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ADVANCED THERMAL ANALYSIS OF UNDERGROUND POWER CABLES

BY
M.A. Mozan, M.A. El-Kady and A.A. Mazi

Electrical Engineering Department, King Saud University
P.O. Box 800, Riyadh 11421, Saudi Arabia
E-Mail: f45e017@saksu00.bitnet

Abstract

The use of underground power distribution has grown significantly over the years with the rapid increase in demand for electric energy and the trend for large infra-structures and vast expansion of highly-populated metropolitan areas. Traditional methods of cable ampacity calculations are all based on the Neher-McGrath analysis which approximates the cable circuit configuration and assumes uniform soil conditions around the cable. Such approximations and assumptions lead to inaccuracies in the calculations and often force cable engineers to use un-necessarily large safety factors and overly conservative designs, this paper presents an improved technique using the finite-element method to calculate the steady-state temperatures at various points of the cable system and, therefore, the overall cable ampacity corresponding to a specified maximum conductor temperature. An application to a cable system in the Saudi Consolidated Electric Company (SCECO-C) network is also presented.

INTRODUCTION

With the rapid increase in demand for electric energy and the trend for large infra-structures and vast expansion of highly-populated metropolitan areas, the use of underground power distribution has grown significantly over the years, both world-wide and in the Kingdom of Saudi Arabia. In the power grid of the Saudi Consolidated Electric Company - Centre (SCECO-C), for example, there is an extensive underground cable network covering thousands of kilometres and spanning various voltage levels, including the 33 kV distribution and the 132 kV transmission systems.

The power losses in the conductor, insulation, sheath and other components of the cable system act as heat sources and cause the temperatures of various cable elements to rise above the ambient temperature. The maximum conductor current is practically limited by the maximum temperature which the insulation can withstand. The cable temperature rise is a function of all parameters representing the thermal circuit of the cable including surrounding soil.

The problem of calculating the power cable temperature rise and ampacity has attracted many researchers since the famous work by Neher and McGrath [1]. Since then, considerable research efforts have been expended in modifying the Neher-McGrath method and enhancing its modelling capabilities under both steady-state and variable loading conditions [2-9]. However, these traditional methods of cable ampacity calculations approximate the cable circuit configuration and assume uniform soil conditions around the cable. Such approximations and assumptions lead to inaccuracies in the calculations and often force cable engineers to use un-necessarily large safety factors and overly conservative designs.

More recently, there has been a growing interest in using the finite-element method [10] for thermal field analysis of underground cables [11-13]. This advanced methodology offers a much better accuracy in the calculated results as it models the cable system and the surrounding environment to any level of details required. Therefore, complex cable configurations and non-uniform soil conditions can easily be taken into account.

This paper deals with recent advances in power cable thermal modelling and steady-state temperature rise calculations which employ the finite-element method. Special attention will be given to modify the finite-element grid modelling and structuring algorithms to handle general detailed cable arrangements and complex configurations which often occur in the underground networks of electric power utilities. In this regard, the finite-element method will be investigated and implemented to calculate the steady-state temperatures at various points of the cable system. Therefore, the overall cable ampacity (current carrying capability) corresponding to a specified maximum conductor temperature can be determined. In addition, a general-purpose automatic grid generation method, developed during the course of this project, will also be presented. Several software modules were developed to implement the new automatic grid generation algorithm and to calculate the cable temperature rise. These programs operate on the recently-developed interactive environment POWER! [14] for general power system analysis.

The paper describes the analytical and computational aspects of the finite-element method for calculating thermal fields of underground cable systems and presents a new method of constructing the finite-element grids for general cable system configurations. An Application is also presented involving a cable configuration used in the local Saudi Consolidated Electric Company (SCECO-C) network. In addition to evaluating the cable ampacity, the application also includes sensitivity analyses to investigate the effects of variations in the soil parameters on the results obtained.

FINITE-ELEMENT METHOD

In the application of the finite-element method to a system of buried cables involves, the conductor, insulation and other internal cable components as well as the surrounding soil are all divided into small triangular elements. The resulting grid (mesh) would then constitute many nodes (points) representing vertices of different triangles. The desired degree of accuracy may be obtained by adjusting the size of the grid elements. Temperatures at some of these nodes can be specified together with other boundary conditions.

The finite-element formulation starts with the general equation for steady-state heat conduction

$$div(k \nabla T) + q = 0 \qquad \mathbf{(1)}$$

in which k is the conductivity coefficient and q denotes the rate of heat generation. The solution of. this equation with appropriate boundary conditions gives the value of the unknown temperature T. In the finite element method [10], equation (1) is solved by using the energy functional concept and dividing the region in which the problem is to be solved into triangular elements leading ultimately to the set of linear equations [2,12]

$$[H]\{T\} = \{k\} \qquad \mathbf{(2)}$$

In this equation [H] is the heat conductivity matrix and {T} is a vector containing the steady-state nodal temperatures. Also, {K} is vector which expresses the distribution of heat sources and heat sinks over the region under consideration as well as its boundary conditions. In constructing the matrix [H]. and vector {K}, the boundary conditions of the cable thermal circuit are taken into account. In the paper, the following boundary types are considered:

a) Constant temperature T (isothermal)
b) Zero normal gradient dT/dn (non-conductive)
c) Constant heat flux Q per unit area
d) The convection loss at the boundary is equal to $\alpha(T-T_a)$, where T_a is the ambient temperature and α is the heat transfer coefficient.

In essence, the finite element method reduces the problem to that of solving a number of simultaneous algebraic equations. The solution of these equations yields the steady-state temperature distribution within the area under consideration.

The heat conductivity matrix [H] is a sparse matrix. Faster execution time as well as higher order weighting factors for the layers, which would lead to more accurate results, can be achieved by using some special handling techniques for sparse matrix manipulations. Some of the techniques available include the linked list and the band-matrix formulations. It is the authors' belief that much higher order grid size can be handled with the adoption of such techniques.

AUTOMATIC GRID GENERATION

In practice, many underground cables have complex configurations and are often buried in non-uniform soil. Direct-buried cables are usually surrounded by a layer of backfill of low thermal resistivity which in turn is surrounded by the native soil. In addition, several other heat sources and heat sinks may be present near the cable system which accordingly alter the thermal field around the cables. Such complex medium must be modelled properly in the finite-element analysis in order to attain an accurate representation of the resulting thermal circuit.

During the course of this project, a new methodology for automatic creation of the entire finite-element grid has been developed. The methodology can handle the majority of practical cable arrangements and soil/backfill configurations and, therefore, is applicable to most underground cable systems in practice. The idea is based on the novel concept of ***objects*** and ***layers*** defining various entities and zones of the cable system and the surrounding media. A set of rules are then established which uniquely define the shapes and locations of various objects and layers and determine the relationships between the resulting grid elements and nodes. Using this set of rules, very fast general-purpose computerized algorithms has been developed which automatically generate customized finite-element grids for most cable installations as will be illustrated next.

Finite-Element Grid Entities:

In the present methodology, the entire area of the cable installation and surrounding media is assumed to constitute different ***entities,*** each of which occupies a ***zone*** in the overall study area. The entities may represent, for example, cables, water pipes, drainage, sewer lines, soil blocks, backfill, concrete layers, duct- banks, etc. We shall use the term "object" to denote an entity (or, in some cases, a part of an entity) in the finite-element grid. The objects should possess the following properties:

1. They are rectangular in shape
2. The object sides are aligned horizontally and vertically in the grid
3. There should be no overlapping between objects

Each object consists of a number of "layers" (at least one) which represent its internal parts having different thermal properties (conductor, insulation, etc.). A weighting factor of multiples of four (4, 8, 12, ...) is assigned to each layer indicating the level of modelling details required.

Software Development;

During the course of the present project, several software modules were developed to implement the new automatic grid generation algorithm and to calculate the steady-state cable temperature rise. These programs were developed using the recently-developed interactive computing environment of POWER! [14] which uses the MATLAB computer package [16]. A flow-chart describing the set of the finite-element software modules for steady-state thermal analysis of power cables, is shown in Figure 1.

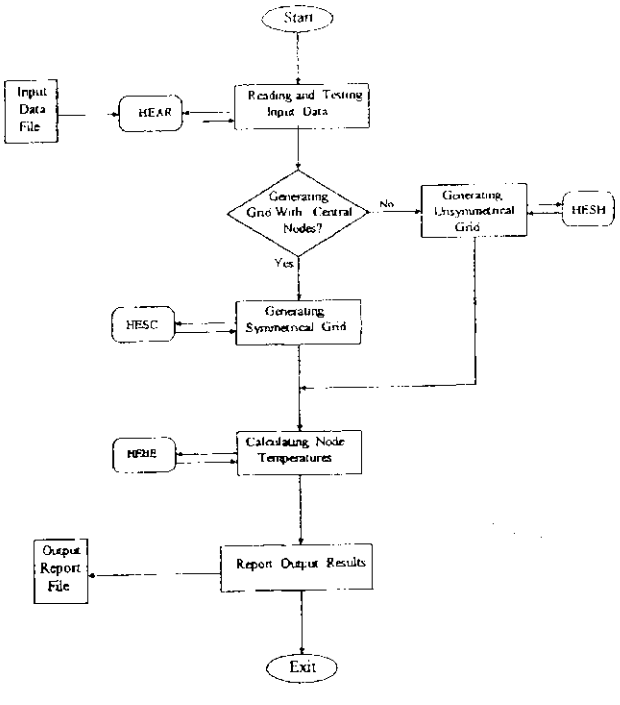

Fig. 1 Flow-Chart of Finite-Element Analysis

APPLICATION

A practical application is presented here to demonstrate the powerful features of the finite-element method for solving the heat equations and determining the hot spots in the cable system. This cable installation in the SCECO-C power system consists of a double-circuit three-phase underground cables as shown in Figure 2.

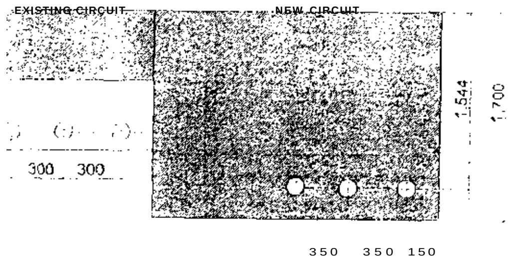

Fig. 2 A Doubles-Circuit SCECO-C Cable System

This cable configuration has resulted from adding a new three-phase cable circuit to an existing one in order to meet the growing demand for power in one sector of the SCECO-C power network. All dimensions in Figure 2 are in mm.

As shown in the figure, the cables are laid horizontally in non-uniform soil and at different circuit depth. Such a complex configuration suits the finite-element analysis very well as was explained earlier in the paper. In this regard, the use of conventional thermal analysis methods for this cable configuration would, undoubtedly, lead to gross errors in the calculated temperatures because of the complexity of cable arrangement as well as the non-uniformity of the surrounding soil which involves a backfill material of thermal resistivity different from that of the native soil.

Because of the relative closeness of the two cable circuits of Figure 2, the mutual thermal coupling between the two circuits is expected to have some effect of the calculated temperatures, especially at those points in the middle portion between the tow cable circuits.

The finite-element grid configuration used to analyze this consists of 10 objects and 22 layers. The ground surface in this study was modelled as an isothermal boundary at 35 °C.

It is of interest to note here that the maximum temperature node on the conductor surface of the new cable circuit did not occur at the bottom central conductor as is always assumed in the conventional methods. It rather occurred on the left-most conductor closest to the existing circuit. This is mainly due to the thermal coupling effect between the two circuits. This effect is already taken into account in the finite-element analysis but is inherently neglected in the conventional methods. Therefore, the current-carrying capability of the cable system estimated by traditional methods would, in this case, be more than the actual value.

The effect of variations in the soil thermal resistivity on the maximum conductor temperature of the new cable circuit, for a range of cable current values, was investigated in this application. Figure 3 shows the results obtained for three different values of soil thermal resistivity, namely 1.0, 2.0 and 4.0 °C m /W. The results of Figure 3 show that the conductor temperature at a cable current of 1.1 kA, for example, would increase from 83 to 91 -C as the thermal resistivity of native soil around the cable increases from 1.0 to 4.0 -C m / W.

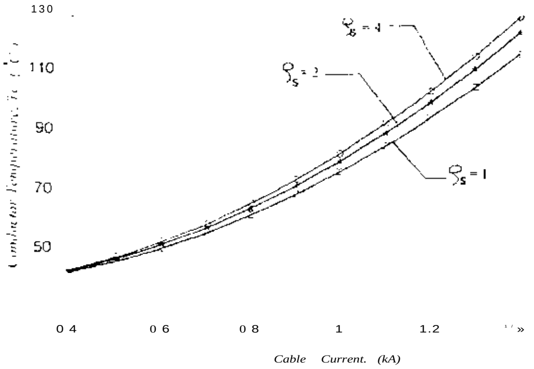

Fig. 3 Conductor Temperature vs Current

CONCLUSIONS

The general-purpose automatic grid generation methodology, presented in this paper permits a simpler, yet more automated, implementation of the finite-element method for thermal field analysis of underground cable systems. The computational algorithms presented offer adjustable modelling details coupled with fast computational schemes which can effectively handle complex cable configurations and non-uniform soil conditions to any desired level of accuracy allowed by the hardware capabilities.

The application presented has demonstrated the versatility and generality of the formulation and computational algorithms developed. It was noted in the application that the effect of the thermal coupling between cables in close proximity has caused the maximum temperature to occur in a point different from the one expected and used in conventional methods to determine the cable ampacity. The significant effects of variations in the thermal resistivity of local soil on the calculated cable ampacity have also been demonstrated. Such variations are extremely important in cable design and operation studies where the soil parameters in some parts of system may experience wide variations due to the effects of the sun heat, seasonal rain, etc.

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