# THERMAL AGING MANAGEMENT FOR ELECTRICITY DISTRIBUTION NETWORKS: FEM-BASED QUALIFICATION OF UNDERGROUND POWER CABLES

***Jelena Lj. KLIMENTA*** [1]***, Marija V. PANIĆ***[2]***, Miodrag S. STOJANOVIĆ***[3]***, Dardan O. KLIMENTA***[4*]***, Miloš J. MILOVANOVIĆ***[4]***, and Bojan D. PEROVIĆ***[4]

[1]ProElectric SD, Kraljevo, Serbia
[2]Technical Faculty in Bor, University of Belgrade, Bor, Serbia
[3]Faculty of Electronic Engineering, University of Niš, Niš, Serbia
[4]Faculty of Technical Sciences, University of Priština in Kosovska Mitrovica, Kosovska Mitrovica, Serbia

[*] Corresponding author; e-mail: dardan.klimenta@pr.ac.rs

*It is well-known that there is no PLAN-DO-CHECK-ACT (PDCA) approach that is used by electricity distribution network operators and asset managers of power cable systems. Accordingly, this paper proposes a novel application of the PDCA approach to thermal aging management of underground power cables in electricity distribution networks. Another novelty of the proposed approach is that the finite element method (FEM) is used in combination with the traditional Arrhenius model to calculate the unknown temperature of cable conductors under service conditions. In particular, this means that the FEM-based Arrhenius model can involve the effects of other heat sources, wind, solar irradiation, etc. in procedures for qualification of underground power cables. The Arrhenius model is applied to an actual hot spot of a 110 kV underground cable line of most importance to reliable operation of the electricity distribution network of the City of Belgrade. In the hot spot, the 110 kV cable line is installed in parallel with the group of 35 kV cables and crosses an underground heating pipeline. The proposed approach is successfully validated using the existing experimental data on cross-linked polyethylene insulation. Finally, it is found that the hot spot effect can shorten the expected total service lifespan of the 110 kV cables in the hot spot area by 36.84 %, as well as that the largest consumption of total thermal lifespan occurs in the presence of all the existing thermal effects.*

Key words*: Arrhenius model, finite element method (FEM), hot spot, qualification, thermal aging management, underground power cable*

## 1. Introduction

Underground cable lines are vital components of electricity distribution networks within electric power systems since they connect two transformer stations, a power consumption with a transformer station, or a power consumption with the power supply in general. All equipment important to reliability, including power cables, therefore need to be qualified to perform their functions properly under normal, emergency and fault conditions at any moment during their service lifespans. According to [1-3], qualification procedures can be applied to any equipment in a nuclear power plant (NPP).

Thus, the procedures can be used to qualify power cables [1], instrumentation and control cables [2], reactor vessel internals [4], concrete containment structures [5], and so on. All previously mentioned publications refer to equipment in NPPs, but the knowledge acquired in this area can be generalized to the case of electricity distribution networks and associated companies.

The first part of any procedure for qualification of underground cable lines should be the development of a detailed qualification plan, which would contain the selected condition indicators and acceptance criteria. Such plan would also describe the limiting service conditions, the targeted service lifespan, and the technique applied. According to [6,7], qualification can be undertaken in several manners, as type testing, operating experience, and theoretical analysis. These manners can be applied individually or in combination depending on the specific problem. In type testing, samples of power cables are exposed to test conditions in order to simulate thermally induced degradation during the qualified lifespan and design-basis events [6,7]. Qualification of power cables by means of type testing is generally undertaken. Operating experience is available for qualification of power cables that actually operated under specific service conditions, but design-basis event testing must be performed using a test cable [6,7]. Qualification of power cables only by means of theoretical analysis (for instance, based on the physical properties of cable insulation) is not acceptable, but must be undertaken in combination with type testing or operating experience [6,7].

For asset managers of power cable systems around the world, the main challenge is how to manage effectively the vast electricity distribution networks consisted of a large number of expensive underground cable lines, many of which are approaching the end of, or have passed, their designed lifespans [8]. The researchers and scientists have so far analyzed load diagrams [9,10], thermal IEC-based (analytical) models [9,10], and thermal finite element method (FEM)-based (numerical) models [11-13] of various power cables for the purposes of associated thermal aging management. The most frequently analyzed power cables are those with cross-linked polyethylene (XLPE) insulation, which have the expected total service lifespan of 40 years and which are not considered to be replaced or relocated during their designed lifespans [9,12,14,15]. Since the underground cable lines have limitations in terms of accessibility, visual and physical inspections, and applications of diagnosis techniques, it is crucial to estimate the condition of power cables and determine appropriate time for replacement or relocation of them [9,16,17]. Hence, it is necessary to estimate the condition of underground cable lines based on limited available data such as cable specifications and service (environmental and operating) conditions. In addition, it is known that hot spots can accelerate thermal aging of cable insulation [18], as well as that the Arrhenius model is widely used to quantify the effects of temperature and time on the aging process [1,2,6,7,9,10,14,16]. There are a large number of publications dedicated to the thermal aging management of power cables and the application of the Arrhenius model. A review on research towards life cycle management of power cables is given in [8].

In this paper, the PLAN-DO-CHECK-ACT (PDCA) approach or cycle, that is usually used for carrying out control and continuous quality improvement in organizations and companies, is adjusted and applied to thermal aging management of underground cable lines in the electricity distribution company of the City of Belgrade. The continuous improvement methodology is established on the Deming Cycle principle (PDCA Cycle), which was popularized by W. E. Deming. The interaction of PDCA methodology and process approach is the essence of the ISO 9001 quality management system. The process approach is based on the premise that for an organization to operate effectively, its interrelated actions (processes) must be identified and managed in a simple, efficient, and effective manner. According to the ISO 9001 standard, a process is a collection of activities that use resources to convert inputs into outputs (products or services). The principle of continuous improvement is directly related to the process approach to organizational management. It is based on the fact that continuous improvement of the overall working capacity of the organization is the ultimate goal of any organization with an established quality management system.

The application of the adjusted PDCA approach is regarded as the first novelty. In addition to this, the PLAN- and CHECK-stages of the proposed management approach, that respectively use the Arrhenius model to qualify equipment (power cables and their accessories) and analyze data from accelerated thermal aging tests, are modified by the introduction of the FEM in the Arrhenius model. This modification is done to include the potential effects of problem geometry, adjacent heat sources, initial conditions, boundary conditions, and various material properties on the unknown temperature of conductors in an underground cable line. The FEM-based Arrhenius model represents the second novelty of this paper. Then, such an Arrhenius model is applied to an actual hot spot of a 110 kV underground cable line, consisting of three single-core cables with XLPE insulation. In the hot spot, in addition to these 110 kV cables, there are the group of four 35 kV underground cables with impregnated paper insulation and one underground heating pipeline [19,20]. The 110 kV underground cable line belongs to the ring electricity distribution network of the City of Belgrade and is of most importance to its reliable operation. This particular case study and its analysis can be regarded as the third novelty. Finally, in order to combine thermal FEM-based analysis with experimental data, validate the proposed management approach, and avoid possible uncertainties, XLPE insulation materials with different values of the activation energy (1.24 eV and 1.34 eV) are considered [1,21]. The experimental data from [1] were provided by Ogden Environmental and Energy Services Co., Inc. from the USA, while those from [21] were provided by the U.S. Nuclear Regulatory Commission (also called, the NRC).

After the introducing section of this paper, Section 2 provides general requirements for the considered thermal aging management approach, and Section 3 proposes the FEM-based Arrhenius model. The results and associated discussions are presented in Section 4, while the conclusions are outlined in Section 5. Nomenclature and references are given at the end.

## 2. General requirements for thermal aging management

Underground power cables are very durable under favourable thermal environmental conditions, and their performance as components of electricity distribution networks has usually been satisfactory. Operating experiences show that thermally induced degradation can be a result of exposure to unfavourable thermal and radiation environments, emergency and fault (short-circuit) conditions, and the use of unsuitable cable bedding materials or inadequate thermal insulation in hot spots. In other words, thermal stresses can result from high ambient temperatures, high solar irradiation, hot spots (the proximity of other heat sources), or heating resulting from losses generated within the cable construction elements. These environmental and operating factors are known as thermal stressors.

The effects of thermally induced degradation of the cable construction elements can involve embrittlement, melting, softening, discoloration, cracking or crazing, and changes in the electrical, mechanical and thermal properties of materials that are essential for the power cables to perform their design functions. Thus, the unfavorable service conditions can cause chemical and/or physical processes at the molecular level of materials in the cable construction [2]. These processes represent the thermal aging mechanisms. In addition to this, the consequences at the macroscopic level are slow and irreversible changes in the material properties. According to [2], typical macroscopic changes in the properties of cable construction materials are: (i) a decrease in the tensile elongation of materials, (ii) an increase in the hardness or compressive modulus of materials used for outer protective sheaths, (iii) an increase in the material density, and (iv) changes in the electrical properties of materials. In the worst cases, these issues can affect the reliable and long term operation of an electricity distribution network. The issues can require various actions ranging from inspection and monitoring up to and including maintenance activities such as relocation or replacement of power cables. However, the performance requirements defined by the basic design parameters and reliability analysis of the underground cable lines should not be affected by the mentioned issues if the cable lines are kept in good conditions by timely detection and mitigation or elimination of thermally induced degradations. These degradations may be short- and long-term thermal degradations [1].

The data and knowledge from a large number of reports on operating experiences with NPPs around the world can be utilized for development of a systematic and integrated approach to manage thermal aging of underground power cables in electricity distribution networks. Such an approach to managing the aging of instrumentation and control cables used in NPPs is presented in [2]. According to [3], the same approach can be applied to the aging of any equipment in a NPP. Furthermore, this approach can be used to manage the aging of reactor vessel internals [4], concrete containment structures [5], and so on. Accordingly, it is obvious that there is a PDCA approach that can be linked to management programs commonly implemented in electricity distribution networks. Such a PDCA approach suitable to electricity distribution networks is shown in Fig. 1.

An understanding of the relevant thermal aging mechanisms and their potential effects on underground cable lines is the key to a systematic and integrated approach for thermal aging management. A set of key knowledge for effective thermal aging management includes the following: **(i)** materials and their properties; **(ii)** thermal stressors; **(iii)** service conditions; **(iv)** principal thermal aging mechanisms; **(v)** localization and mapping of hot spots; **(vi)** consequences of thermally induced degradation; **(vii)** existing historical data on emergency and fault (short-circuit) conditions; **(viii)** thermal indicators (temperature, thermal gradients, thermal conductivity, etc.) of actual conditions; **(ix)** research and development results; **(x)** methods for mitigation or elimination of hot spots; and **(xi)** knowledge gathered from the latest experiences worldwide.

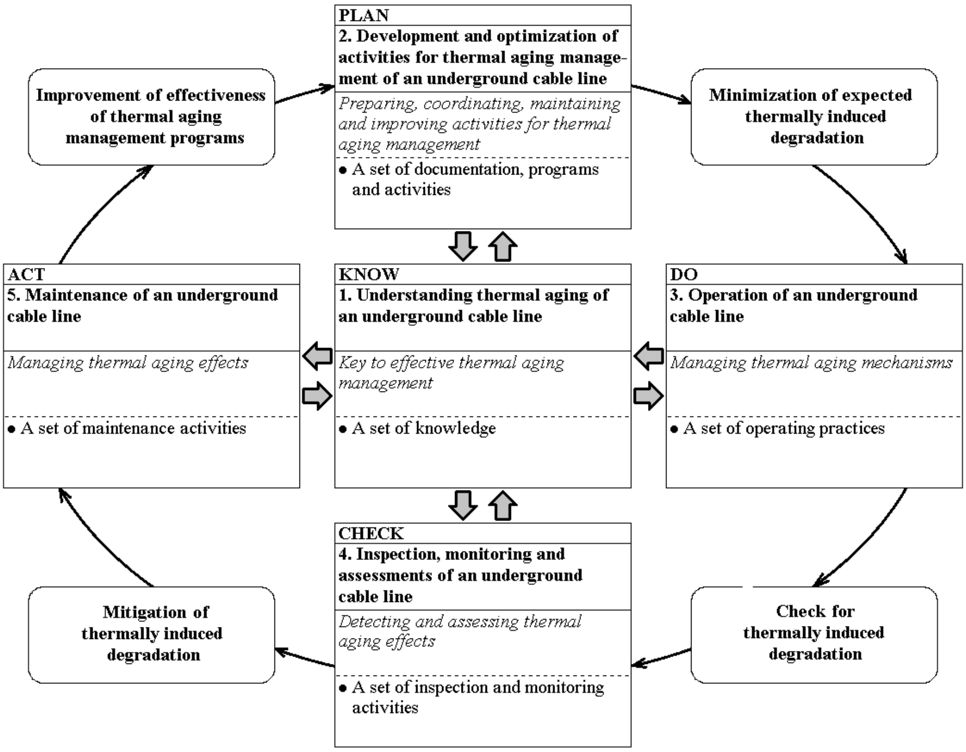

**Figure 1. Systematic and integrated approach to manage thermal aging of underground cable lines in electricity distribution networks [2,3]**

The PLAN-stage of the management approach in Fig. 1 refers to the development, coordination, maintaining, improvement, integration and optimization of the documentation, programs and activities related to thermal aging management of an underground cable line. A set of documentation, programs and activities for thermal aging management should include but is not limited to: **(i)** optimizing the operation, maintenance and useful lifespan of power cables and their accessories; **(ii)** maintaining an acceptable level of performance and safety; **(iii)** maximizing return on investment over the useful lifespan of the cable line; **(iv)** actions to improve the condition of any power cable or accessory prior to its failure; **(v)** documenting regulatory requirements and safety criteria; **(vi)** qualification of equipment (power cables and their accessories, etc.); and **(vii)** technical support.

The DO-stage of the approach in Fig. 1 involves the management of thermal aging mechanisms by minimizing the expected thermally induced degradation of an underground cable line operating according to the approved procedures and technical specifications. A set of operating practices to manage thermal aging mechanisms includes: **(i)** operation according to procedures and technical specifications: thermal environment (ambient temperature, thermal conductivity, solar irradiation), and load conditions; **(ii)** mitigation of hot spots: avoiding drying-out of the surroundings, eliminating the effects of solar irradiation, and the use of qualified methods for increasing the cable ampacity; **(iii)** careful handling during utilization and inspection of power cables and their accessories; and **(iv)** operating history: thermal environment, and daily, weekly, monthly or annual load diagrams.

The CHECK-stage of the management approach in Fig. 1 includes the inspection, monitoring, and assessments of an underground cable line to ensure timely detection and evaluation of thermal aging effects. A set of inspection and monitoring activities to detect and assess thermal aging effects includes the following: **(i)** visual and physical inspection; **(ii)** thermographic inspection; **(iii)** surveillance or other in-service testing; **(iv)** monitoring of temperature or/and other environmental conditions; and **(v)** Arrhenius analysis and the use of accelerated thermal aging data.

The ACT-stage of the approach in Fig. 1 refers to timely maintenance of thermally induced degradations of insulation in an underground cable line by the implementation of maintenance activities. A set of maintenance activities to manage thermal aging effects includes the following: **(i)** relocation of cables to avoid hot spots; **(ii)** the use of retrofitting procedures for modifying the thermal environment; **(iii)** replacement of thermally degraded cables; **(iv)** installation of spare cables at thermally-critical sections; and **(v)** maintenance history.

### 2.1. Key attributes of the PDCA approach

According to [5], a systematic and integrated approach to manage thermal aging of underground cable lines in electricity distribution networks can consist of existing programs such as periodic inspections, maintenance, condition assessments, obsolescence management monitoring, cables' health monitoring, and so on, and if required, development of new programs. There are several key attributes of the mentioned approach which are essential to effective thermal aging management of underground cable lines. The approach should include the following key attributes [2,3,5]:

- **Knowledge on actual thermal environments** – is essential to any effective thermal aging management approach for underground cable lines in electricity distribution networks. Without these specific data, particularly temperatures and thermal conductivity, it is not possible to focus efforts of the thermal aging management approach on those cable lines in thermal environments that can affect the ageing capabilities of materials in cable constructions. Without these details it is also difficult to estimate thermal aging of power cables with an acceptable degree of certainty.
- **Knowledge on materials in cable construction** – it is essential to know what organic materials are used for the insulation and outer protective sheath of power cables in electricity distribution networks. It is not sufficient to know only the type. This is because degradation of materials used for the insulation and outer protective sheath can be affected by additives, fillers, etc.
- **Visual inspection or condition monitoring** – visual inspection of power cables and their accessories provides valuable data on the current state of thermally induced degradation of materials. For electricity distribution network operators, this represents a practical manner to perform condition monitoring. In the case of underground cable lines of most concern, it can be necessary to combine visual inspection with other existing methods for condition monitoring.
- **Program for qualification of equipment (power cables and their accessories)** – Qualification of power cables and their accessories provides the basis for the thermal aging management approach, showing the ability of an underground cable line to operate satisfactorily during its lifespan, as well as during a failure, where required. The conservatism built into the program for qualification of power cables and their accessories should be balanced against the uncertainties in the accelerated thermal aging test (qualification method), when deciding on the extent of thermal aging management activities required in the approach from Fig. 1.
- **Focused approach on underground cable lines of concern** – it is not appropriate or practical to perform thermal aging management activities to all underground cable lines in an electricity distribution network. The best approach is to focus efforts on those cable lines which should

most likely be significantly degraded from their service conditions, thermal environments, or any failure, or are of most importance to reliable operation of the network.

## 3. FEM-based Arrhenius model

### 3.1. Case study

Fig. 2 illustrates the case study consisting of one 110 kV underground cable line and its hot spot. Fig. 2a presents the design of the 110 kV underground cable line outside the hot spot, while Fig. 2b presents the design of the same cable line in the hot spot. As this hot spot was discussed previously, the design of the group of four 35 kV cables outside the hot spot is not provided here. This is also due to the fact that the 110 kV cable line is of higher importance for network reliability than the group of 35 kV cables.

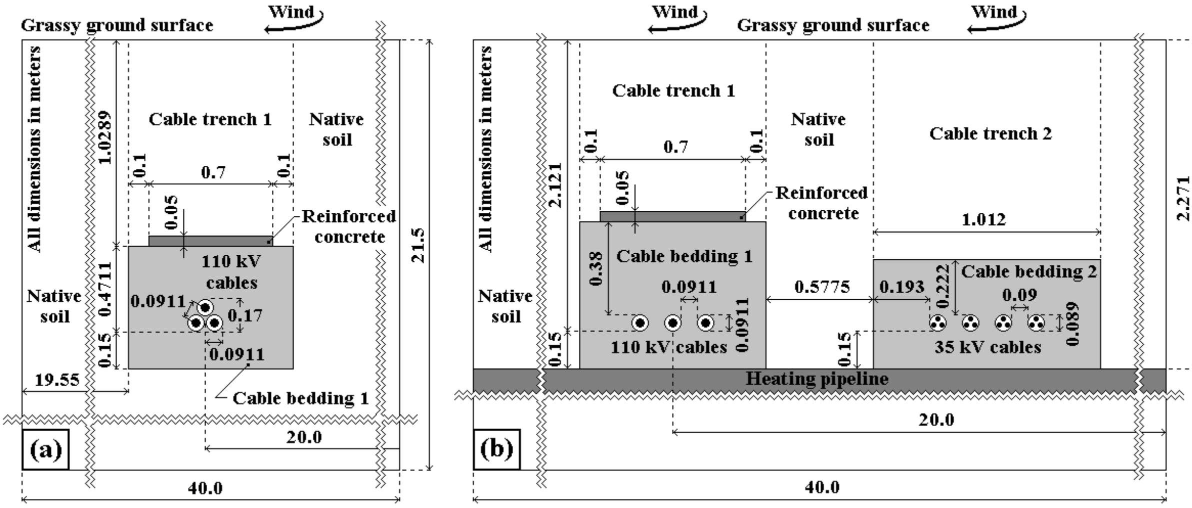

**Figure 2. Presentation of computational domains: (a) design of the 110 kV cable line outside the hot spot and (b) design of the 110 kV cable line in the hot spot [19,20]**

According to Fig. 2, the 110 kV cable line and group of four 35 kV cables are installed in the cable trenches 1 and 2, respectively. The 110 kV and 35 kV cables are of the following types: NA2XS(FL)2Y 1×1000/95 mm$^2$ 64/110 kV, and NAEKEBA 3×150 mm$^2$ 20/35 kV. A concrete duct of the heating pipeline in Fig. 2 has outer dimensions of 1.9 m×1.185 m [19]. For the purposes of FEM-based simulations with COMSOL Multiphysics software, according to IEC 60287 and IEC TR 62095, each of the 110 kV cables is modelled by an equivalent single-core cable composed of the aluminium conductor, XLPE insulation, copper screen, and outer high-density polyethylene (HDPE) sheath with outer diameters 0.0383 m, 0.0805 m, 0.0833 m, and 0.0911 m, respectively. In addition, each of the 35 kV cables is modelled by an equivalent three-core cable composed of the aluminium conductors, impregnated paper core insulation, separate lead sheaths, impregnated jute filling, steel armouring, and bitumen impregnated jute serving with outer diameters 0.0143 m, 0.0303 m, 0.0349 m, 0.0818 m, 0.085 m, and 0.089 m, respectively. All other relevant data on this case study can be found in [19,20].

### 3.2. FEM-based models for steady-state temperature distribution

For the computational domains in Fig. 2, steady-state heat conduction is governed by the following two-dimensional second-order partial differential equation:

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+Q_v=0, \tag{1}$$

that is solved by the FEM. In this equation, $T$ is the unknown temperature in K; $k$ is the thermal conductivity in Wm$^{-1}$K$^{-1}$; $x$ and $y$ are the Cartesian spatial coordinates in m; and $Q_v$ is the volume power of heat sources in $\mathrm{Wm}^{-3}$. The thermal conductivity for all materials appearing in the FEM-based models created are given in Tab. 1. The existence of the radiation boundary condition on the ground surface ensures nonlinearity of Eq. (1).

**Table 1. Thermal conductivity of all used materials [19,20]**

| **Material** | ***k*** | **Material** | ***k*** |
|---|---|---|---|
|  | **$\mathrm{Wm}^{-1}\mathrm{K}^{-1}$** |  | **$\mathrm{Wm}^{-1}\mathrm{K}^{-1}$** |
| Aluminium | 239 | Compounded jute | 0.167 |
| Copper | 385 | Paper insulation in solid type cables | 0.167 |
| Steel | 48 | Bedding around the 110 kV cables (cable bedding 1) | 0.55 |
| Lead | 34.5 | Bedding around the 35 kV cables (cable bedding 2) | 0.326 |
| HDPE | 0.286 | Native soil | 0.4 |
| XLPE | 0.286 | Reinforced concrete, 2000 kg/m$^3$ | 1.16 |

The volume power of heat sources $Q_v$ in each conductor of the 110 kV and 35 kV cables is

$$Q_v = \frac{R_{ac}(T_{cp})}{S'_c} \cdot I^2 \tag{2}$$

where $R_{ac}(T_{cp}=90\ °\mathrm{C})=40.3772\cdot10^{-6}\ \Omega\mathrm{m}^{-1}$ and $R_{ac}(T_{cp}=60\ °\mathrm{C})=243\cdot10^{-6}\ \Omega\mathrm{m}^{-1}$ are the effective conductor resistances to the flow of alternating current per unit length of the 110 kV and 35 kV cables at $T_{cp}$=90 °C and $T_{cp}$=60 °C, respectively; $T_{cp}$ is the continuously permissible temperature in °C; $S'_c=1152.093\cdot10^{-6}\ \mathrm{m}^2$ and $S'_c=160.606\cdot10^{-6}\ \mathrm{m}^2$ are the geometric cross-section areas of the 110 kV and 35 kV cable conductors, respectively; and $I$ is the cable ampacity (or load current) in A. The effective conductor resistances take the skin and proximity effects into account, together with losses in the metal screens or sheaths. For the 110 kV cables, this resistance corresponds to a trefoil formation from Fig. 2a, because of the 110 kV cables are installed in a flat formation in the hot spot only. According to IEC 60287, losses in the insulation and metal screens or sheaths of the 110 kV and 35 kV cables are absolutely negligible or equal to zero. Accordingly, it is assumed that the corresponding volume powers of heat sources are equal to zero. The facts supporting this assumption can be found in [19,20].

The left-hand, right-hand and bottom sides of the domain in Fig. 2a, and left-hand and right-hand sides of the domain in Fig. 2b are modelled by the zero heat flux boundary condition, i.e.

$$k \cdot \frac{\partial T}{\partial n} = 0\ \ \mathrm{Wm}^{-2} \tag{3}$$

where $T$ is the unknown temperature of the corresponding model boundaries in K, and $n$ is the length of the normal vector $\vec{n}$ in m.

The model boundary coinciding with the upper surface of the heating-pipe duct in Fig. 2b is represented with the constant heat flux boundary condition, i.e.

$$k \cdot \frac{\partial T}{\partial n} = -q_0 = -0.94\ \ \mathrm{Wm}^{-2} \tag{4}$$

or

$$k \cdot \frac{\partial T}{\partial n} = -q_0 = -8.05\ \ \mathrm{Wm}^{-2}, \tag{5}$$

where $q_0$ is the specified heat flux in $\mathrm{Wm}^{-2}$. In this manner, the thermal effect of the heating pipeline on the 110 kV and 35 kV underground power cables is represented accurately enough for the most unfavorable summer conditions and the most common winter conditions. Explanations regarding the introduction of boundary conditions (4) and (5) can be found in [19,20].

The boundary condition (4) corresponds to the following most unfavourable summer conditions [19,20]: (i) $T_a$=40 °C – temperature of the air contacting the ground surface; (ii) $v_a$=0.22 m/s – wind velocity; (iii) $Q_{S,s}=1000\ \mathrm{Wm}^{-2}$ – solar irradiance incident on the ground surface; (iv) $T_{ns}$=20 °C – temperature of reference soil; (v) $T_{hp}$=50 °C – temperature of the exterior of the heating-pipe duct, along the entire length of the duct when the 110 kV and 35 kV cables are not loaded, or at a reference distance from the cable trenches 1 and 2 when the 110 kV and 35 kV cables are loaded, and (vi) thermal conductivities of the bedding material around the 110 kV cables, bedding material around the

35 kV cables, and native soil whose values correspond to their dried-out states, i.e. 0.55 $\mathrm{Wm^{-1}K^{-1}}$, 0.326 $\mathrm{Wm^{-1}K^{-1}}$, and 0.4 $\mathrm{Wm^{-1}K^{-1}}$, respectively.

The boundary condition (5) corresponds to the following most common winter conditions [19,20]: $T_a$=5 °C, $v_a$=0.22 m/s, $Q_{S,s}$=500 $\mathrm{Wm^{-2}}$, $T_{ns}$=10 °C, $T_{hp}$=50 °C (making the same assumptions as for the most unfavorable summer conditions), and thermal conductivities of the two cable beddings and native soil in the dried-out condition (i.e. 0.55 $\mathrm{Wm^{-1}K^{-1}}$, 0.326 $\mathrm{Wm^{-1}K^{-1}}$, and 0.4 $\mathrm{Wm^{-1}K^{-1}}$).

The heat transfer along the grassy ground surface is represented by a combination of

$$k \cdot \frac{\partial T}{\partial n} = h \cdot (T - T_a) \tag{6}$$

– convection boundary condition, and

$$k \cdot \frac{\partial T}{\partial n} = \varepsilon \cdot \sigma_{SB} \cdot T^4 - \alpha \cdot Q_{S,s} \tag{7}$$

– radiation boundary condition, where $T$ is the unknown temperature of the grassy ground surface in K, $h$=12.654 $\mathrm{Wm^{-2}\cdot K^{-1}}$ is the convection heat transfer coefficient for a dry grassy surface when $v_a$=0.22 m/s, $\varepsilon$=0.94 and $\alpha$=0.6 are the thermal emissivity and solar absorptivity for a dry grassy surface, and $\sigma_{SB}$=5.67·$10^{-8}$ $\mathrm{Wm^{-2}\cdot K^{-4}}$ is the Stefan-Boltzmann constant. It is assumed that the coefficient $h$, in addition to the thermal effects of free and forced convection, takes into account evaporation of water from the grassy ground surface.

The maximum temperature of a conductor in the 110 kV underground cable line, obtained using the corresponding FEM-based model for the specified service conditions, will be further used in the traditional Arrhenius model as a service (or practical use) temperature.

### 3.3. Thermal aging model

The most common form of the Arrhenius model correlates the degradation time (i.e. lifespan) for an insulation material (of an activation energy) at one temperature to that at another temperature. Accordingly, in the case of 110 kV XLPE-insulated cables, the Arrhenius model is as follows [1,21]:

$$t(T) = t_R \cdot \exp\left[\frac{E_a}{\sigma_B} \cdot \left(\frac{1}{T + 273.15} - \frac{1}{T_R + 273.15}\right)\right] \tag{8}$$

where $t(T)$ is the service lifespan at temperature $T$ in hours, $T$ is the service temperature (obtained using the FEM) in °C, $t_R$=876 h is the reference or test lifespan at temperature $T_R$, $T_R$=150 °C is the reference or accelerated test temperature, $E_a$ is the activation energy for XLPE insulation ranging approximately between 1.24 eV and 1.34 eV, and $\sigma_B$=0.8617·$10^{-4}$ eV/K is the Boltzmann constant. The values for activation energy $E_a$, reference temperature $T_R$, and reference lifespan $t_R$ are taken from [1,21], where the results of relevant accelerated thermal aging experiments were presented.

In general, the activation energy can be correlated to the rate of thermal degradation, i.e. thermal aging rate [1]. This practically means that XLPE insulation with a higher activation energy will thermally degrade at a slower rate than that with a lower activation energy. According to [22], when a failure occurs in a 110 kV XLPE-insulated cable, its service lifespan $t(T)$ becomes the total thermal lifespan $L_{tot}(T)$ which is inversely proportional to the thermal aging rate $R_a(T)$. Accordingly, based on the general lifespan equation from [22], the thermal aging rate $R_a(T)$ in %/h can be expressed as

$$R_a(T) = \frac{A_{\max,p}}{t(T)} = \frac{100}{L_{tot}(T)} \tag{9}$$

where $L_{tot}(T)$=$t(T)$ is the total thermal lifespan at temperature $T$ (in hours) calculated using Eq. (8), and $A_{\max,p}$=100 % is the maximum possible fraction of total thermal lifespan at temperature $T$.

A fraction of total thermal lifespan consumed during a specific operating period (for instance, an overload or accelerated thermal aging test period in hours) can be estimated by means of an appropriate number of thermal aging rates for the known temperature profile. Any temperature profile varies with changes in the corresponding load diagram and can be estimated using the IEC 60287, FEM or operating experience. By dividing the temperature profile of a specific operating period $t_{op}$

into $K$ intervals, the thermal aging rate $R_{a,i}(T)$ and duration $t_{D,i}=t_{op}/K$ of each interval can be used to estimate the fraction of total thermal lifespan for that interval $A_{F,p,i}(T)$ [9]. The fraction of total thermal lifespan consumed during the entire operating period $t_{op}=K\cdot t_{D,i}$ is given by the Miner's cumulative damage law [9,22]:

$$A_{tot,p} = \sum_{i=1}^{K} A_{F,p,i}(T) = \sum_{i=1}^{K} R_{a,i}(T) \cdot t_{D,i} \tag{10}$$

in percentage; where $A_{F,p,i}(T)$ is the fraction of total thermal lifespan consumed during the $i^{\text{th}}$ interval in percentage, $R_{a,i}(T)$ is the thermal aging rate taking place at a specific temperature $T$ during the $i^{\text{th}}$ interval in percentage per hour, and $t_{D,i}$ is the duration of the $i^{\text{th}}$ interval in hours. Thus, the fraction of total thermal lifespan $A_{tot,p}$ represents the total loss of thermal lifespan for the entire operating period $t_{op}$.

Finally, considering that the total thermal lifespan can be equal to the expected total service lifespan, the total thermal lifespan consumption $A_{tot,h}$ in hours is

$$A_{tot,h} = 8760 \cdot L_{tot,e} \cdot \frac{A_{tot,p}}{A_{\max,p}} \tag{11}$$

where $L_{tot,e}$=40 years is the expected total service lifespan, $A_{tot,p}$ is the fraction of the expected total service lifespan consumed during $t_{op}$ in percentage, and $A_{\max,p}$=100 %. For instance, in the case of a 110 kV XLPE-insulated cable, if $A_{tot,p}$=40 %, it means that 16 years of its expected total service lifespan ($L_{tot,e}$=40 years) is consumed.

## 4. Results and discussion

Tab. 2 shows the ampacity, volume power of heat sources, and temperature of the conductors of the 110 kV cable line and group of four 35 kV cables calculated for their designs outside and in the hot spot, under the most unfavourable summer conditions and the most common winter conditions. The first and second rows of this table relate respectively to the designs of the cable trenches 1 and 2 outside the hot spot. The design of the cable trench 1 is illustrated in Fig. 2a, while the design of the cable trench 2 can be found in [19,20]. The two remaining rows of Tab. 2 relate to the designs of the cable trenches 1 and 2 in the hot spot, i.e. the domain shown in Fig. 2b. The data from the first and second rows of Tab. 2 correspond respectively to the continuously permissible temperatures of the 110 kV and 35 kV cables and the associated designs outside the hot spot. The data from the third row of Tab. 2 are adjusted by ignoring the effect of heat sources from the cable trench 2. In addition, the dimensions, materials, and thermal conductivity values of the cable beddings 1 and 2 in Fig. 2b remained the same as in [19,20].

**Table 2. Ampacity (or load current), volume power of heat sources, and temperature of the conductors of the 110 kV cable line and group of four 35 kV cables calculated for their designs outside and within the hot spot area in the summer and winter periods**

| **Power cables / Thermal effect of other power cables** | **Design in relation to the hot spot area** | **Results calculated for the most unfavourable summer conditions** | | | **Results calculated for the most common winter conditions** | | |
|---|---|---|---|---|---|---|---|
| | | ***I*** | **$Q_v$** | ***T*** | ***I*** | **$Q_v$** | ***T*** |
| | | **A** | **Wm$^{-3}$** | **°C** | **A** | **Wm$^{-3}$** | **°C** |
| **110 kV** / Not applicable [19,20] | Outside | 518 | 9405 | 90 | 712.6 | 17795 | 90 |
| **35 kV** / Not applicable [19,20] | Outside | 66.3 | 6650 | 60 | 126.1 | 24075 | 60 |
| **110 kV** / *I*=0 A for 35 kV cables | Within | 518 | 9405 | 113 | 712.6 | 17795 | 165.2 |
| **110 kV** / *I* of 35 kV cables is equal to 66.3 A – for summer or 126.1 A – for winter | Within | 518 | 9405 | 120.3 | 712.6 | 17795 | 191.6 |

Based on the content of Tab. 2, it is evident that the 110 kV cables are loaded with a current of 518 A in summer or a current of 712.6 A in winter. This means that, in any of these cases, the 110 kV cables are loaded with the ampacity corresponding to their thermal environment outside the hot spot. In addition, the 35 kV cables are de-energized (*I*=0 A) or loaded with the ampacity corresponding to their thermal environment outside the hot spot ($I$=66.3 A or $I$=126.1 A). Therefore, the data from the third row of Tab. 2 are obtained by taking into account only the effect of the heating pipeline, while the data from the fourth row of Tab. 2 are obtained by taking into account the effects of both the heating pipeline and the group of 35 kV cables.

The service temperature values from Tab. 2 and the continuously permissible temperature $T_{cp}$=90 °C are then used to give an indication on how the total thermal lifespan of the 110 kV cables could be affected by the hot spot under consideration. The total thermal lifespan and thermal aging rate obtained for these and other service temperatures and activation energies of 1.24 eV and 1.34 eV are outlined in Tab. 3. In Tab. 3, the service and continuously permissible temperatures calculated using the FEM are presented in bold.

**Table 3. Total thermal lifespan and thermal aging rate for different service temperatures and different activation energies of XLPE insulation**

| **Service temperature** | | **Results obtained for $E_a$=1.24 eV** | | **Results obtained for $E_a$=1.34 eV** | |
|---|---|---|---|---|---|
| **$T$** | **$T$+273.15** | **$L_{tot}(T)$** | **$R_a(T)$** | **$L_{tot}(T)$** | **$R_a(T)$** |
| **°C** | **K** | **h** | **%/h** | **h** | **%/h** |
| **191.6** | **464.75** | **41.7** | **2.396017** | **32.7** | **3.062685** |
| **165.2** | **438.35** | **269.4** | **$3.712132\cdot10^{-1}$** | **244.9** | **$4.08248\cdot10^{-1}$** |
| 150* | 423.15* | 876.0* | $1.141553\cdot10^{-1}$ | 876.0* | $1.141553\cdot10^{-1}$ |
| 140 | 413.15 | 1 995.2 | $5.012093\cdot10^{-2}$ | 2 132.1 | $4.690189\cdot10^{-2}$ |
| 130 | 403.15 | 4 733.6 | $2.112556\cdot10^{-2}$ | 5 423.5 | $1.843828\cdot10^{-2}$ |
| **120.3** | **393.45** | **11 412.2** | **$8.762549\cdot10^{-3}$** | **14 037.1** | **$7.123968\cdot10^{-3}$** |
| **113** | **386.15** | **22 785.1** | **$4.388842\cdot10^{-3}$** | **29 632.9** | **$3.374623\cdot10^{-3}$** |
| 100 | 373.15 | 83 461.7 | $1.198154\cdot10^{-3}$ | 120 526.6 | $8.296926\cdot10^{-4}$ |
| **90** | **363.15** | **241 367.0** | **$4.143068\cdot10^{-4}$** | **379 722.3** | **$2.633503\cdot10^{-4}$** |
| 80 | 353.15 | 741 288.3 | $1.349003\cdot10^{-4}$ | 1 276 657.8 | $7.832953\cdot10^{-5}$ |
| 70 | 343.15 | 2 430 516.1 | $4.114352\cdot10^{-5}$ | 4 606 546.5 | $2.170824\cdot10^{-5}$ |
| 60 | 333.15 | 8 557 946.3 | $1.168505\cdot10^{-5}$ | 17 952 829.1 | $5.570153\cdot10^{-6}$ |
| 50 | 323.15 | 32 574 255.8 | $3.069909\cdot10^{-6}$ | 76 111 934.6 | $1.313854\cdot10^{-6}$ |
| 40 | 313.15 | 135 037 581.4 | $7.405346\cdot10^{-7}$ | 353 865 122.0 | $2.825935\cdot10^{-7}$ |
| 30 | 303.15 | 614 863 899.0 | $1.626376\cdot10^{-7}$ | 1 820 760 302.6 | $5.492211\cdot10^{-8}$ |
| 20 | 293.15 | 3 104 682 261.5 | $3.220942\cdot10^{-8}$ | 10 476 197 975.6 | $9.545448\cdot10^{-9}$ |

* Data taken from accelerated thermal aging tests presented in [1,21]

Based on Tab. 3, it is obvious that, for XLPE insulation, an exponential function represents the model of dependency of the thermal aging rate on the service temperature. In order to represent how the thermal aging rate of XLPE insulation changes with temperature and activation energy, the function is plotted on a base 10 logarithmic scale for the two considered activation energies as shown in Fig. 3.

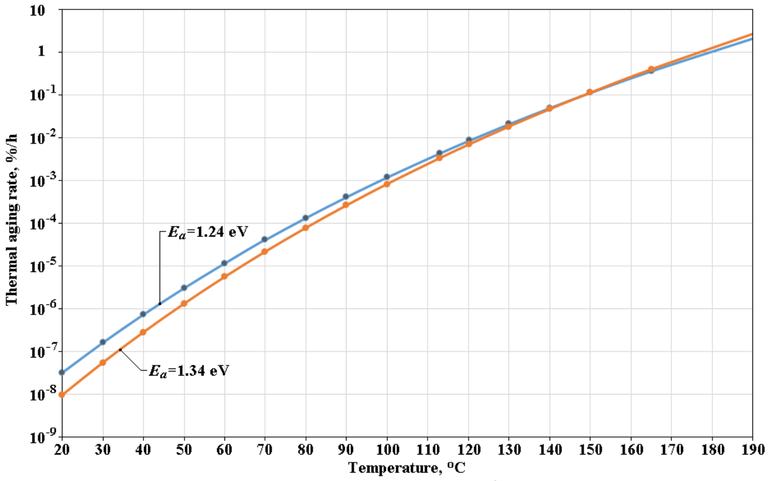

**Figure 3. Thermal aging rate of XLPE insulation as a function of the service temperature and activation energy**

According to [1], the activation energy may be a function of service temperature, rather than constant, and in some instances the values of activation energy for specific formulations of XLPE insulation may be unavailable. The results given in Tab. 3 and Fig. 3 illustrate the potential effects of these two practical limitations on the Arrhenius model. Accordingly, appropriate values of the thermal aging rate for any XLPE formulation should be between the two dependencies shown in Fig. 3.

From Tab. 3 it can also be seen that estimated total thermal lifespans at service temperatures equal to or lower than 60 °C are extremely long. Accordingly, additional thermal aging caused by these temperatures can be neglected when estimating the total thermal lifespan consumption due to the hot spot effect. In connection with this, the total thermal lifespan at the service temperature of 60 °C is 8557946.3 hours (or 976.9 years) – for the activation energy of 1.24 eV, or 17952829.1 hours (or 2049.4 years) – for the activation energy of 1.34 eV, which goes significantly beyond the expected total service lifespan of 40 years. However, this lifespan at the continuously permissible temperature of 90 °C is 27.6 years – for the activation energy of 1.24 eV, and 43.3 years – for the activation energy of 1.34 eV. The total thermal lifespan of 27.6 years is significantly shorter than the expected one, which means that the XLPE insulation having the activation energy of 1.24 eV does not meet the prescribed standards for the voltage level of 110 kV. Therefore, only thermal aging rates corresponding to the service temperatures higher than 60 °C and activation energy of 1.34 eV should be used in the estimation of the total thermal lifespan consumption using assumed daily temperature profiles for the 110 kV conductors.

To estimate the total thermal lifespan consumption using Eq. (10) and Eq. (11), it is assumed that the year has two six-month periods, namely: summer and winter, and appropriate daily temperature profiles are introduced. In addition, the following is assumed: (i) the most unfavourable summer conditions prevail in the summer, lasting 12 or 6 hours a day, and (ii) the most common winter conditions prevail in the winter, also lasting 12 or 6 hours a day. In the case when any single set of these environmental conditions last for 6 hours a day, it is assumed that during the remaining hours service temperatures will not exceed 60 °C. Thus, four different daily temperature profiles for the 110 kV conductors are obtained, namely: Profiles A, B, C, and D, as defined in Tab. 4. This table also shows the total thermal lifespan consumption (i.e. total thermal aging) due to the hot spot effect for the considered 110 kV cable line. In practice, the actual load data have been measured once every hour, so that the duration of the $i^{\text{th}}$ interval is $t_{D,i}$=1 h. In Tab. 4, the parameter $A_{tot,p}$ in percentage represents the fraction of total thermal lifespan at temperature $T$ consumed during the period $t_{op}$ ($t_{op}$=12 h or $t_{op}$=6 h), while $A_{tot,h}$ in hours represents the corresponding total thermal lifespan consumption.

**Table 4. Total thermal lifespan consumption due to the hot spot effect for the considered 110 kV underground cable line**

| Thermal effects | Profile / $A_{tot,h}$ in h | $t_{op}$ | $T$ | $R_{a,i}(T)$ from Tab. 3 | $A_{tot,p}$ | $A_{tot,h}$ |
|---|---|---|---|---|---|---|
| | | h | °C | %/h | % | h |
| Heating pipeline only | Profile A | 0-12 | 113 | $3.374623 \cdot 10^{-3}$ | 0.040495476 | 141.9 |
| | | 12-24 | 165.2 | $4.08248 \cdot 10^{-1}$ | 4.898976 | 17 166.0 |
| | **$A_{tot,h}$ in h** | | | | | **17 307.9** |
| | Profile B | 0-12 | ≤60 | 0.0 | 0.0 | 0.0 |
| | | 12-18 | 113 | $3.374623 \cdot 10^{-3}$ | 0.020247738 | 70.9 |
| | | 18-24 | 165.2 | $4.08248 \cdot 10^{-1}$ | 2.449488 | 8 583.0 |
| | **$A_{tot,h}$ in h** | | | | | **8 653.9** |
| Heating pipeline and group of 35 kV cables | Profile C | 0-12 | 120.3 | $7.123968 \cdot 10^{-3}$ | 0.085487616 | 299.5 |
| | | 12-24 | 191.6 | 3.062685 | 36.75222 | 128 779.8 |
| | **$A_{tot,h}$ in h** | | | | | **129 079.3** |
| | Profile D | 0-12 | ≤60 | 0.0 | 0.0 | 0.0 |
| | | 12-18 | 120.3 | $7.123968 \cdot 10^{-3}$ | 0.042743808 | 149.8 |
| | | 18-24 | 191.6 | 3.062685 | 18.37611 | 64 389.9 |

| | | |
|---|---|---|
| | **$A_{tot,h}$ in h** | **64 539.7** |

Based on Tab. 4, the total thermal lifespan consumption could be 1.976 years – for Profile A, 0.988 years – for Profile B, 14.735 years – for Profile C, and 7.3675 years – for Profile D. Accordingly, the largest consumption of total thermal lifespan occurs in the case when there are the thermal effects of both the heating pipeline and the group of four 35 kV cables, and when the ampacity values of the 110 kV cable line and group of 35 kV cables correspond to their designs outside the hot spot. Compared to the two cases where there is only the effect of the heating pipeline, the total thermal lifespan consumption is 7.458 times higher, which means that the thermal effect of the group of four 35 kV cables is significantly more pronounced. In addition, if the most unfavourable summer conditions or the most common winter conditions last for only half of the summer or winter period, then the corresponding total thermal lifespan consumption can be halved.

## 5. Conclusions

In this paper, it was successfully established that the so-called PDCA approach could be applied to thermal aging management of underground power cables in electricity distribution networks. The proposed management approach was also innovated and improved in the area of qualification of underground power cables and Arrhenius thermal aging analysis, which belong respectively to the PLAN- and CHECK-stages of the PDCA approach. This was done by introducing FEM-based steady-state thermal models into the Arrhenius thermal aging model and analysis. The innovation was introduced in accordance with the standards IEC 60287 and IEC TR 62095, which opens up the possibility for electricity distribution network operators and asset managers of power cable systems to apply the proposed management approach in practice, i.e. in electricity distribution and associated companies. The innovation has enabled professionals to involve the effects of other heat sources, wind, solar irradiation, thermal conductivity of various materials, cable bedding size, etc. in procedures for qualification of underground power cables. Such a FEM-based Arrhenius model was then applied to one actual hot spot of the 110 kV underground cable line, which is of the utmost importance for the local electricity distribution company. Applying the FEM-based Arrhenius model to the hot spot considered, the following was found: **(i)** the hot spot effect can shorten the expected total service lifespan of the 110 kV XLPE-insulated cables in the hot spot area by 36.84 %; **(ii)** the largest consumption of total thermal lifespan occurs in the presence of all the possible thermal effects in the hot spot area; **(iii)** the thermal effect of the group of four 35 kV cables on the lifespan of the 110 kV cables in the hot spot area is significantly more pronounced than the thermal effect of the heating pipeline; and **(iv)** if the considered environmental conditions last for only half of the associated six-month period, then the corresponding total thermal lifespan consumption can be halved. Future work in this area will cover thermal aging of underground and overhead distribution cables and their accessories in actual environments in the context of FEM-based qualification of equipment during emergency and fault conditions.

## Nomenclature

*Variables and coefficients*

$A_{F,p,i}$ – fraction of $L_{tot}$ consumed during the $i^{th}$ interval, [%]
$A_{\max,p}$ – max possible fraction of $L_{tot}$, [%]
$A_{tot,h}$ – total thermal lifespan consumption, [h]
$A_{tot,p}$ – fraction of $L_{tot}$ consumed during the period $t_{op}$, [%]
$E_a$ – activation energy, [eV]
$h$ – convection coefficient, [Wm$^{-2}$K$^{-1}$]
$t_{op}$ – specific operating period, [h]
$t_R$ – reference lifespan, [h]
$v_a$ – wind velocity, [m/s]
$x, y$ – Cartesian spatial coordinates, [m]
$\alpha$ – solar absorptivity, [–]
$\varepsilon$ – thermal emissivity, [–]
$\sigma_B$ – Boltzmann constant, [eV/K]
$\sigma_{SB}$ – Stefan-Boltzmann constant, [Wm$^{-2}$K$^{-4}$]

| | |
|---|---|
| $I$ | – ampacity or load current, [A] |
| $i$ | – designation for the $i^{th}$ interval |
| $K$ | – number of intervals $t_{D,i}$ in $t_{op}$ |
| $k$ | – thermal conductivity, [$Wm^{-1}K^{-1}$] |
| $L_{tot}$ | – total thermal lifespan, [h] |
| $L_{tot,e}$ | – expected total service lifespan, [y] |
| $n$ | – length of the normal vector $\vec{n}$, [m] |
| $Q_{S,s}$ | – solar irradiance incident on the ground surface, [$Wm^{-2}$] |
| $Q_v$ | – volume power of heat sources, [$Wm^{-3}$] |
| $q_0$ | – specified heat flux on the upper surface of the heating-pipe duct, [$Wm^{-2}$] |
| $R_a$ | – thermal aging rate, [%/h] |
| $R_{a,i}$ | – thermal aging rate taking place during the $i^{th}$ interval, [%/h] |
| $R_{ac}$ | – effective a.c. resistance, [$\Omega m^{-1}$] |
| $S'_c$ | – geometric cross-section area of one conductor, [$m^2$] |
| $T$ | – unknown temperature, or unknown surface temperature, [K] |
| $T$ | – service temperature, [°C] |
| $T_a$ | – temperature of the air contacting the ground surface, [°C] |
| $T_{cp}$ | – continuously permissible temperature of cables, [°C] |
| $T_{hp}$ | – temperature of the exterior of the heating-pipe duct, [°C] |
| $T_{ns}$ | – temperature of reference soil, [°C] |
| $T_R$ | – reference temperature, [°C] |
| $t$ | – service lifespan, [h] |
| $t_{D,i}$ | – duration of the $i^{th}$ interval, [h] |

*Abbreviations*

| | |
|---|---|
| FEM | – finite element method |
| HDPE | – high-density polyethylene |
| IEC | – International Electrotechnical Commission |
| ISO | – International Standards Organization |
| NA2XS(FL)2Y | – single-core power cable, N – standardized/norm type, A – aluminium conductor, 2X – cross-linked polyethylene insulation, S – copper screen, FL – longitudinally and crosswise water-tight, and 2Y – polyethylene outer sheath |
| NAEKEBA | – three-core power cable, N – standardized/norm type, A – aluminium conductor, EK – metal sheath of lead with corrosion protection on each sheath, E – thermoplastic sheath and inner protective covering, lapped bedding with additional layer of plastic tape, B – armor of steel tape, and A – outer protection of fibreous material (jute) in compound |
| NPP | – nuclear power plant |
| NRC | – U.S. Nuclear Regulatory Commission |
| PDCA | – PLAN-DO-CHECK-ACT |
| TR | – Technical Report |
| XLPE | – cross-linked polyethylene |

## References

[1] Gazdzinski, R. F., *et al.*, Ageing Management Guideline for Commercial Nuclear Power Plants – Electrical Cable and Terminations, Report SAND96-0344, Ogden Environmental and Energy Services Co., Inc., Penn., USA, 1996

[2] IAEA, Assessment and Management of Aging of Major Nuclear Power Plant Components Important to Safety: In-containment Instrumentation and Control Cables, Volume I, IAEA-TECDOC-1188, International Atomic Energy Agency, Vienna, Austria, 2000

[3] CNSC, Aging Management for Nuclear Power Plants, RD-334, Canadian Nuclear Safety Commission, Ottawa, Canada, 2011

[4] Ichikawa, T., Post Design Evaluation (Ageing Mechanisms, Effects, Management, Monitoring, PSR, ISI), Mitsubishi Heavy Industries, LTD, Japan, 2001

[5] Tcherner, J., Seto, D., Aging Management of Concrete Containment Structure – Standard Development, *Transactions*, 23rd Conference on Structural Mechanics in Reactor Technology (SMiRT-23), Manchester, UK, August 10-14, 2015, Division X, Paper ID 183

[6] Verardi, L., Aging of Nuclear Power Plant Cables: In Search of Non-Destructive Diagnostic Quantities, Ph. D. thesis, ALMA MATER STUDIORUM - Università di Bologna, Bologna, Italy, 2013

[7] Spång, K., Ståhl, G., Qualification of Electrical Equipment in Nuclear Power Plants – Management of Ageing, Report No. 2013:10, The Swedish Radiation Safety Authority, Stockholm, Sweden, 2013

[8] Zhou, C., Yi, H., Dong, X., Review of Recent Research towards Power Cable Life Cycle Management, *IET High Voltage*, *2* (2017), 3, pp. 179-187

[9] Han, Y. J., Lee, H. M., Shin, Y.-J., Thermal Aging Estimation with Load Cycle and Thermal Transients for XLPE-insulated Underground Cable, 2017 IEEE Conference on Electrical Insulation and Dielectric Phenomenon (CEIDP), Fort Worth, Tex., USA, October 22-25, 2017, pp. 205-208

[10] Zapf, M., *et al*., Lifetime Assessment of PILC Cables with Regard to Thermal Aging Based on a Medium Voltage Distribution Network Benchmark and Representative Load Scenarios in the Course of the Expansion of Distributed Energy Resources, *Energies, 14* (2021), Paper ID 494

[11] Meng, X., *et al*., Working Temperature Calculation of Single-Core Cable by Nonlinear Finite Element Method, *Archives of Electrical Engineering*, *68* (2019), 3, pp. 643-656

[12] Ge, X., Given, M., Stewart, B. G., FEA Simulation Studies of Accelerated Aging of Power Cables in Water Tanks, 38th IEEE Electrical Insulation Conference (IEC), Virtual conference, June 22-July 3, 2020, pp. 465-468

[13] Jia, F., Zhang, X., Liu, D., Study on Insulation of Middle Joint of Power Supply Line of High Speed Railway, *Proceedings*, The 2017 International Conference on Advances in Materials, Machinery, Electrical Engineering (AMMEE 2017), Tianjin, China, June 10-11, 2017, pp. 163-168

[14] Alghamdi, A. S., Desuqi, R. K., A Study of Expected Lifetime of XLPE Insulation Cables Working at Elevated Temperatures by Applying Accelerated Thermal Ageing, *Heliyon*, *6* (2020), 1, Paper ID e03120

[15] Mustafa, E., Afia, R. S. A., Tamus, Z. Á., Dielectric Loss and Extended Voltage Response Measurements for Low-Voltage Power Cables Used in Nuclear Power Plant: Potential Methods for Aging Detection due to Thermal Stress, *Electrical Engineering*, *103* (2021), pp. 899-908

[16] Buhari, M., Levi, V., Awadallah, S. K. E., Modelling of Ageing Distribution Cable for Replacement Planning, *IEEE Transactions on Power Systems*, *31* (2016), 5, pp. 3996-4004

[17] Xu, L., Brown, R. E., Justifying the Proactive Replacement of Cable, 2011 IEEE Power and Energy Society General Meeting, Detroit, Mich., USA, July 24-28, 2011, pp. 1-6

[18] Wang, K., Kopsidas, K., Modelling Network Reliability Considering Underground Cable Hot Spot Failures, The 16th International Conference on Probabilistic Methods Applied to Power Systems (PMAPS 2020), Liege, Belgium, August 18-21, 2020

[19] Klimenta, D., Tasić, D., Jevtić, M., The Use of Hydronic Asphalt Pavements as an Alternative Method of Eliminating Hot Spots of Underground Power Cables, *Applied Thermal Engineering*, *168* (2020), Paper ID 114818

[20] Klimenta, D., *et al.*, Eliminating the Effect of Hot Spots on Underground Power Cables Using Cool Pavements, *Electrical Engineering*, *101* (2019), 4, pp. 1295-1309

[21] U.S.NRC, SEC Equipment Aging, Subject: M38773 Revision 6, United States Nuclear Regulatory Commission, https://www.nrc.gov/docs/ML1211/ML12116A323.pdf

[22] Montanari, G. C., Mazzanti, G., Simoni, L., Progress in Electrothermal Life Modeling of Electrical Insulation during the Last Decades, *IEEE Transactions on Dielectrics and Electrical Insulation*, *9* (2002), 5, pp. 730-745

Submitted: 28.01.2022

Revised: 28.02.2022

Accepted: 05.03.2022.