging of cables exposed to cyclic daily load profiles. In addition, diagrams can be used for assessment of overload capability of cables in emergency operation preceded by cyclic loading when temperature proceeding to emergency operation is important.

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