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Cyclic Current Ratings of Single-Core XLPE Cables with Respect to Designed Life Time

***Abstract**. This paper provides an overview of overload capacity of single-core XLPE cables buried in the ground. Cyclic rating factor obtained by IEC60853-1 and IEC60853-2 standards is conservative due to assumption that maximum temperature during the cycle is equal to rated temperature. Using the procedure proposed by IEC60853-2, transient temperature response of the cables exposed to daily cyclic loading is calculated. Then, overload capacity of cables is obtained with respect to assigned design life of cables using Arrhenius-IPM electrothermal life model.*

***Streszczenie.** W artykule przedstawiono wyniki analizy możliwości przeciążeniowych jednożyłowego kabla grzebanego w ziemi. Na podstawie procedury zawartej w standardzie IEC60853-2 określono wpływ dobowego obciążenia energetycznego na zmiany temperatury kabla. Następnie korzystając z modelu elektro-termalnego Arrhenius-IPM i uwzględniając dane znamionowe określono możliwości przeciążeniowe kabli. (**Wyznaczanie okresowego obciążenia prądowego kabla jednożyłowego XLPE z uwzględnieniem znamionowego czasu życia**).*

Keywords: single-core cables, cyclic current rating, electrothermal life model.
Słowa kluczowe: kable jednożyłowe, okresowe obciążenie prądowe, model elektrotermiczny.

Introduction

Power cables are designed under the conservative constraints that their maximum temperature is constant and equal to rated temperature, which is the consequence of the fact that rated current of HVAC cables implies the operation at the rated temperature, i.e. the maximum permissible continuous temperature of cable insulation. Calculation of cable current caring capacity, as well as the calculation of the overload capacity of cables under cyclic loading occupies the attention of experts for a long time [1-5]. Fundamentals of these calculations are set out in paper [1]. References [4, 5] among others give a method for calculating the variation of the cable conductor temperature during a stepwise-constant load cycle by calculating the thermal response of the HVAC cable and the surrounding environment to each step change of load current.

Overload capacity of cables is usually quantified by cyclic rating factor. Standard IEC60853-1 [4] provides the method for calculating the cyclic rating factor for cables whose internal thermal capacitance can be neglected. Simplified method presented in this standard requires only knowledge about the shape of the load variation for not more than six hours immediately preceding the time of maximum temperature and an average value of times before that. The method can be applied to all sizes and types of cables for nominal voltage up to and including 18/30 (36) kV. Standard IEC60853-2 [5] provides the manual method for calculating cyclic rating factor for cables whose internal thermal capacitance cannot be neglected. In general, this method is applied to cables for nominal voltages greater than 18/30 (36) kV. Cyclic ratings include temporary overloads under condition that rated temperature is not exceeded. Considering this, cable exposed to cyclic loading with cyclic rating factor calculated according to standard IEC60853, reaches the nominal temperature only at one point. Cable temperature, during all day, is lower than its nominal value. The question is, whether and how much the cables can be additionally loaded without the risk or causing economic damage. Temperatures higher than nominal are allowed in emergency regimes, and these regimes are considered also when determining the life time of cable. Therefore, the limit on the maximal permissible temperature during cyclic loading depends on the life time of cable or maximal permissible temperature in emergency regime.

The procedure for life estimation of high voltage AC cables subjected to voltage and load cycles is proposed in [6-8]. As possible alternatives for representing the effects of the electrothermal aging of insulation, three different life models are considered in [7], each within the probabilistic framework needed for associating time-to-failure with reliability.

In this paper, the overload capability of single-core XLPE cables buried directly in the ground is analyzed. Firstly, the temperature of the cable is calculated for two types of daily load cycle diagram of HVAC cables. Using the Arrhenius-IPM electrothermal life model, expected life time of single-core XLPE cables, as well as failure rate at the end of design life time are calculated for different values of overload factor.

Thermal response of cables and cyclic rating factor

Loading of HVAC power cables varies on the daily cycles. In order to perform computations for variable loading, daily load curves are divided into a series of steps with constant magnitude and with the same duration as that illustrated in Fig. 1. In this figure it can be distinguished two different daily load cycles, Cycle I and Cycle II. Duration of one step is $\Delta t_i = 24/N$, where N is the number of steps. For different successive steps, the computations are done repeatedly, and the final result is obtained using the principle of superposition.

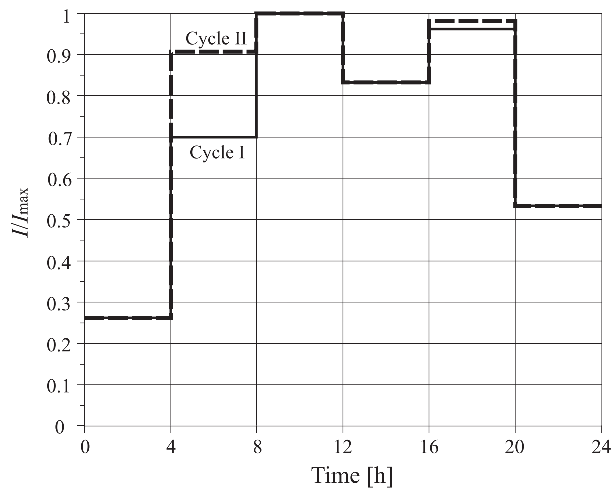

Fig.1. Daily load cycle diagram

The variation of the cable conductor temperature during a stepwise-constant load cycle can be determined by calculating the thermal response of the HVAC cable and the surrounding environment to each step change of load current. The two partial temperature transients are solved separately in a sequence and then combined, thereby finding an analytical solution for the whole transient as follows.

Transient temperature rise of the conductor above the ambient temperature, due to the i^{th} step of stepwise-constant load cycle is:

(1) $$\theta_i(t) = \theta_{c,i}(t) + \alpha_i(t) \cdot \theta_{e,i}(t)$$

where $\theta_{c,i}(t)$ is transient temperature rise of the conductor above cable surface, $\theta_{e,i}(t)$ is cable surface temperature rise above ambient temperature and $\alpha_i(t)$ is attainment factor. Transient temperature rise of the conductor above cable surface is calculated as:

(2) $$\theta_{c,i}(t) = W_{J,i}[T_a(1-e^{-at}) + T_b(1-e^{-bt})]$$

where $W_{J,i}$ is power loss per unit length in a conductor due to the i^{th} current step, and T_a, T_b, a, b are thermal resistances and corresponding coefficients of the first loop of CIGRE transient two loop network [5].

For the case of three single-core cables buried directly in the ground in a flat formation temperature rise of cable surface above the ambient is:

(3) $$\theta_{e,i}(t) = \frac{\rho_{te} W_{1,i}}{4\pi}\left\{-Ei\left(-\frac{D_c^2}{16t\delta}\right) + Ei\left(-\frac{h^2}{t\delta}\right) + 2\left[-Ei\left(-\frac{d_1^2}{16t\delta}\right) + Ei\left(-\frac{d'^2_1}{16t\delta}\right)\right]\right\}$$

where: ρ_{te} is thermal resistivity of soil, δ is diffusivity, D_c is outer diameter of cable, h is laying depth, d_1 is center-to-center distance between cables, $d_1' = \sqrt{(2h)^2 + d_1^2}$, $W_{1,i} = W_{J,i}(1+\lambda_1)$, λ_1 is sheath loss factor, and Ei is exponential integral [9].

The attainment factor in equation (1) is calculated as:

(4) $$\alpha_i(t) = \frac{\theta_{c,i}(t)}{W_{J,i}(T_a + T_b)}$$

Finally, the temperature of conductor is obtained by adding the temperature rise for each step of the load diagram, calculated by (1), to temperature of the ground and temperature rise due to dielectric losses. Electrical resistance of conductor and corresponding Joule losses are calculated with respect to temperature of conductor reached in each step of daily diagram.

The cyclic rating factor is defined as the factor by which the rated current may be multiplied to obtain the permissible peak value of current during a daily load cycle such that the conductor attains, but does not exceed the rated temperature. For calculating cyclic rated factor, according to standard IEC60853-2, only load cycle over a period of six hours before the time of maximum temperature is needed, while earlier values are replaced with constant one, proportional to loss-load factor. Therefore, the cyclic rating factor is given by:

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

where:

(6) $$\frac{\theta_R(t)}{\theta_R(\infty)} = \alpha(t)(1 - k_1 + \beta(t)k_1)$$

(7) $$k_1 = \frac{W_1(T_4 + \Delta T_4)}{W_J(T_A + T_B) + W_1(T_4 + \Delta T_4)}$$

(8) $$\beta(t) = \frac{\rho_{te}}{4\pi(T_4 + \Delta T_4)}\left\{-\mathrm{Ei}\left(-\frac{D_c^2}{16t\delta}\right) + \mathrm{Ei}\left(-\frac{h^2}{t\delta}\right) + 2\left[-\mathrm{Ei}\left(-\frac{d_1^2}{16t\delta}\right) + \mathrm{Ei}\left(-\frac{d_1'^2}{t\delta}\right)\right]\right\}$$

Thermal resistance T_4 for cable buried directly in the ground is:

(9) $$T_4 = \frac{\rho_{te}}{2\pi}\ln\left(\frac{2h}{D_c} + \sqrt{\left(\frac{2h}{D_c}\right)^2 - 1}\right)$$

while thermal resistance ΔT_4 in the case of cable line consisted of three single-core cables is:

(10) $$\Delta T_4 = \frac{\rho_{te}}{\pi}\ln\left(\frac{d_1'}{d_1}\right)$$

Obviously, the method for cyclic rating factor calculation does not take into account the variation of conductor temperature and assumes that Joule losses are directly proportional to square of current. The results obtained on this way are therefore also conservative.

Electrothermal life model

Electrical stress and thermal stress are dominant factors when considering the aging of HVAC cables. The most popular electrothermal life model is the combination of two single-stress life models, the Arrhenius model for thermal life and the Inverse power model for electrical life [7, 8]. Expected life time of the cable whose temperature is T and electric field in insulation is E can be calculated:

(11) $$L = L_0\, e^{-B\,cT}\left(\frac{E}{E_0}\right)^{-(n_0 - b\,cT)}$$

where E_0 is value of electric field below which electrical aging is negligible, $cT=1/T_0-1/T$ is conventional thermal stress, T_0 is reference temperature, n_0 is voltage endurance coefficient, L_0 is life at $T=T_0$ and $E=E_0$, $B=\Delta W/k$, ΔW is activation energy of the main thermal degradation reaction, k is Boltzmann constant, and b is parameter that rules synergism between electrical and thermal stress. The parameters of Arrhenius-IPM model for XLPE insulation are given in Table 1 [7]. During one step of daily stepwise-constant load cycle temperature of insulation varies. Therefore, different values of thermal life of cable insulation are obtained for each moment during the day. Loss-of-life fraction relevant to the i^{th} step of stepwise-constant load diagram (Fig. 1) is defined as:

(12) $$LF_i = \int_0^{\Delta t_i} \frac{dt}{L_i(T)}$$

Table 1. Parameters of Arrhenius-IPM model

Parameter	Value
b [K]	4420
B [K]	12430
n_0 [non-dimensional]	15
E_0 [kV/mm]	5
T_0 [K]	293
β_t	2

According to Miner's cumulative damage theory, the sum of all loss-of-life fractions should yield 1 at failure. So, number of cycles to failure (number of days to failure in case of daily cycles) is:

(13) $$K=\left(\sum_{i=1}^{N}LF_i\right)^{-1}$$

Design life of cable corresponds to certain design failure probability. The cumulative probability distribution function that is commonly used for associating time to failure probability in case of polymeric insulation for power cables is the Weibull's one. Failure probability at mission time t_p is:

(14) $$P(t_p,E,T)=1-e^{[-(t_p/L_{63\%})^{\beta_t}]}$$

where β_t is share parameter of cumulative probability distribution function and $L_{63\%}$ is failure-time with 63.2% probability. The relevant failure rate at time t_p can be estimated through the following hazard function:

(15) $$h(t_p,E,T)=\frac{\beta_t}{L_{63\%}}\left(\frac{t_p}{L_{63\%}}\right)^{\beta_t-1}$$

Based on the equation (15) failure rate can be calculated for insulation of cable loaded by defined daily stepwise-constant cycle at the end of design life time.

Test example

The procedure described in the previous sections is applied to HVAC XLPE insulated single-core cables [10] with aluminium conductors and copper wire screen. Maximum voltage of cables is 123 kV. The data about cables are shown in the Table 2. In Table 2, S_c is conductor cross section, d_c is diameter of conductor, D_i is diameter above the insulation, δ_i is insulation thickness, D_c is outer diameter of cable, and I_R is rated current for considered cable formation and used bonding method of metal screens. It is assumed that three single-core cables are laid in a flat formation and metal screens of cables are cross-bounded.

Table 2. Cable data

S_c [mm^2]		630	800	1000	1200	1400
d_c [mm]		29.8	33.7	37.9	42.8	46.4
D_i [mm]		58.6	62.5	67.3	73.8	77.4
δ_i [mm]		13	13	13	13	13
D_c [mm^2]		72.3	76.8	82	89.5	93.3
I_R [A]		740	845	950	1025	1100
M	Cycle I	1.174	1.18	1.186	1.192	1.196
	Cycle II	1.146	1.15	1.154	1.159	1.162

Laying depth of cables is 1 m, ground temperature 20°C and distance between cables is d_l=D_k+70 mm. Design life of cables is 30 years, while rated temperature of conductor is 90°C. Thermal resistivity and thermal capacity of cross-linked polyethylene are 3.5 Km/W and 2.4·10^6 J/(m^{3}K), respectively; thermal resistivity of soil 1 Km/W, and thermal capacities of aluminium and copper are 2.5·10^6 J/(m^{3}K) and 3.45·10^6 J/(m^{3}K), respectively. It is assumed that the constant electric field is equal to design values. Currents that correspond to each step of daily load cycle are given in Table 3.

Table 3. Daily load cycle

Step. No.	Time [h]	I/I_{max}	
		Cycle I	Cycle II
1	00-04	0.26	0.26
2	04-08	0.70	0.91
3	08-12	1	1
4	12-16	0.83	0.83
5	16-20	0.96	0.98
6	20-24	0.52	0.52

Daily variation of conductor temperature for the Cycle I of single-core XLPE cable with 1000 mm^2 cross-section is shown in Fig. 2 for different values of overload factor (maximum current relative to rated current). Numerical values of stepwise-constant cycle loadings shown in Fig. 1 are given in Table 3. For overload factor (I_{max}/I_R) value of 1, difference between maximum and minimum temperatures is only 16.8ºC (varies between 47.1ºC and 63.9ºC), while for overload factor value of 1.4 this difference is 39.4ºC (varies between 82ºC and 121.4ºC). Also, from the Fig. 2 it can be noted that for overload factor value of 1.2, the maximum temperature of conductor is close to 90ºC. Having in mind that XLPE cable may be overloaded up to 105°C in emergency regime, from Fig. 2 can be concluded that the overload factor for cycle I loading must be lower than 1.3.

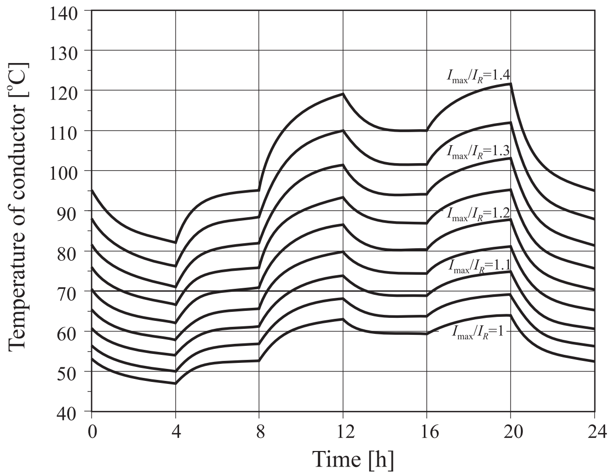

Fig. 2. Temperature variation during daily cyclic loading I

The last row of Table 2 shows the results of cyclic rating factors (Cycle I and Cycle II) calculated by (5). As can be seen, these values vary in very narrow range between 1.174 and 1.196 for the Cycle I, and between 1.146 and 1.162 for the Cycle II. For 1000 mm^2 cross-section cyclic rating factors have values of 1.186 (Cycle I) and 1.154 (Cycle II). For obtained daily variations of conductor temperature, the expected life time of cable during cyclic loading (shown on Fig. 1) for different values of overload factor is calculated using relations (11)-(13).

Fig. 3 shows expected life time of single-core XLPE cables for the case of cycle loading I, with different cross-section areas in the case of daily cyclic loading as function of overload factor. Having in mind that design life of cable is 30 years, it is obvious that for daily cyclic diagram I cables can be overloaded more than 28% without shortening the life time. As previously noticed, according to the Fig. 2, overload factor of the cable for given daily cycle diagram and maximal temperature of 90ºC is slightly above 1.2. Fig. 3 shows that cable life time from the aspect of electrothermal aging, for given overload factor of 1.2, is nearly 80 years. For cyclic rating factor of 1.186 calculated according to relevant standard, life time from the aspect of electrothermal aging is approximately 90 years.

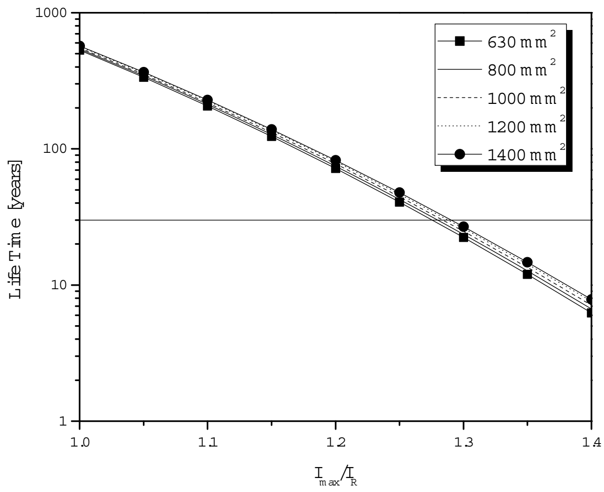

Fig. 3. Life time of cables for cyclic loading I

Fig. 4 shows results of failure rate calculation at the end of design life time. As can be seen from this figure, for overload factor of 1.186 or 1.2, values of failure rates at the end of design life time are very low. Having in mind all the facts stated above, it can be concluded that considered power cable (with 1000 mm^2 cross-section) has the potential for additional current load increase of 8.3% compared to the value obtained by the standard. This additional current load increase is similar to ones which correspond to other power cables with different cross-sections.

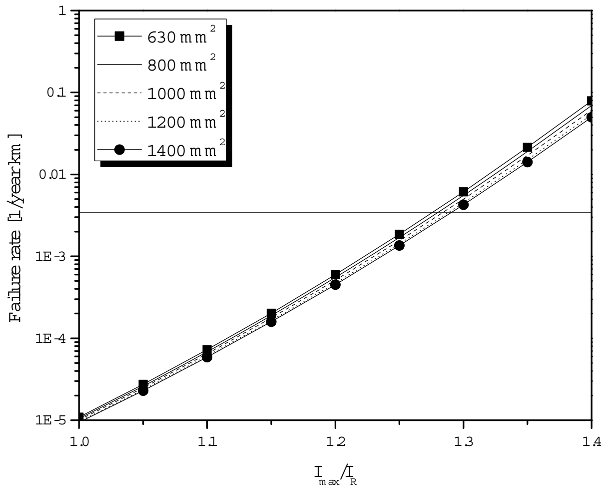

Fig. 4. Cables failure rate at the end of design life for cycle I

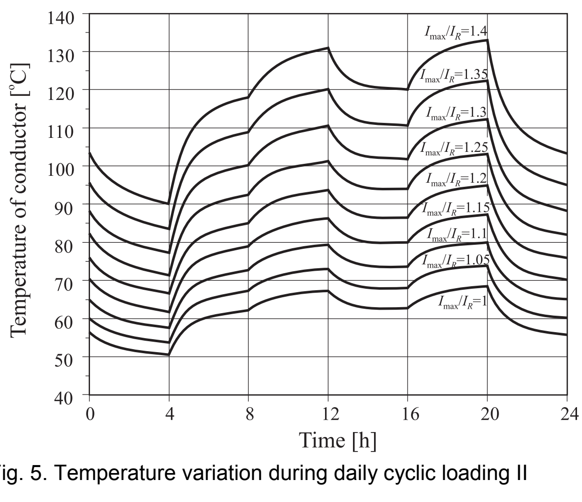

Fig. 5. Temperature variation during daily cyclic loading II

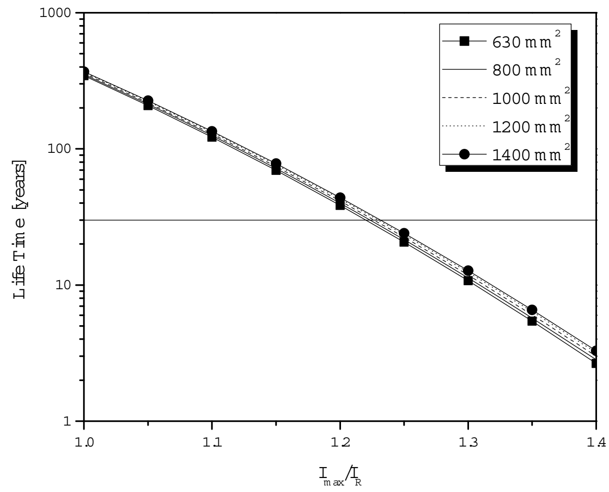

Fig. 6. Life time of cables for cyclic loading II

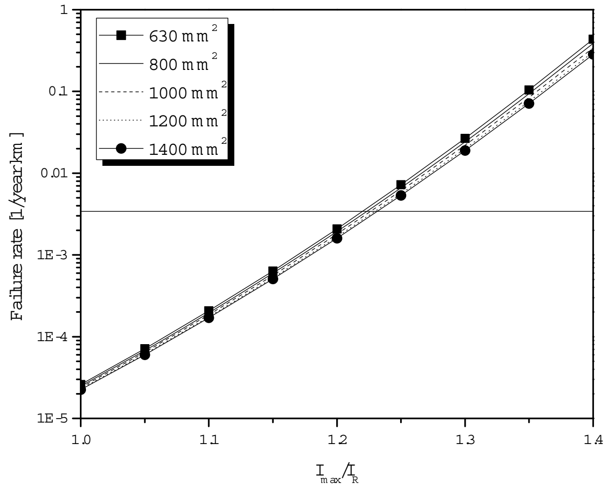

Fig. 7. Cables failure rate at the end of design life for cycle II

Fig. 5 illustrates the temperature variation during daily cycling loading II, while Fig. 6 and fig. 7 illustrate life time of cables and cables failure rate at the end of design life for cycle II, respectively. The same analysis can be carried out for the case of cycle loading II and also, the same conclusion can be derived. The only difference between two cycles is that for the cycle loading II, additional current load increase is approximately 6% and for the cycle loading I it accounts approximately 8%, compared to values obtained by the standard.

Conclusion

In this paper, a transient temperature response calculation of single-core XLPE cables buried in the ground, at two daily load cycles, is conducted. For the assumed daily load cycles, cyclic rating factors and daily temperature variations at different values of overload factor are determined. On the basis of obtained results, it is shown that rated temperature is attained at values of overload factors slightly higher than cyclic rating factor values. Using the Arrhenius-IPM electrothermal model, expected cable life time for different values of overload factors, respecting the daily cable temperature variations, is determined. On the basis of obtained results, it is concluded that overload capability of single-core XLPE cables, considering the design life time, is higher than one obtained by relevant IEC standard. It is shown that cables can be additionally loaded up to 8%, depending on the cycle.

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