UNIVERSITI PUTRA MALAYSIA

HARSH ENVIRONMENTAL IMPACT ON PERFORMANCE OF LOW VOLTAGE UNDERGROUND POWER CABLES IN HOT COUNTRIES

SABAH HASAN ALWAN

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By

SABAH HASAN ALWAN

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

January 2017

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DEDICATION

To my Parents,

My lovely Wife, Zahra Naser,

My Son: Mohammed Ali, and my daughters: Noor and Fatima

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Degree of Master of Science

HARSH ENVIRONMENTAL IMPACT ON PERFORMANCE OF LOW VOLTAGE UNDERGROUND POWER CABLES IN HOT COUNTRIES

By

SABAH HASAN ALWAN

January 2017

Chairman : Jasronita Jasni, PhD
Faculty : Engineering

It is a well-known fact that underground cable loads are affected by many factors such as depth of installation, number of parallel circuits of cables, ambient temperature, conductor size, duct size, size of backfill (or duct bank), and soil thermal resistivity. It is also recognized that resistivity changes with moisture migration under loading conditions. One important factor that is usually ignored is a harsh environment. In hot countries, extreme environmental conditions exist, where the air temperature during the summer season overrides 50^0C and the dry soil creates very high thermal resistivity.

This dissertation takes a direct and comprehensive approach to study the effect of harsh environment on thermal performance of the buried power cables to evaluate the cable temperature rise as well as the effect upon life reduction under constant loading conditions, using the dry zone formulation which provides a simple but consistent framework to model cables and their installed environment.

In this thesis, the effect of a harsh environment on the current-carrying capacity (or ampacity) of underground power cables is also presented.

The method is given to extend the use of a thermal circuit to cover the entire environment rather than just the cable itself. This is because the nodal solutions in the environment support the prediction of moisture migration in the steady-state adaptation of the two-zone approach to moisture migration employed in the standards, where the native soil surrounding cables is assumed to dry out when the temperature overrides a predefined critical temperature rise above ambient.

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The main application of the FEM is to predict conductor temperatures in real time from thermal resistivity measurements and a realistic knowledge of the thermal environment of a cable. A full thermal analysis of the installed cable system can lead to high accuracy in the finite element method and predict the conductor temperature from thermal resistivity measurements.

The phenomenon of the formation of the dry zone around the cable related to three types of soil is considered, when these types of soil are subjected to constant loading conditions.

The IEC-60287 was taken as a reference, while ANSYS software was used to calculate the temperature distribution at the cables with the surrounding environment for different types of native soils with some experimental data. The results have demonstrated that the ambient temperature in Iraq has a direct impact upon cable life temperature and useful life.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Master Sains

KESAN PERSEKITARAN TERLAMPAU KE ATAS PRESTASI KABEL BAWAH TANAH BERVOLTAN RENDAH DI NEGARA-NEGARA BERCUACA PANAS

Oleh

SABAH HASAN ALWAN

Januari 2017

Pengerusi : Jasronita Jasni, PhD
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Beban kabel bawah tanah diketahui adalah dipengaruhi oleh banyak faktor seperti kedalaman pemasangan, jumlah litar selari kabel, suhu ambien, saiz konduktor, saiz salur, saiz kambus balik (atau bank salur), dan keberintangan terma tanah. Keberintangan terma tanah juga diketahui berubah mengikut perubahan kelembapan dalam keadaan dengan beban. Salah satu faktor yang diabaikan adalah persekitaran terlampau. Keadaan persekitaran terlampau wujud di negara-negara bercuaca panas di mana suhu semasa musim panas melebihi 50^0C dan keadaan tanah yang kering akibat cuaca panas terlampau menyebabkan keberintangan haba yang tinggi.

Disertasi ini mengambil pendekatan menyeluruh untuk mengkaji kesan persekitaran terlampau terhadap prestasi terma yang terdapat pada kabel kuasa bawah tanah. Kajian ini juga adalah untuk menilai kesan kenaikan suhu kabel terhadap pengurangan jangka hayat kabel dalam keadaan beban malar. Selain itu, kajian ini juga menggunakan formulasi zon kering yang menyediakan rangka kerja yang mudah dan konsisten untuk merekabentuk model kabel dan persekitaran pemasasangan kabel.

Tesis ini juga membentangkan kesan persekitaran terlampau terhadap kapasiti arus pembawa (atau ampasiti) kabel kuasa bawah tanah.

Kaedah yang digunapakai adalah bagi memperluaskan penggunaan litar terma untuk meliputi keseluruhan keadaan berbanding hanya kabel sahaja. Ini adalah kerana penyelesaian nodal di dalam keadaan sekitar yang dapat menyokong ramalan bagi penghijrahan kelembapan di dalam keadaan mantap bagi pendekatan dua zon yang digunakan di dalam standard, di mana keadaan asal tanah di sekeliling kabel

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dianggap terlau kering apabila suhu melebihi kenaikan suhu kritikal di atas suhu persekitaran.

Aplikasi FEM yang utama adalah untuk meramal suhu sebenar konduktor daripada pengukuran keberintangan terma dan pengetahuan realistik tentang persekitaran terma di dalam kabel. Analisis penuh terma terhadap sistem kabel yang dipasang boleh membawa kepada ketepatan yang tinggi dalam FEM dan meramal suhu konduktor dalam pengukuran keberintangan terma – Fenomena formulasi zon kering di sekeliling kabel mengambil kira tiga jenis tanah di mana jenis tanah ini adalah keadaan beban malar.

Standard IEC-60827 dijadikan sebagai bahan rujukan, manakalan perisian ANSYS digunakan untuk mengira taburan suhu kabel dalam keadaan jenis tanah yang berbeza dengan data eksperimen. Keputusan kajian menunjukkan suhu ambien di Iraq mempunyai kesan langsung terhadap suhu kabel hidup dan jangka hayat kabel.

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In the Name of Allah, Most Gracious, Most Merciful, all praise and thanks are due to Allah, and peace and blessings be upon His Messenger. I would like to express the most sincere appreciation to those who made this work possible; supervisory members, family and friends.

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I certify that a Thesis Examination Committee has met on 17 January 2017 to conduct the final examination of Sabah Hasan Alwan on his thesis entitled "Harsh Environmental Impact on Performance of Low Voltage Underground Power Cables in Hot Countries" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Master of Science.

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Declaration by Members of Supervisory Committee

This is to confirm that:
- the research conducted and the writing of this thesis was under our supervision;
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Name of Member of Supervisory Committee: Dr. Norhafiz Azis

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LIST OF SYMBOLS

Qent	rate of energy entering the cable
Qint	rate of the heat generated internally in the cable by joule
Qout	Energy dissipated by conduction, convection and radiation
ΔQst	Change of energy stored within the cable
ρ	Thermal resistivity
A	Conductor area
K	Thermal conductivity
Q	The heat generation
H	global conductivity matrix
T	vector for temperature
b	load vector
I	current
R_{AC}	Alternating Current Resistance
WC	losses (joule) of the conductor
R_{DC}	Direct current resistance
$\propto 20$	temperature coefficient at 20 ^{0}C
Y_S	skin effect factor
Y_P	proximity effect factor
F	Frequency
W_d	Dielectric loss
W	angular frequency
$Tan\delta$	Loss factor
ε	Relative permittivity of insulation material
T_1	Thermal resistance between one conductor and the sheath
T_2	Thermal resistance between sheath and armour
T_3	Thermal resistance of outer covering
T_4	Thermal resistance for the soil
V	the ratio between thermal resistivity for the dry zone upon thermal resistivity for wet zone
T_X	critical temperature rise above ambient temperature between dry zone and wet zone
ΔTX	difference between critical temperature and ambient temperature of the native soil

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Ta	Ambient temperature
T_C	Conductor temperature
dR/dT	life expectancy variation
E	activation energy
K	Boltzman constant

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CHAPTER 1

INTRODUCTION

1.1 Background to the Study

For the purpose of transmitting and distributing power to the networks, power generating companies depend greatly on power cables. While it is true that the use of overhead lines is the common transmission method, there is increasing preference for power cables as they offer safety of life, and for also aesthetical and reliability considerations.

Poly vinyl chloride commonly shortened as PVC is widely used polymer in many applications like in construction of pipes and cables. PVC insulated cables are used as a main link between substation and end user, it also contributes in indoor transmission lines between main distribution boards and loads. Underground power cables consist usually of several layers. Which are the metal conductor, insulation, sheath and jacket for protection against mechanical damage. However, this simple construction of underground power cables has become a very complicated structure under thermal, environmental and mechanical challenges.

The main source of heat at the underground power cables is the electrical power losses produced through current that flows into conductors with resistance. The electrical power losses that occur during the flow of electrical energy into the conductor, turns into heat energy within the power cable. Power cables have a maximum current carrying capacity. This capacity (ampacity) which cables is defined as the maximum current amount the conductor can carry safely and uninterrupted without overriding the nominal temperature values of the cable components, particularly that of the material that insulates the power cable. As such, it is important that the temperature of the cable insulation material should be determined under continuous operation conditions. In other words, what determines the maximum current value is the nominal temperature of the cable insulation. Otherwise, should the conductor temperature exceed the nominal value, the cable will malfunction and be operationally unsafe. The life of the insulator will also experience rapid aging or even be damaged and destroyed. For this reason, the insulator is a vital component of the power cable. Therefore, temperature itself is problematic if excessive. On the other hand, power cables are usually installed under earth and the soil around the cable operates as an even greater hindrance to heat dissipation. Besides the losses in the conductor there are other losses in the cables due to circulating currents. These losses are the sheath losses and armor losses. Therefore, loss calculation is not an important issue, but the temperature calculation is, and it is the focus of this thesis. Consequently, it is important to know, as accurately as possible, the temperature distribution around the underground power cables that can increase significantly during load. As insulation of the cable and the surrounding soil around the cable are not good thermal conductors, the generated heat in the conductor may not be transmitted efficiently away from the cable, which

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leads to thermal instability in the soil around the cable. And thus, this leads to the eventual thermal failure of the cable. For this reason, transferring the generated heat in the conductor to the surrounding atmosphere is a priority [1].

The calculation of temperature distribution has traditionally used the formula of Neher and McGrath [2] in 1957 which was later officially accepted by the International Electrotechnical Commission (IEC). In the case of power cables buried underground, several factors can contribute to the limitation of their current ratings: installation depth, ambient temperature, existence and number of parallel circuits of cables, sheath bonding method, thermal properties of the soil, size of conductor and of backfill and also duct bank. Two of these factors, the ambient temperature and surrounding soil characteristics are weather-influenced. Additionally, it is important to note that cable-generated heat due to loading conditions can significantly vary the thermal characteristics of the soil. Hence, the cable ratings are invariably dynamic.

This thesis firstly focuses on the thermal performance of the soil around the cable, which is considered the most challenging for prediction as it is usually subjected to geographic and seasonal changes in terms of its ability to dissipate heat. Because the inclination, which this thesis supports, is toward steady-state rating and temperature prediction based on thermal resistivity measurements in harsh environments such as the three types of native soil under constant loading conditions. This is in addition to the phenomenon of a dry region around the cable, which will minimize the ability of the ambient soil to dissipate the generated heat through the cable.

This thesis investigates these challenges, which lead to thermal instability in the ambient environment around the cable, leading to thermal failure of the cable insulation. For this reason, correction (de-rating) factors are used in loading with respect to the dry region, which should be included at the design stage of the cable network.

In this thesis, the thermal field analysis is based on the standard (IEC 60287, 2006) which can be applied in a geometrical structure and in homogeneous soil conditions. For example, the thermal circuit parameters of the cable consist of diverse thermal properties; formation of ambient environment around the cable, and other heat sources adjacent to the cables. Meanwhile, the IEC has adopted a dual-zone model: first zone is the moist zone with uniform thermal resistivity and second zone is the dry zone while the boundary between the two zones zone is for the purpose of synchronizing with the critical temperature. In soil temperatures that exceed the critical isotherm, there must be uniformity of the thermal resistivity and similarity with that of dry soil. Furthermore, the critical isotherm of 30^0C higher than the ambient soil temperature should be taken into consideration and supported. All these situations make the analytical solution very complicated.

In light of all these factors, the most practical method these days is to estimate the simple cable installations, or complicated installations in a pragmatic way by using numerical calculation methods as has been followed by many researchers [3-6],

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especially the finite element method (FEM), which is applied in the analysis and calculation of the temperature distribution and the current-carrying capacity of buried power cables. The effectiveness of the method to numerically calculate the temperature has been proven as it provides superior representation of how the heat between different power cables interacts with each other and with other external heat sources. Additionally, this approach offers greater modeling accuracy for the region's boundaries. On the other hand, in FEM, the current-carrying capacity relies on the assumption of values being constant for thermal parameters such as soil thermal resistivity and heat conduction coefficients at the borders. Meanwhile, all the thermal circuit parameters are subjected to seasonal and geographical changes which affect the permitted loading conditions for all types of cables. In this study, all finite-element simulations were carried out employing ANSYS Multiphysics to compute temperature distribution in the cable with its immediate surroundings for various native soil types with some experimental data.

In addition, cable installations consisting of three single-core cables (flat formation) will be modeled as three-phase circuit in a harsh environment as a case study. This circuit contains nodes at the conductor, and in each layer of the cable until the outer layer, and nodes distributed in every homogenous area of the ambient environment to capture the temperature and heat flux density. Also, the distribution of the temperature between every node allows the determination of the critical temperature that distinguishes the dry zone from the wet zone.

1.2 Problem statement

The actual lifetime of PVC cables depends on its operation, environment and its service condition. The working of PVC cables in low power transmission lines is common, and their degradation can affect the whole system or grid. The biggest challenge faced in case of buried PVC cables is temperature. Heat generated in low voltage cables should be dissipated through the surrounding soil. Dissipation must preserve the cable temperature safely and reliably. The cable working temperature relies mainly on the soil's ability to dissipate the generated heat. The main problem faced regarding PVC is thermal ageing over time due to changes in temperature which may cause PVC to lose all its insulation properties and render it unsafe for commercial use in the long term.

In hot countries such as Iraq, extreme environmental conditions exist, where the air temperature during the summer season overrides 50^0C and the dry soil creates very high thermal resistivity. The environmental and soil parameters reduce the dissipated heat from underground power cables to the surrounding medium due to the high thermal resistivity of the soil and ambient temperature. This situation leads rapidly to increase the dry zone around the cables which leads to thermal instability of the soil around the buried power cable, which leads to thermal failure (aging) of the cable. Under such conditions, the environmental and soil parameters significantly influence the current-carrying capacity of the power cable. For this reason, derating factors are also presented in this work.

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1.3 Objectives

The objectives of this study are

i. To determine the effect of the dry soil and the ambient temperature in summer season on the thermal performance of underground power cables for different types of soil in hot areas.
ii. To study the relationship between temperature and PVC cable life under extreme soil and environmental conditions for three types of soil.
iii. To determine the effect of the dry soil and the ambient temperature on underground power cables current ratings (ampacity) under constant loading conditions to find a suitable correction factor for each type of soil.

1.4 Scope of the research work

This thesis tends to focus on two main scopes. First, the research in this thesis is restricted to underground PVC power cables. Second, this work only focuses on the ambient temperature and the soil thermal resistivity that influences the current-carrying capacity of the cable and the cable insulation temperature. Also, this thesis deals with the phenomenon the dry region around the cable as related to three types of the soil (according to their composition). On the other hand, method of the cables installation is directly buried in the soil. The burial depth is usually 0.8m and the configuration of the cables is generally flat formation.

Shortly, the potential implementations of the main objects offered in this thesis are in hot areas, which involve the problems of buried power cables, besides other heat transfer problems of homogenous soil only, where parameters of the thermal circuit are subjected to geographical and seasonal changes. The applications in this thesis are certainly limited; however, the focus is on varying soil and harsh environmental conditions particularly common in south of Iraq. The study will be only done in the areas that the temperature reaches about 50 ^{0}C and more.

1.5 Motivation

Insulation is a basic part of many power systems. The expected life of most insulation materials is typically many decades in line with standard working conditions. However, many insulation materials (organic and inorganic) are degraded by fluctuating temperatures that may be higher than the nominal value. Besides, the underground cables are more costly than overhead lines. For building transmission lines of the same distance at the similar voltage level, underground lines cost about four to 14 times more than overhead lines [7].

Furthermore, the high cost of underground installation involves time to excavate as well as backfill the cable trenches and to install the power cables. The high initial

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cost associated with cable installations and the cable itself makes it important to carefully select the proper cable types and sizes to serve the loads.

1.6 Contributions of this thesis

This thesis endeavors

i. To model changing nominal environmental parameters due to seasonal changes in the moisture content of the cable surroundings is embodied into the FEM via the dependent variable *V*.
ii. To determine the proper size of buried power cables in suitable soil to prolong cable life and achieve an acceptable ampacity level of power cables in harsh environment. Therefore, the correction factors are used to conserve cable life in service.
iii. And offer greater flexibility in project implementation (numerical simulations of heat transfer processes could be an attractive alternative to experimental investigations, which are usually costly and time consuming).

1.7 Organization of the Thesis

Chapter 1 introduces the basic system of the cables, methods of installation, the heat generation sources, type of environment, and the overall research direction. Also presented are the research Objectives and Scope with a discussion of simulations and how they are executed. The Research Methodology is also briefly discussed indicating the general approach to the research. The methodology is provided to better understand the research approach. Also included is the overview of the project contribution to give a clear indication of the research outcomes and their implications to planners and practitioners in the field.

The literature review in Chapter 2 essentially details past research works that are related to the field of this current research are presented, studied and discussed. The knowledge gained from the study and discussion of previous assists this researcher with useful insights into some of the problems faced in the current research which have been investigated.

In Chapter 3, each procedure carried out in the current study is presented, whether as flow charts or in textual explanations. Finite-element software package ANSYS Multiphysics is used as the tool for simulating three single-core cables to calculate and analyze temperature distribution for three types of soil under harsh environmental conditions.

Chapter 4 contains the simulations and data analysis with the findings presented in graphs and tables for better comprehension of the significance of particular

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variables. The graphic presentations are given in great detail to ensure complete understanding of the project and its benefits.

The final chapter, Chapter 5 consists of conclusions on the overall study including how the research objectives have been achieved. This is followed by recommendations for other researches to continue investigating areas related to this current research to further add new knowledge to the field.

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REFFERENCES

[1] C. Garrido, A . F. Otero, and J. Cidras, "Theoretical Model to Calculate Steady-State and Transient ampacity and Temperature in Buried Cables," IEEE Transactions on Power Delivery, vol. 18, pp. 667-678, Oct 2003.

[2] J. H. Neher and M. H. McGrath, "The Calculation of the Temperature Rise and Load Capability of Cable Systems," AlEE Trans. (power apparatus and systems), vol. 76, no.3, pp. 752-772. September 1957.

[3] Hwang, C. C., Jiang, Y. H., (2003). "Extensions to the Finite Element Method for Thermal Analysis of Underground Cable Systems", Elsevier Electric Power Systems Research, vol. 64, no.5, pp. 159-164.

[4] Kocar, I., Ertas, A., (2004). "Thermal Analysis for Determination of Current Carrying Capacity of PE and XLPE Insulated Power Cables Using Finite Element Method", IEEE MELECON, Dubrovnik, Croatia,vol.12, no.20, pp. 905-908, May 2004.

[5] Li, H. J., Estimation of Soil Thermal Parameters From Surface Temperature of Underground Cables and Prediction of Cable Rating, IEE Proceedings, Transmission and Distribution, vol. 152, no. 6, pp. 455-501 November 2005.

[6] Su, Q., Li, H. J. and Tan, K. C., Hotspot Location and Mitigation for Underground Power Cables, IEE Proceedings, Transmission and Distribution, vol. 152, no. 6,pp. 524-532, November 2005.

[7] F. Kiessling, P. Nefzger, J. F. Nolasco and U. Kaintzyk “Overhead Power Lines: Planning, Design, Construction (Power Systems)” New York, Springer, vol.30, no.12, pp. 630-634, Oct 2003.

[8] “ IEC Std 60287 Electric cables - Calculation of the Current Rating, 2006.”

[9] “IEEE Std 399-1997, IEEE Recommended Practice for Industrial and Commercial Power Systems Analysis."

[10] H. C. Zhao, J. S. Lyall, and G. Nourbakhsh, "Probabilistic Cable Rating Based on Cable Thermal Environment Studying," presented at International Conference on Power System Technology, vol.15, no. 3, pp. 333-339, Oct 2000.

[11] J. S. Lyall, G. Nourbakhsh, and H. C. Zhao, "Underground Power Cable Environment on-Line Monitoring and Analysis," presented at IEEE Power Engineering Society Summer Meeting, vol. 30, no.14, pp. 150-157, April 2000.

[12] M. R. Sredojevic, R. M. Naumov, D. P. Popovic, and M. D. Simie, "Long Term Investigation of Thermal Behavior of 110 kV Underground Transmission Lines in the Belgrade Area," presented at 14th International Conference and Exhibition on Electricity Distribution (lEE Conf. Publ. no. 438), Jan 1997.

[13] M. Sankaran, C. Cooper, M. L. Dyer, and G. Karady, "Investigation of the Heat Distribution Around Cable Ducts in a Desert Climate," presented at Power Engineering Society General Meeting, IEEE. vol.40, no. 56, pp. 250-

© COPYRIGHT UPM

255, Mar 2004.

[14] C. L. Cooper, M. L. Dyer, and G. G. Karady, "Investigation of the Seasonal Variation of Ground Thermal Conductivity on High Voltage Cable Ampacity," Presented at Large Engineering Systems Conference on Power Engineering, (LESCOPE-04), vol.15, no.25,pp. 340-347, June 2004.

[15] H. Brakelmann and G. Anders, "Ampacity Reduction Factors for Cables Crossing Thermally Unfavorable Regions," IEEE Transactions on Power Delivery, vol. 16,no.18, pp. 444-448, sep 2001.

[16] G. Anders, J. M. Braun, M. Vainberg, S. Rizzetto, and H. Brakelmann, "Rating of Cables in a Non-Uniform Thermal Environment," Presented at Transmission and Distribution Conference, IEEE. vol.17, no.3, pp.400-406, June 1999.

[17] Rasmus Olsen, George J. Anders and Joachim holboell, Modeling of Dynamic Transmission Cable Temperature Considering Soil-Specific Heat, Thermal Resistivity and Precipitation, IEEE Transactions on Power Delivery, vol. 28, No. 3, July, 2013.

[18] Lu, S., Ren, T., Gong, Y. and Horton, R. An Improved Model for Predicting Soil Thermal Conductivity from Water Content at Room Temperature. SSSAJ, vol.71, no. 1, pp. 8-14, Oct 2007.

[19] H. J. Li, K. C. Tan, and Qi Su, Assessment of Underground Cable Ratings Based on Distributed Temperature Sensing, IEEE Transactions on Power Delivery, vol. 21, no. 4, Oct 2006.

[20] Millar, R.J. and Lehtonen, M. Real-Time Transient Temperature Computation of Power Cables Including Moisture Migration Modelling. The 15th PSCC, Liege, vol. 4, no.5, pp 22-26, August 2005.

[21] Ossama E. Gouda, Adel Z. EL Dein and Ghada M. Amer, Effect of Formation of the Dry Zone around Underground Power Cables on Their Ratings, IEEE Transaction on Power Delivery, vol. 26, no. 2, April 2011.

[22] Swaffield, D. J., Lewin, P. L. and Sutton, S. J. 2008. Methods for Rating Directly Buried High Voltage Cable Circuits. ISSN 1751-8687. IET Generation, Transmission & Distribution, vol. 2, no. 3, pp 2393-401.

[23] P. Vaucheret, R. A. Hartlein, and W. Z. Black, "Ampacity Derating Factors for Cables Buried in Short Segments of Conduit," IEEE Transactions on Power Delivery, vol. 20, no.3, pp. 560-565, September 2005.

[24] Ngockhoa Nguyen, Phan Tu Vu and Josef Tlusty, New Approach of Thermal Field and Ampacity of Underground Cables Using Adaptive HP-FEM, IEEE Transactions on Power Delivery, vol.23, no.2, pp. 231-235, April 2010.

[25] Marc Diaz-Aguilo, Francisco de leon and Matthew terracciano, Ladder-Type Soil Model for Dynamic Thermal Rating of Underground Power Cables, IEEE Power and Energy Technology System Journal, vol. 21, no.3, pp.405-412 oct 2014.

[26] Francisco de leon, Major Factors Affecting Cable Ampacity, IEEE Transactions on Power Delivery, vol.20, no. 2, April 2006.

© COPYRIGHT UPM

[27] Francisco de leon and George J. Anders, Effects of Backfilling on Cable Ampacity Analyzed with the Finite Element Method, IEEE Transactions on Power Delivery, vol. 23, no. 2, April 2008.

[28] Eric Dorison, George J. Anders and Frederic, Ampacity Calculations for Deeply Installed Cables, IEEE Transactions on Power Delivery, vol.25, no. 2, pp. 640-648 April, 2010.

[29] M. S. AL-Saud, M. A. El-Kady and R. D. Findlay, Advanced Thermal Field Sensitivity Analysis of Power Cables, IEEE Transactions on Power Delivery, vol. 23, no. 2, pp. 133-136. April 2007.

[30] G. Mazzanti, The Combination of Electro-Thermal Stress, Load Cycling and Thermal Transients and Its Effects on the Life of High Voltage AC Cables, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 16, No. 4, pp.1168-1179, August 2009.

[31] Zhiqiang Wang, Changliang Zhou and Guofeng LI, Thermal Life Estimation of Ethylene Propylene Rubber Insulated Shipboard Power Cable Using Artificial Neural Network, Journal of Computational Information Systems,vol.23, no.22, PP. 2999-3006. June 2012.

[32] S. A. Taylor and J. W. Cary. Linear Equations for The Simultaneous Flow of Matter and Energy in a Continuous soil System. Soil Science Society of America Proceedings, 28:167-172, Mar 1964.

[33] J. R. Philip and D. A. de Vries. Moisture Movement in Porous Materials Under Temperature Gradients. Transactions of the American Geophysical Union, vol.38, no. 2, pp. 222-232, April 1957.

[34] D. Hillel. Fundamentals of Soil Physics. Academic Press Inc, 1980.

[35] D. K. Cassel, D. R. Nielsen, and J. W. Biggar. Soil Water Movement in Response to Temperature Gradient. Soil Science Society of America Proceedings, vol.3, no.25, pp. 493-499, Feb 1969.

[36] V. Dakshanamurthy and D. G. Fredlund. A Mathematical Model for Predicting Moisture Flow in an Unsaturated Soil under Hydraulic and Temperature Gradient, Water Resources Research, vol. 17, no.50, pp. 714-722, September1981.

[37] J. G. Hartley and W. Z. Black. Transient Simultaneous Heat and Mass Transfer in Moist Unsaturated Soils. Transactions of the ASME, vol.19, no.103, pp.376-382, April1981.

[38] Power Cable Manual, South Wire Company, USA, 1999.

[39] P. E. Allaire, "Basic of the Finite Element Method, Solid Mechanics, Heat Transfer, and Fluid Mechanics," Brown publisher 1985.

[40] G. J. Anders, "Rating of Electrical Power Cables, Ampacity Computation for Transmission, Distribution and Industrial Applications," IEEE Press. vol. 22, no.25, pp. 433-438, Oct 1994.

[41] M.A. El-Kady, "Calculation of the Sensitivity of Power Cable Ampacity to Variations of Design and Environmental Parameters," IEEE Transaction on Power Apparatus and Systems, vol. PAS-103, No. 8, Feb 1984.

© COPYRIGHT UPM

[42] Anders, G. Rating of Electric Power Cables, Ampacity Computations for transmission, Distribution, and Industrial Applications, IEEE Press, vol. 30, no.4, pp.670-677, Oct1997.

[43] Gyger, C. The Laying of Medium-Voltage Cables in Conduit, Verlegung von Mittelspannungskabeln in Schutzrohren, Unipede Workshop on MV Cables, Darmstadt, vol.3, no.5, pp. 25-26, November 1996.

[44] Freitas, D.S., et al., Thermal Performance of Underground Power Cables with Constant and Cyclic Currents in Presence of Moisture Migration in the Surrounding Soil, IEEE Transactions on Power Delivery, vol. 11, no.3 pp. 1159-1170, July 1996.

[45] Milne, A.G. & Mochlinski, K., Characteristics of soil affecting cable ratings, Proceedings IEE, vol. 111, No. 5, pp. 1017-1039, May 1964.

[46] Millar R.J., A Comprehensive Approach to Real Time Power Cable Temperature Prediction and Rating in Thermally Unstable Environments, Doctoral Dissertation, Helsinki University of Technology, vo.15, no.4, pp.50-57, April 2006.

[47] Mochlinski, K. Assessment of the Influence of Soil Thermal Resistivity on the Ratings of Distribution Cables, Proceedings, IEE, Vol. 123, No. 1, pp.345-351, January 1976.

[48] CIGRÈ, Determination of a Value of Critical Temperature Rise for a Cable Backfill Material, Electra, vol.21, no. 145, pp. 15-29, Mar 1992.

[49] Gouda, O.E. et al. Effect of Dry Zone Formation around Underground Power Cables on Their Ratings, International Journal of Emerging Electric Power Systems, vol. 10, Issue 3, Article 2, Berkeley 2009.

[50] J. H. Neher, The Temperature Rise of Buried Cables and Pipes, AIEE Transactions, vol. 68,no.25, pp. 9-21, April 1949.

[51] IEEE Std. 442-1981 IEEE Guide for Soil Thermal Resistivity Measurements.

[52] V.V. Mason and Moshe Krutz Rapid Method of Thermal Resistivity of Soil, Transactions of the American Institute of Electrical Engineers,vol.13,no.4, pp. 570-577, August 1952.

[53] M. A. Martin, Jr., R. A. Bush, W. Z. Black, and J.G. Hartley, Practical Aspects of Applying Soil Thermal Stability Measurements to the Rating of Underground Power Cables, IEEE Transactions on Power Apparatus and Systems vol. PAS-100 No, 9, pp 4236-4249, September 1981.

[54] F. Donazzi, E. Occhini, and A. Seppi, “Soil Thermal and Hydrological Characteristics in Designing Underground Cables,” in Proc. Inst. Elect. Eng, vol. 126, no. 6, Jun 1979.

[55] J. G. Hartley and W. Z. Black, “Transient Simultaneous Heat and Mass Transfer in Moist Unsaturated Soils,” ASME Trans., vol. 103, pp. 376–382, May 1981.

[56] G. J Anders, Rating of Electric Power Cables. New York: IEEE Press/ McGraw-Hill, vol.3, pp. 132-137 June 1998.

[57] D. S. Freitas, A. T. Prata, and A. J. de Lima, “Thermal Performance of

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Underground Power Cables with Constant and Cyclic Currents in Presence of Moisture Migration in the Surrounding Soil," IEEE Trans. Power Del., vol. 11, no. 3, pp.1159–1170, Jul 1996.

[58] Kelen, A., "Short Time Ageing Tests." NORDIC Insulation Symposium, 1974.

[59] Boulter, A., "Mechanical Stresses as Ageing Factors of Electrical Insulation Systems." International Electrotechnical Commission Technical Committee: Insulation Systems (DRAFT), no.63, pp. 273-281, June 1976.

[60] R.R. Dixon. "Thermal Aging Prediction from an Arrhenius plot with only Data Point", IEEE transaction electrical insulation, vol. EI-15, no. 4, pp.331-334, June 1980.

[61] V. Plaček, "Assessment of Parameters for Simulation of Thermal Ageing of Materials in Nuclear Power Plants Using DSC," Akadémiai Kiadó, Budapest, pp. 185-201, June 2005.

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