MV Cable Lifetime Improvement Analysis through Transformer Tap Changes

B. Sheng, F. P. Mohamed, W. H. Siew, B. G. Stewart
Institute of Energy and Environment, University of Strathclyde
204 George Street
Glasgow, G1 1XW, UK

***Abstract*- Cable life depends mainly on the thermal stress, which relates to the current applied on the cable. Voltage changes in medium voltage (MV) cables due to transformer tap changes will also change the current flowing through the cable, which will change the cable temperature. In order to extend the cable life, this paper aims to simulate and analyse the potential thermal lifetime improvement of cables through long-term tap changes within the statutory levels. Firstly, the IEC standard (60287) method for rating and modelling cables is applied to evaluate the cable temperature under different voltages and relative currents. Different cable configurations will also be considered in simulations as temperature is dependent on the cable dimensions. Then, typical thermal lifetime analytical expressions will be used to evaluate the long-term influence of voltage changes. Lastly, the obtained thermal lifetime assessments under different transformer tap changes and different cable configurations will provide a potential understanding of cable lifetime changes through implementation of permitted regulatory voltage changes.**

I. INTRODUCTION

The majority of cables and associated plant in the UK's medium voltage (MV) distribution networks were installed in the 1950s and 1960s [1]. By comparing the typical design life of MV cables ranging from 60 years (33/132 kV cables) to 70 years (6.6/11kV underground cables), they are approaching, or have exceeded, their expected operational life [1]. Because of constantly increasing energy demand, robustness and flexibility of the power network is essential. To ensure reliability, existing cables could be replaced by new cables, but to minimise operating costs, maximum service should be extracted from existing cables. Consequently, it is important to develop methods to extend the cable lifetime.

Thermal ageing is the major cause of insulation failure [2]. High temperatures due to overloading of the cable cause faster thermal aging and reduce the remaining cable service lifetime. The thermal stress on the cables relates mainly to the current applied on the cable. Presently, industry voltage statutory requirements are ±6% of the nominal voltage on distribution networks which can be achieved by changing the transformer taps. Assuming in the first instance the load in low voltage (LV) systems is constant, voltage changes in MV cables due to tap changes will also change the current flowing through the cable, which will change the cable temperature. Therefore, this paper aims to simulate and analyse the potential thermal lifetime improvement of distribution cables through long-term movement of voltages within statutory levels of tap changers in transformers.

However, the statutory voltage requirements only apply to customer connections, which means a greater scope for varying the voltage at certain points on the network. For example, if all customers in an area are connected at 11kV, the 33kV voltage could vary considerably as long as the 11kV voltage remains within statutory limits. Therefore cable lifetime will be analyzed for voltage changes between ± 10% of the nominal voltage in the paper. The IEC standard (60287) [3, 4] method for rating and modelling cables is applied to evaluate the cable temperature under different voltages and relative currents. Different cable configurations will also be considered in simulations as temperature is dependent on the cable dimensions (trefoil touching, three horizontal touching and vertical touching formation). Typical thermal lifetime analytical expressions will then be used to evaluate the long term influence of voltage changes on theoretical life-time evaluations.

This paper is organized as follows: parameters of a practical MV cable used in modeling are given in Section II. The modeling methods to simulate cable temperature and lifetime are introduced in Section III. Then Section IV shows and discusses the simulation results of different cable configurations. Lastly, conclusions are drawn and future work is presented in Section V.

II. MODEL PARAMETERS

A single core 33kV XLPE cable has been used to model the cable temperature and lifetime through transformer tap changes. Cross section and parameters of the cable are illustrated in Fig. 1 and Table I. In this paper, the cable models are based four layers, i.e. copper conductor, XLPE insulation, copper screen, and external medium-density polyethylene (MDPE) sheath.

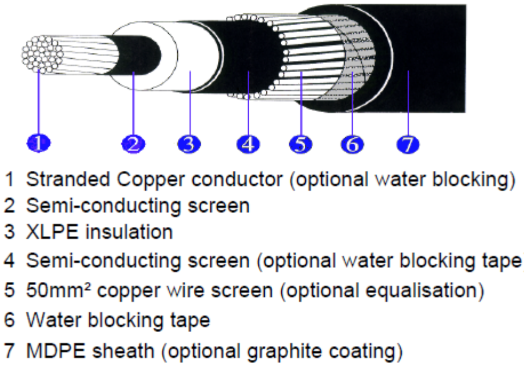


Fig. 1. Cross section cable for 33 KV [5]

Among the various installation methods of cable systems, one of the most commonly used is to set the cable in free air. Therefore, all the simulations in the paper model the cable installed in this environment. The current rating of the cable in free air is set at 995 A.

TABLE I

CABLE PARAMETERS

Parameters	Value	Units
Number of conductor in the cable	1	-
Diameter of conductor	27.1	mm
Nominal cross-sectional area of conductor	500	mm^2
Insulation thickness	8	mm
Nominal area of copper wire screen	50	mm^2
Oversheath thickness	2.6	mm
Overall diameter	57.0	mm
Maximum DC resistance of conductor at 20 ℃	0.037	Ω/km
Maximum DC resistance of copper wire screen at 20 ℃	0.379	Ω/km
Current rating -- laid in air	995	A
Thermal resistivity of screen insulation (XLPE)	3.5	K.m /W
Thermal resistivity of sheath insulation (MDPE)	3.5	K.m/W

III. MODELING METHODS

Assuming in the first instance the load in low voltage (LV) systems is constant, voltage changes in MV cables due to transformer tap changes will also change the current flowing through the cable. This will change the cable temperature and thus change the cable lifetime.

Firstly, the cable current can be calculated from

$$I_i = P / U_i \qquad (1)$$

where I_i and U_i are the changed current and voltage due to tap change respectively. P is a constant power demand due to the assumed constant load. In this work, voltage changes between ± 10% of the nominal voltage are considered. Consequently the current related to the changed voltage can be obtained by (1), and this is shown in Table II.

TABLE II

CURRENT AND VOLTAGE CHANGES DUE TO TAP CHANGES

Change in percent	U_i (kV)	I_i (A)
-10%	29.7	1105.6
-6%	31.02	1058.5
-3%	32.01	1025.8
0%	33	995
+3%	33.99	966.0
+6%	34.98	938.7
+10%	36.3	904.5

The IEC method (60287) is then applied to model the cable temperature based on the changed current and voltage. Lastly, a thermal aging model is used to simulate the cable lifetime based on the different cable temperatures. In the modelling, different cable configurations (trefoil touching, three horizontal touching and vertical touching formation) are considered. Both of the adopted analysis methods are now detailed.

A. *IEC Method for Cable Temperature Modeling*

IEC 60287-1-1 [3] provides method for calculation of ampacity of cable for different design parameters of cable (cross section, thermal resistivity, thickness of layer … etc.) as well as for different environment (ambient temperature, soil condition, depth of cable, spacing of phases … etc.). The cable temperature can be obtained from

$$\Delta\theta = (I^2R + 0.5W_d)T_1 + [I^2R(1+\lambda_1) + W_d]nT_2 + [I^2R(1+\lambda_1+\lambda_2) + W_d]n(T_3+T_4) \qquad (2)$$

where, Δθ (°C) is the temperature rise between ambient temperature and cable conductor temperature; I (A) is the current flowing in one conductor; R (Ω/m) is the alternating current resistance of the conductor at maximum temperature; W_d (W/m) is the dielectric loss of cable insulation; T_1, T_2, T_3 (K.m/W) are equivalent thermal resistances calculated from the cable material's thermal properties; T_4 (K.m/W) is the cable external thermal resistance between the cable surface and the surrounding medium; n is the number of conductors; λ_1 and λ_2 are respectively the ratio of losses in the metal sheath to total losses in all conductors and the ratio of losses in the armouring to total losses in all conductors.

All the parameters in (2) can be calculated based on the IEC Standard 60287-1-1 [3], except the thermal resistances T1 - T4, which are given by the IEC Standard 60287-2-1 [4]. Reference [4] proposes an iterative method for the calculation of cable surface temperature above ambient temperature $\Delta\theta_s$ (°C). Consequently both the cable conductor and surface temperatures can be obtained based on the standards.

As different cable configurations (trefoil touching, three horizontal touching and vertical touching formation) can result in different cable temperatures, the standards also give different solutions for (2) for different configurations. With respect to different ambient temperatures, the cable temperature is different. Therefore, in modeling, the IEC method is applied to simulate the cable temperature for different cable configurations with a range of ambient temperatures from 0 °C to 60 °C. The results are presented in Section IV-A.

B. *Thermal Aging Method for Cable Lifetime Modeling*

A great deal of effort has been undertaken in the literature to model cable thermal aging. Table III shows the different possible thermal models [6]. Threshold materials are materials that exhibit a value of thermal or electric stress below which aging is negligible, while unthreshold materials exhibit a threshold value that is too small to be of significance [6]. The Arrhenius model (AM) and Eyring model (EM) have been used for unthreshold materials. The Arrhenius threshold method (ATM) and 4-parameter Arrhenius threshold method (4pATM) have been used for threshold materials.

TABLE III

DIFFERENT THERMAL MODELS [6]

Model	Formula
AM	$L = L_0 e^{-BcT}$
ATM	$L = \dfrac{L_0 e^{-BcT}}{(T / T_{t0}) - 1}$
EM	$L = \dfrac{C}{T} e^{D/T}$
4pATM	$L = \dfrac{L_0 e^{-BcT}}{(\{T / T_{t0}\} - 1)^{\mu 4pATM}}$

Since AM has previously been chosen to model XLPE insulation aging for optimal placement of underground cables [7], this model is also applied in this paper to simulate the XLPE cable thermal lifetime, i.e.

$$L = L_0 e^{-BcT} \tag{3}$$

where $cT = 1/T_0 - 1/T$ is the so-called conventional thermal stress; T is the maximum temperature (^{0}K) and T_0 is a proper reference temperature, commonly set to ambient temperature. L_0 is the cable life at $T = T_0$ and B equals to $\Delta w/k$, where Δw is the activation energy of the main thermal degree radiation reduction and k is Boltzmann's constant, 1.38×10^{-23} J/K. Although Δw varies at different temperatures, it changes only slightly e.g. [8, 9]. In this paper, it is considered to be a constant value of 1.6×10^{-19} J [9]. Parameters of equation (3) used in this paper for XLPE cables are given in Table IV.

TABLE IV

PARAMETERS FOR XLPE CABLE AGING THERMAL MODEL

Parameters	Value
L_0	40 years
T_0	363.15 K
B	11594 K

Based on the cable temperature of different cable configurations resulting from the above IEC method, equation (3) is applied to evaluate the cable lifetime. As different voltage changes due to tap changes lead to different cable temperatures, different cable lifetimes will be obtained. The cable life extension (Le) can be determined by

$$Le = \frac{L_c - L_n}{L_n} * 100\% \tag{3}$$

where L_n is cable lifetime when the tap is not changed, while L_c is the lifetime value under different voltage tap changes.

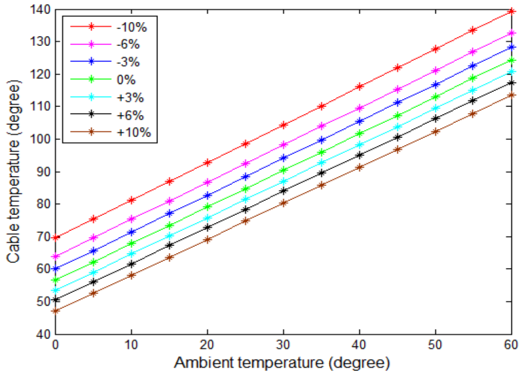
Cable lifetime improvements between different tap changes can then be compared and results are illustrated in Section IV-B.

IV. RESULTS AND DISCUSSION

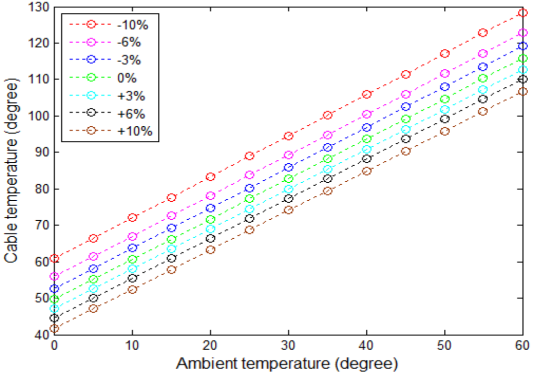
A. *Cable Temperature*

Based on the above IEC method, cable temperature with ambient temperatures ranging from 0 ^{o}C to 60 ^{o}C due to tap changes are obtained. A typical cable (trefoil touching formation) temperature is presented in Fig. 2, while the other cable configurations (three horizontal touching and vertical touching formation) follow the same pattern as in this Figure. It illustrates that for a certain level of tap change, both cable conductor and surface temperatures increase linearly with increased ambient temperature. For a certain ambient temperature, the cable temperature decreases along with corresponding voltage increases from -10% to +10%.

A comparison of cable temperatures between different cable configurations at 25 ^{o}C ambient temperature is shown in Fig. 3. Clearly, for a certain level of tap change, the cable temperature difference between different configurations is less than 1.5 ^{o}C. The cable with trefoil touching formation has the highest temperature, while cable with vertical touching formation has the lowest temperature.



a. Conductor temperature



b. Surface temperature

Fig. 2. Cable (trefoil touching formation) temperature under different ambient temperature

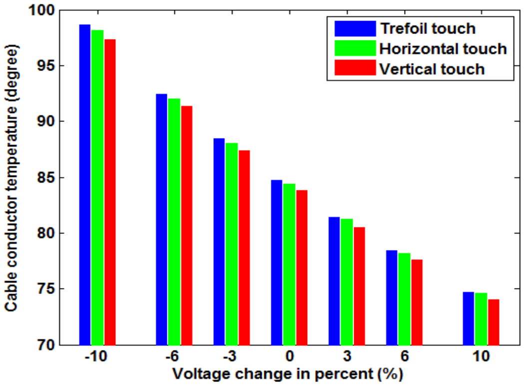


Fig. 3. Comparison of cable conductor temperature between different configurations at 25 ^{o}C due to tap changes

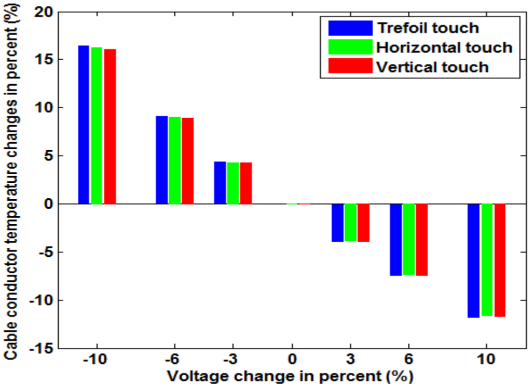


Fig. 4. Comparison of cable conductor temperature changes in percent between different configurations at 25 ^{o}C due to tap changes

Furthermore, for each cable configuration, a comparison of cable temperature between the standard voltage (tap does not change) and the changed voltage (tap changes) is presented in Fig. 4. The figure shows that when voltage decreases by -10%, cable temperature increases by around 16%, while cable temperature decreases by around -12% when voltage increases by +10%.

B. Cable Lifetime

According to the cable thermal aging method detailed in Section III-B, cable lifetime estimation between different configurations at 25 °C ambient temperature are shown in Fig. 5. This depicts that cable lifetime increases along with increased voltage. Between the three configurations, for a certain level of tap change, the cable with trefoil touching formation has the shortest lifetime, while the cable with vertical touching formation has the longest lifetime. The lifetime difference between different configurations increases along with increased voltage.

The extended cable lifetime between different configurations at 25 °C ambient temperature is shown in Fig. 6. It can be seen that when the voltage decreases by -10%, the cable lifetime decreases by about -70%, while the cable lifetime increases by around 150% when the voltage increases by +10%. This means increased voltage improves cable thermal lifetime. Between the three different configurations, although they have similar lifetime improvements, the cable with trefoil touching formation has the best improvement, while the cable with vertical touching formation has the least lifetime improvement.

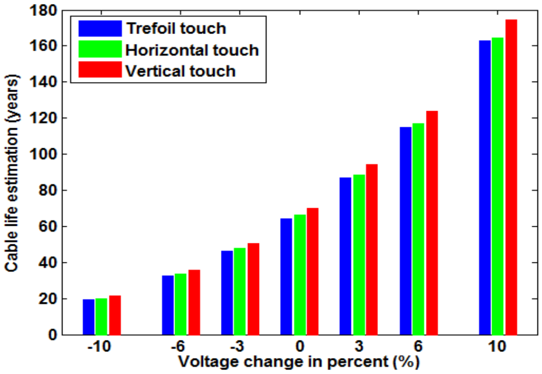


Fig. 5. Comparison of cable life estimation between different configurations at 25 °C due to tap changes

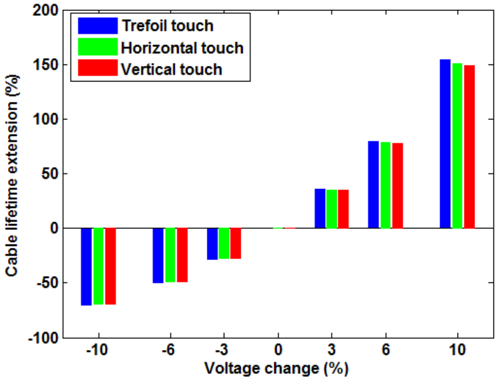


Fig. 6. Comparison of cable lifetime extension in percent between different configurations at 25 °C due to tap changes

V. CONCLUSIONS

This paper has uniquely combined the IEC 60287 method and an appropriate cable thermal aging model to analyse the potential cable lifetime improvements through long-term transformer tap changes around statutory permitted levels. Due to the tap changes, system voltage and current will change. The paper has applied the IEC method to determine cable temperature under different voltages and relative currents to feed a thermal model and thus evaluate cable lifetime. Results indicate that on the thermal bases, increased voltage due to tap change improves cable lifetime. Between the improvements of three different configurations, although they show similar improvement, the cable with trefoil touching formation shows the best improvement, while the cable with vertical touching formation shows the least improvement. As system distribution voltage is variable, this modeling method can provide a potential understanding for implementation of long-term regulatory voltage movements in relation to anticipated cable lifetime changes.

During normal working conditions thermal and electric stresses act simultaneously, therefore electric stress must also be considered in this study in future. As partial discharge (PD) is also a key aging mechanism of MV cables, PD effects will also be investigated to understand the implications on cable lifetime through regulatory transformer tap changes.

ACKNOWLEDGMENT

This work was funded though EPSRC Hubnet, the Supergen Energy Networks Hub, under Grant EP/N030028/1.

REFERENCES

[1] Renforth, L., Mackinlay, R., Michel, M., “MV cable diagnostics-applying online PD testing monitoring”, MNCCIRED Asia Pacific Conference on MV Power Cable Technologies, paper number 14. 2005.

[2] J. G. Head, P. S. Gale, D. J. Skipper, and A. W. Stannet, “Ageing of oil-filled cable insulation”, CIGRE paper 15-08, 1982.

[3] IEC Standard – Electrical cables – Calculation of the current rating – Current rating equations and calculation of losses -- general, IEC Standard 60287-1-1, 2014.

[4] IEC Standard – Electrical cables – Calculation of the current rating – Thermal resistance – Calculation of thermal resistance, IEC Standard 60287-2-1, 2015.

[5] http://www.cablejoints.co.uk/upload/33kV_Single_Core_XLPE_Insulated_Copper_Wire_Screened_BS7870_Prysmian_500sqmm.pdf.

[6] Di Silvestre, M.L., Massaro, F., Mineo, L., Zizzo, G, “A statistical approach of cables ageing in MV lines on thermal and electrical combined stresses”, Int. Symp. Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), May 2006, pp. 846 ‑ 851.

[7] D. A. Zarchi, B. Vahidi, “Optimal placement of underground cables to maximize total ampacity considering cable lifetime”, IET Generation, Transmission & Distribution, vol. 10, no. 1, p. 263-269, 2016.

[8] A. Rawangpai, B. Maraungsri, N. Chomnawang, “Artificial accelerated ageing test of 22 kV XLPE cable for distribution system applications in Thailand”, International journal of electrical, computer, energetic, electronic and communication engineering, Vol. 4, No:5, pp.797-802, 2010.

[9] L. Boukezzi, A. Boubakeur, M. Lallouani, “Life Time Estimation with Different Models of XLPE Insulation Cables under Thermal Aging”, 7th National Conference on High Voltage, CNHT09, Sidi Bel-Abbès, Vol. 1, pp. 1-4, 2009.