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Trend adjusted lifetime monitoring of underground power cable

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ABSTRACT

Insulated power cables are the most critical devices used in electrical network for urban areas. Also, lifespan knowledge of these devices is the important information for decision-makers to make their investment planning. This study has presented a practical method for estimating the remaining lifetime of a power cable. The validation of the method has been tested under two different cases for 154 kV XLPE insulated underground power cable system. Power cable thermal network has been modeled for a short-duration transient according to electrical analogy. Lifetime monitoring has been carried out by considering loss of life trend depending on the load raising an annual basis. The results show that the accuracy of the remaining service life estimation is related to receiving data with high sample-rate and determining loss of life trend curve belonging to the power cable. The realistic estimations are carried out using trend-adjusted exponential smoothing.

1. Introduction

Utilization rate of underground power cables is increasing in electrical network from the early 1890s. Especially, installation of high-voltage underground power cables has advantages such as security and safety features for the environment and humanity [1]. However, the cost of manufacturing and installation costs of underground power cables are more expensive than the overhead power lines. In addition, the finding of a possible fault location and the total maintenance/repair time are longer. Therefore, condition monitoring and proactive maintenance are important for prolonged lifetime of such critical equipment [2–5].

The design life of underground power cables is determined for the rated operating load and specified conditions. But in reality, these parameters are ever-changing according to the power demand and environmental characteristics. Therefore, lifespan will be different from the specified design life of power cable for the different electricity networks.

The power cable loadability is limited by the temperature. This limitation is necessary to protect the insulation of the power cable and the power cable is generally operated under variable load below this limitation [6,7]. In addition, the useful service life of the underground power cable is negatively affected by its operating temperature rise and it is known that thermal stress varying according to load is critical factor on insulation aging but not alone [7–10]. Electrical stress is another critical factor on aging due to the synergism between electrical and thermal stress for high-voltage insulated cables, especially [10,11]. Insulation aging depends on other stresses such as mechanical and environmental stress as well [8–10]. However, aging effects of mechanical and environmental stresses are greatly reduced on the insulation of power cable that is buried in the ground by taking necessary preventive measures [11]. Therefore, thermal and electrical stresses are considered to be predominant aging factors on underground power cable insulation [10,11].

The aging condition of insulated power cable can be determined by applying a number of offline test/methods such as dissipation factor, partial discharges, dielectric strength, FTIR, and insulation resistance [6,12–14]. Determination of the remaining service life of a cable is carried out on a sample in the laboratory test environment. However, applying these tests frequently is not practical and some of them require samples. The results of these test/methods give an idea for particular area and they do not give precise information about the remaining life of the whole power cable. However, a linear relationship could be established among the loss of life (LOL) value achieved with offline tests and remaining lifetime of the cable if the cable system installation date is known [15]. Some online monitoring technologies are also available [16–19]. But these technologies focus on finding potential or occurred faults on the cable system, generally. Online lifetime monitoring studies which include the determining of LOL and remaining service life of cable in real-time operation are very few [16,17].

This paper presents a trend-based method to estimate the remaining service life of underground power cables. The aging

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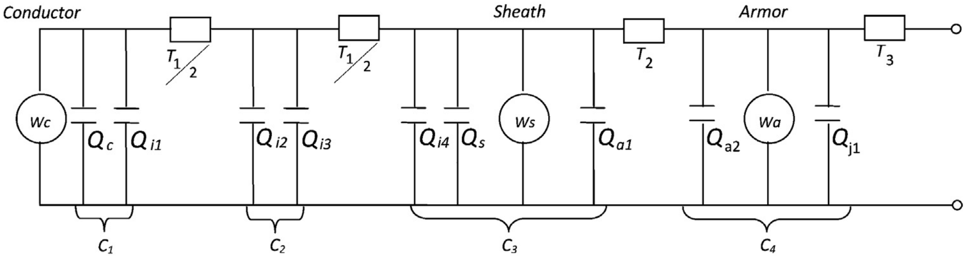

Fig. 1. Insulated power cable thermal networks (for short-duration transient).

acceleration and cumulative LOL could be calculated continuously in small time intervals in the model (to the extent permitted by online monitoring technology in practice). The main novelty of this method is to determine the remaining service life of the underground power cable considering the LOL trend on an annual basis. The details of the method are presented in Section 3 after theoretical framework specified in Section 2. The validity of the method has been tested by modeling of the 154 kV high-voltage underground power cable system in Section 4.

2. Insulation aging mechanisms and life models

Electrical insulation failures occur as a result of aging caused by the presence of stresses. Which stress is more dominant depends on where insulation is in service and its operating conditions. In terms of insulated power cables, electrical and thermal stresses are indicated as predominant aging factors in many studies [8–11]. Stresses may apply separately for single-stress evaluation and sequentially or simultaneously for multi-stress evaluation [6,8].

Single-stress models express that lifetime is a function of only one stress prevailing over other stresses [8]. Life models such as the inverse power law or the exponential model for the electrical lifetimes and the Arrhenius or the Eyring Models for thermal lifetimes, based on single stress phenomena are well known for many years [8–11,20].

Multi-stress models express that lifetime is a function of more than one stresses and include phenomenological multi-stress models (linear/threshold models) or thermodynamic models [8,21,22]. The underlying concept for the phenomenological multi-stress models is the multiplicative effects of stress functions on the lifetime [8,10]. On the other hand, thermodynamic models explain that the electrical/mechanical stress reduces the height of the potential energy barrier [6,8]. The concepts of thermodynamic models derived from the general Eyring equation as thermodynamic model by Crine [6,21] and Zhurkov [6,11].

The empirical exponential dependence model proposed by Zhurkov reflects the thermo-fluctuations of long-term strength of solid materials under mechanical stress [6,23] given as:

$$t = t_0 \exp\left[\frac{w - \gamma\sigma}{RT}\right] \quad (1)$$

where t is time-to-fracture of a solid material versus applied stress, t_0 is a constant close to the period of oscillations of atoms, w is activation energy of the fracture process, γ is a structure parameter, σ is mechanical stress, R is universal gas constant, and T is the operating temperature of the material.

For electrical and thermal stresses acting on insulation together, the model has been updated [6] as follows:

$$t = t_0 \exp\left[\frac{w - \chi E}{RT}\right] \quad (2)$$

where t is electrothermal lifetime, t_0 is a constant, w is activation energy of fracture process, χ is structure parameter (kJmm/mol kV), and E is electric field. R and T are the same as the previous definition.

3. Thermal modeling of underground power cables

Neher–McGrath equation describes the transient temperature rise calculation based on R–C thermal equivalent circuit for underground power cable systems [24,25]. Anders and El-Kady have presented a comprehensive mathematical method based on a proper ladder network to determine thermal transient response of the buried cables [24].

Thermal-electric analogy can be used for heat-transferring from cable to the surface as shown in Fig. 1. In this structure, the thermal resistance prevents heat flow while thermal capacitances store heat energy [24–26]. The analogy can be written as follows:

$$R = \frac{V_1 - V_2}{I} = \frac{\Delta V}{I} \quad (3)$$

$$T = \frac{\theta_c - \theta_{amb}}{W} = \frac{\Delta\theta}{W} \quad (4)$$

where R electrical resistance (Ω) and T are thermal resistance (Km/W), V is the electrical potentials, θ is the temperature indicating different points such as conductor temperature θ_c and ambient temperature θ_{amb} on the thermal circuit, I is the conductor current and W denotes heat losses in the metal parts of the cables per unit (W/m).

The equivalent thermal circuit consists of some parameters; Wc is joule loss (I^2.R) of the conductor, Ws is sheath loss that can be calculated as ($\lambda_1.Wc$). Wa is armor loss that can be calculated as ($\lambda_2.Wc$). Here λ_1 is sheath loss factor and λ_2 is armor loss factor that can be calculated according to IEC60287 standard [27]. Wd is dielectric losses that occurs when the cable is energized. It can be neglected for distribution voltages [7,27]. It is calculated as in the following equation:

$$W_d = 2\pi f C U_o{}^2 \tan\delta \quad (5)$$

T_1 is the thermal resistance of the main insulation, T_2 is the thermal resistance between the armor and the screen, and T_3 is the thermal resistance of the external serving [25]. The generalized insulation thermal resistance formula can be given as:

$$T = \frac{\rho_i}{2\pi}\ln\left(\frac{D_{out}}{D_{in}}\right) \quad (6)$$

where ρi is insulation thermal resistivity (Km/W), D_{in} is insulation inner diameter (mm), and D_{out} is insulation external diameter (mm).

Temperature rise/fall of the cable is affected by the thermal capacitances in transient operation. However, thermal capacitances have no effect in steady-state operation. The thermal capacitance is calculated by,

$$Q = \frac{\pi}{4}\left(D_{out}{}^2 - D_{in}{}^2\right)c \quad (7)$$

where Q is the thermal capacitance (J/Km), c is the specific heat (J/Km^3) of the material. It is known that the thermal capacitance is a nonlinear function depending on the dielectric's thickness in transient conditions. Therefore, Van Wormer coefficients (p, p', p^*)