

CALCULATION OF TEMPERATURE AND AMPACITY OF UNDERGROUND CABLES USING THE ADAPTIVE FINITE ELEMENT METHODS
TÍNH TOÁN NHIỆT VÀ KHẢ NĂNG MANG DÒNG CỦA CÁP NGẦM BẰNG PHƯƠNG PHÁP PHẦN TỬ HỮU HẠN THÍCH NGHI

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ABSTRACT

This paper presents the application of the adaptive finite element method (A-FEM) to calculate the thermal fields and ampacity of underground cables in steady state. In respect of mathematics, the Delaunay mesh is developed into the FEM algorithm to make the adaption of the grid in the cable surroundings. Its advantage is to obtain the faster solution but still insure the high accuracy. In respect of physics, due to the calculation of thermal distribution in whole system, the readers can realize that the thermal field of any cable can be distorted due to the affect of thermal fields of the other cables and it reflects the essential phenomena of physics (IEC 60287 standard propose that thermal field of any cable is affected by thermal fields of other cables but its thermal field can not be distorted proposes for advantages in calculating using the analytical method). The results of the Ampacity tested for many different configurations of underground cables compared to the ones by boundary element method (BEM) and the real datum of manufacturer. It has shown the significant reality and primacy of the proposed method .

Keywords: Underground cables, ampacity, Adaptive finite element method (A-FEM), temperature distribution.

TÓM TẮT

Bài báo trình bày việc áp dụng phương pháp Phần tử hữu hạn (PTHH) thích nghi cho việc tính toán trường nhiệt và khả năng mang tải của cáp ngầm cao áp trong trạng thái ổn định. Về phương diện toán học, lưới Delaunay được chúng tôi phát triển trong thuật toán của PTHH để tạo nên sự thích nghi lưới xung quanh cáp. Ưu điểm của nó là thu được lời giải nhanh hơn nhưng vẫn đảm bảo độ chính xác cao. Về phương diện vật lý, thông qua việc tính toán phân bố trường nhiệt của toàn hệ thống, người đọc có thể nhận thấy trường nhiệt của mỗi cáp hoàn toàn có thể bị “bóp méo” dưới sự ảnh hưởng của trường nhiệt gây bởi các sợi cáp khác và điều này hoàn toàn phản ánh đúng bản chất vật lý (tiêu chuẩn IEC 60287 giả thiết rằng trường nhiệt của mỗi cáp có chịu ảnh hưởng bởi trường nhiệt của các cáp khác nhưng bản thân trường nhiệt của nó thì không bị “bóp méo” để thuận lợi cho việc tính toán dùng phương pháp giải tích). Kết quả tính toán khả năng mang dòng kiểm tra cho các trường hợp nhiều cấu trúc khác nhau của cáp ngầm được so sánh với lời giải bằng phương pháp Phần tử biên và dữ liệu thực tế được cung cấp bởi nhà sản xuất cáp. Từ đó cho thấy ý nghĩa thực tiễn cũng như tính ưu việt của phương pháp được đề nghị.

I. INTRODUCTION

The system of underground cables is one of the main component of a modern power network in the developed cities due to the advantages compared to overhead lines. The stability and safety operation of buried cables are the expecting of power utilities. Therefore, the calculation of temperature and ampacity of underground cables is the important task for designing and operating underground cable systems. The cable ampacity is mainly

determined by the thermal properties its surrounding soil. So, it is very necessary to know the temperature distribution in and around buried cables. Many authors have used two approaches: i) the analytical method was used in IEEE and IEC standards - [8, 12, 14, 15]. ii) The numerical methods (Finite Difference Method (FDM)-[7], Boundary Element Method (BEM)-[6], Finite Element Method (FEM)- [4, 5, 9, 10, 11, 13], etc.) have been used for the analysis of the heat transfer of underground cables. Among them, the FEM is widely used

because of the adaptive geometry around of cables.

In this paper, we concentrate on the application of the adaptive finite element method (A-FEM) for computing the temperature distribution and ampacity of underground cables in the steady state. The accuracy of the procedure is verified by comparison with results that obtained by the BEM in [6] and the real results are given by manufacturer in [16].

II. THE A-FEM FOR AMPACITY CALCULATION

2.1 A-FEM for Heat Transfer Equation

In order to present the analysis, the following assumptions are made:

- The effect of radiation and convection at the ground surface are neglected.
- Thermal resistivity of soil is constant.
- The length of cable is very larger than its buried depth.

The Poisson equation describes the steady state of heat transfer for the cable in 2D can be written as [2]:

$$\frac{\partial^2 \theta}{\partial x^2} + \frac{\partial^2 \theta}{\partial y^2} + \rho_s W = 0 \tag{1}$$

Where ρ_s ($^{\circ}\text{Cm/W}$) is the thermal resistivity of soil. W (W/m) is the heat generation rate in the cable. θ ($^{\circ}\text{C}$) is the unknown temperature.

For computing the thermal field distribution, we firstly determine the region of field domain that is restricted by the rectangle of cross section of soil and cables (or ducts). Secondly, we use the Delaunay algorithm for discretizing the field domain into many triangular elements that made the coarse mesh. Thirdly, we resize the triangles from the expecting dimensions. In particular, the triangle elements near cables are needed higher accuracy than far ones. So, the size of these elements is smaller. From the coarse mesh, the nodes will be moved after each iteration until obtain the expecting sizes. Where, we use a simple function can be described as follows:

$$l = \min\left(\sqrt{(x-x_c)^2 + (y-y_c)^2}\right) \tag{2}$$

Where l is the expecting length of edge of triangles. (x_c, y_c) is the coordinate of circle. (x, y) is coordinate of nodes.

The algorithm will stop when $|l' - l| < \varepsilon$, where: l' is the length of edge triangles of previous iteration, ε is small gap. After this step, we obtain a fine mesh region.

Each cable surface (or duct if cable is installed into duct) is represented by N nodes. If the total of losses generated by one cable is W then a heat flux at each of N nodes will be W/N .

2.2 Procedure of Ampacity Calculation of Underground Cable

After finish the computation of temperature distribution, the value of the cable (or duct) surface temperature is used for calculating the thermal resistance of surrounding soil is written as -[4]:

$$T_4'' = \frac{\Delta\theta_{d-a}}{W} \tag{3}$$

Where: $\Delta\theta_{d-a}$ ($^{\circ}\text{C}$) is the cable (or duct) surface temperature relative to that of the ambient temperature. W (W/m) is the heat generation rate per unit of cable circuit.

Thermal resistance between cable conductor and surrounding soil can be divided into two part of thermal resistance between the cable conductor and the retaining duct can be determined by the analytical procedure (thermal resistance between conductor and sheath is T_1 , thermal resistance between sheath and armour is T_2 , thermal resistance of outer covering is T_3 , thermal resistance of material between cable surface and internal surface of duct is T_4' , thermal resistance of duct is T_4'' , and thermal resistance of soil is T_4''' , $T_4 = T_4' + T_4'' + T_4'''$).

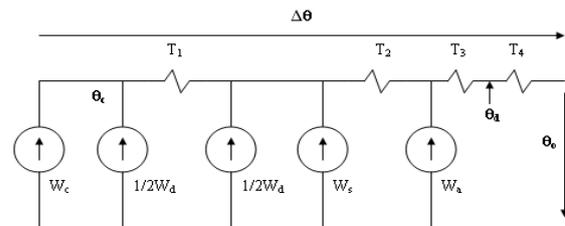


Fig. 1 Model of thermal-electrical circuit equivalent

The Ampacity cables can be written as [14]:

$$I = \sqrt{\frac{\Delta\theta - W_d [0.5T_1 + T_2 + T_3 + T_4]}{RT_1 + R(1 + \lambda_1)T_2 + R(1 + \lambda_1 + \lambda_2)(T_3 + T_4)}} \quad (A) \quad (4)$$

Where: $\Delta\theta$ (°C) is the conductor temperature rises above the ambient temperature. W_d (W/m) is the dielectric loss per unit length. R (Ω /m) is the resistance of conductor at 90°C.

T_1, T_2, T_3, T_4 (°Cm/W) are the thermal resistances. λ_1 is the sheath loss factor, λ_2 is the armour loss factor.

III. CALCULATION OF THERMAL FIELDS

3.1 Case 1: Three single-phase cables buried in homogeneous soil

Fig.2. illustrates the three single-phase cables in homogeneous soil. The heat for each cable is 43.5W/m ($W_1 = W_2 = W_3 = 43.5$). The diameter of three cables are equal ($d_1 = d_2 = d_3 = 0.03155$ m). A rectangular region of 12.2m in width and 6.1m in depth is selected for this computation [6].

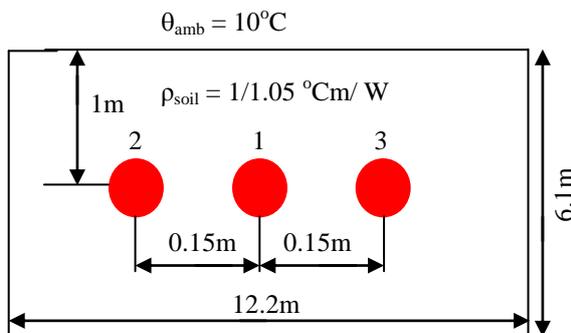


Fig. 2 Three phase cables in homogeneous soil

The field domain is subdivided into 294 nodes and 534 triangle elements which shown in Fig.3. The Fig.4a and Fig.4b show the results of temperature distribution over domain. Moreover, we compare to the results in [6] using BEM which given in TABLE 1-A. The tolerance temperature between FEM and BEM is 1.5479°C approximately because the surface of each cable in our model is represented by 13 nodes. So, we can determine the maximum and minimum temperature distribute on each cable surface (can see in Fig.4b, the value given in TABLE 1-A is mean value) while the

temperature on cable surface in [6] is isotherm. When we decrease the number of nodes and elements, the results will move toward the result from BEM. When we increase the number of nodes and elements, the temperature of cable 1 will converge to the approximate value 75°C (which given by TABLE .1-B).

Table 1-A. Comparison between the results of FEM and BEM for three single-phase cables in homogeneous soil

Temperature at each node θ (°C)			
Node	Cable 2	Cable 1	Cable 3
1	66.8524	73.5413	70.9117
2	66.8278	73.3171	70.3810
3	66.9655	72.9580	70.5234
4	67.7476	73.5840	70.8470
5	67.0898	72.6664	68.5208
6	68.5404	72.5845	69.6769
7	67.9373	73.5920	69.4534
8	69.4727	72.7189	68.2082
9	68.7652	73.2549	67.0415
10	70.1255	73.4654	67.3527
11	70.1863	73.2863	66.6579
12	69.5884	73.0210	66.0870
13	70.4190	73.3364	66.0526
A-FEM	68.5014	73.1789	68.5934
BEM [6]	67.0400	71.5500	67.0400

Table 1-B. Comparison among the results of FEM when remesh geometry for single-phase cables in homogeneous soil

Number of nodes	225	280	294	1148	
Number of elements	404	507	534	2184	
Number of nodes per cable	11	13	13	25	
Temperature (°C)	2	67.8965	68.2754	68.5014	69.9643
	1	72.5616	72.9498	73.1789	74.7693
	3	67.9878	68.4164	68.5934	70.6600

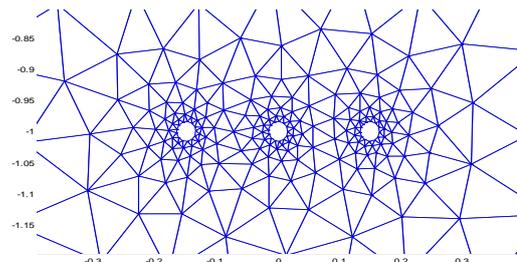
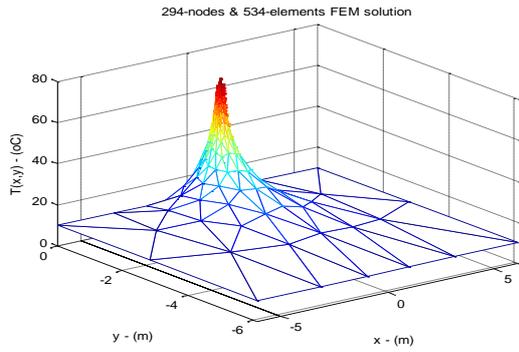
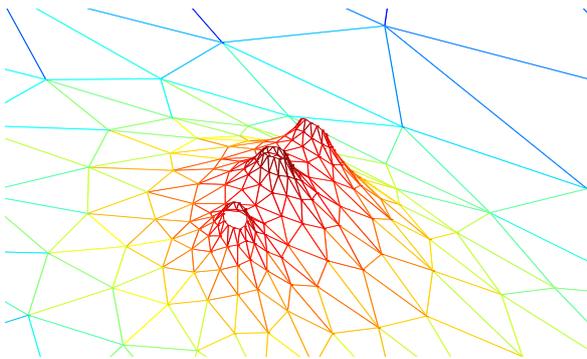


Fig. 3 Discretised field domain of the horizontal three-phase underground cable



a) Whole domain



b) Zoom domain

Fig. 4 A-FEM solutions of temperature distribution

3.2 Case 2: Three single-phase cables laid in duct are buried in homogeneous soil (horizontal configuration)

In this case, we use the parameters of the project of Hoa Xa-Tan Son Nhat 110kV underground cable system in Vietnam. The distance is 1737m. All parameters of cable, laid configuration are provided by Prysmian Baosheng Cable Co.Ltd. – [16]

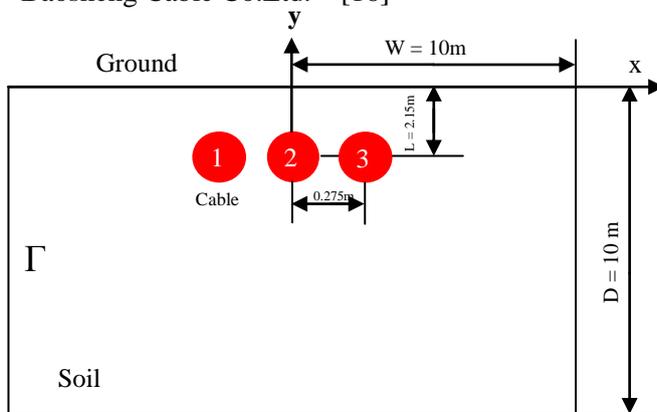


Fig. 5 Model of the horizontal three-phase cable

The Fig.5 illustrates the horizontal three phase cables. Each cable is installed in one HDPE (high density polyethylene) duct has internal diameter is 180mm and external diameter is 200mm and buried in homogeneous soil at the depth of 2.15m. The rectangular region of width of 20m and depth of 10m is selected for this case. This size is based on other researcher’s experiences in the location of boundary in numerical studies - [11].

Table 2. *Parameters specification*

Diameter of conductor (mm)	34.8
External diameter of cable (mm)	98.1
Resistance of conductor at 90°C (Ω/km)	0.0287
Sheath loss factor	0.0607
Thermal resistance T_1 (°Cm/W)	0.5302
Thermal resistance T_2 (°Cm/W)	0.0000
Thermal resistance T_3 (°Cm/W)	0.0779
Thermal resistance T'_4 (°Cm/W)	0.3046
Thermal resistance T''_4 (°Cm/W)	0.0587
Thermal resistivity of homogeneous soil (°Cm/W)	1.2
Ambient temperature Γ (°C)	27
Maximum temperature of conductor (°C)	90
Losses (for each phase when cable loaded 662A)	
Conductor (W/m)	11.542
Screen (W/m)	0.8040
Dielectric (W/m)	0.3563
Total losses (for three phase) (W/m)	36.919

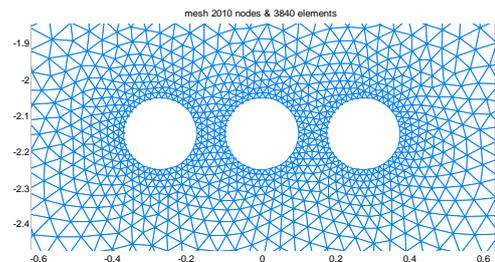
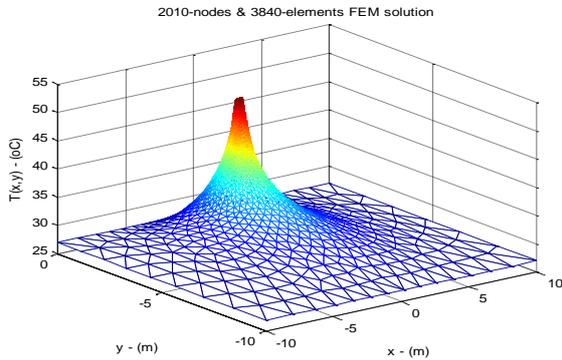
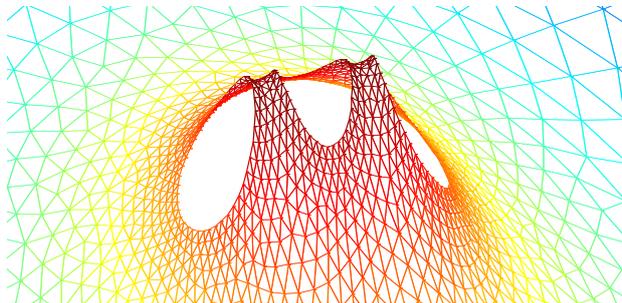


Fig. 6 Discretised field domain of the horizontal three-phase underground cable

In this case, parameters of cables are given in TABLE.2. The cables carry a steady current of 662A/phase causing the heat generation rate of 36.919W/m of circuit. Each surface of duct is represented by 41 nodes. Therefore, the heat generation of each node is 0.3002W/m.



a) Whole domain



b) Zoom domain

Fig. 7 A-FEM solutions of temperature distribution

The result of temperature distribution is shown in Fig.7a. and Fig.7b. The temperature of cable 2 is the largest, the maximum temperature on surface of each duct is given in TABLE. 4. in Section IV.

3.3 Case 3: The horizontal Double-circuit cables laid in duct buried directly in homogeneous soil

Fig.8. shows the double-circuit three-phase underground cables are parallel operating. The first circuit consists of cable 1, 2 and 3. The second circuit includes cables of 4, 5 and 6. The distance of two adjacent cables is 0.275m. All cables are installed in ducts (the internal and external diameter are 180mm and 200mm) and laid at depth of 2.15m.

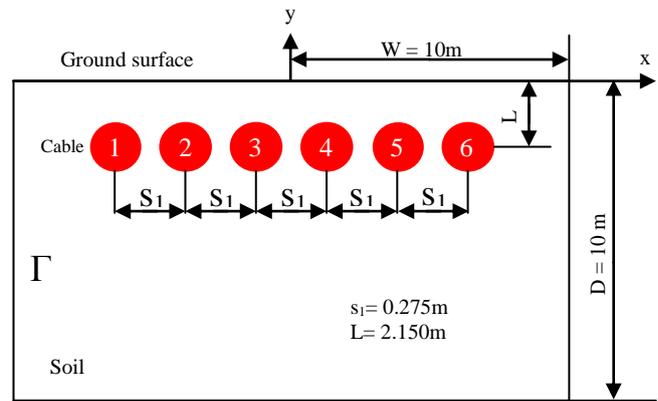


Fig. 8 Model of the horizontal double-circuit three-phase underground cable

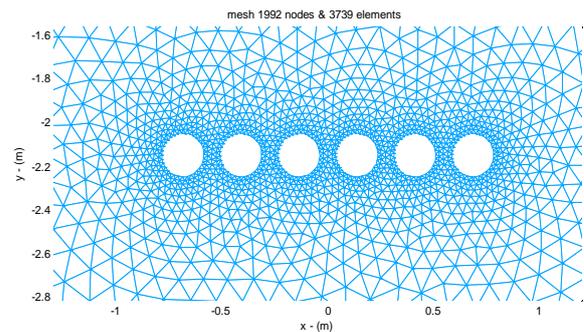


Fig. 9 The FE domain of the horizontal double-circuit three-phase underground cable

In this case, some parameters of cables are the same as in Case 2, but the losses of cables is different from Case 2 which given in TABLE.3. The cables carry a steady current of 609A/phase causing the heat generation rate of 32.029W/m of one circuit. Each surface of duct is represented by 33 nodes. Therefore, the heat generation of each node is 0.3235W/m.

The temperature distribution is shown in Fig.10a and Fig.10b. The temperature of cable 3 and cable 4 is largest, the maximum temperature on surface of each duct is given in TABLE. 4. in Section IV.

Table 3. Parameters specification

Losses (for each phase when cable loaded 609A)

Conductor (W/m)	9.9810
Screen (W/m)	0.6690
Dielectric (W/m)	0.3563
<u>Total losses (for three phase) (W/m)</u>	<u>32.029</u>

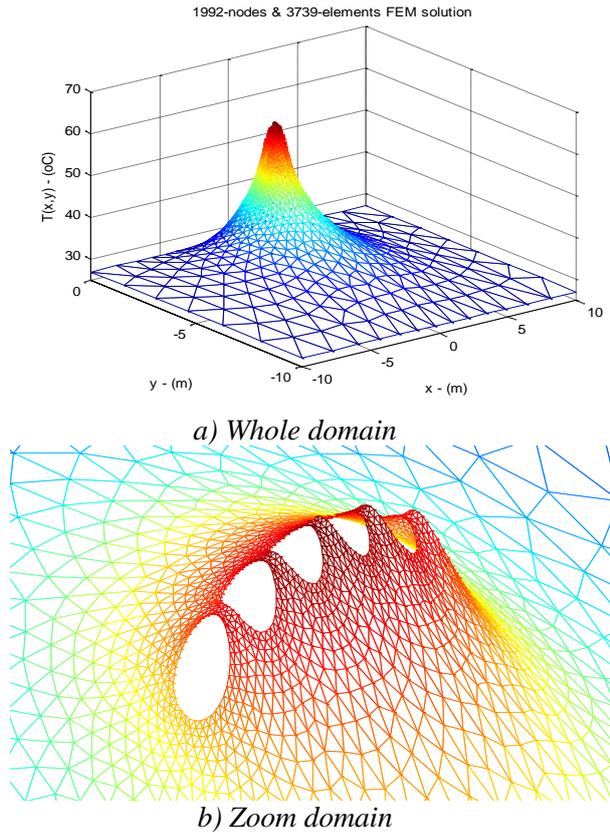


Fig. 10 Temperature distribution A-FEM solutions

IV. NUMERICAL RESULTS OF UNDERGROUND CABLES AMPACITY

The temperature values of duct surfaces are given in TABLE.4. may be used to determine the thermal resistance of surrounding soil using Equ. (3). Then, the ampacity of cables can be calculated by using Equ. (4).

The values of current capacity corresponding to the cables are shown in TABLE .4.. We compare those values with the current capacity which given by manufacturer. It is observed that the current capacity values obtained by the analytical procedure (given by PIRELLY PRYSMIAN Cables) are consistently higher by 3% than the corresponding ones of A-FEM (difference about 4-12% in reference [4]).

From values in TABLE .4., we observe that the ampacity of double-circuit cable is smaller than the single- circuit one.

Table 4. Ampacity by A-FEM and the manufacturer's data

Terms	Case		
	2	3	
Number of nodes	2010	1992	
Number of elements	3840	3739	
Time CPU (seconds)	227.0183	212.8181	
Maximum temperature at each surface of ducts (°C)	1	50.2029	55.8701
	2	50.3524	58.3104
	3	50.3445	59.2451
	4		59.2736
	5		58.2918
	6		55.9107
Resistance of soil (°Cm/W)	1.89759	3.02291	
Ampacity calculated using A-FEM (A)	848.27	715.52	
Ampacity provided by PRYSMIAN (A) -[16]	874.10	738.00	
Errors (%)	2.955	3.0461	

V. CONCLUSIONS

This paper has described the A-FEM for calculating the ampacity and temperature of buried cables in homogeneous soil. The proposed method has tested for many different types of the transmission and distribution underground cables such as the single circuit and double circuit cales, horizontal and triangular configurations and the others...The computed results compared to one of BEM and the manufacturer's data are also presented. The main contribution of this paper are as:

1. Using the adaptive algorithm that made the thick mesh around the cables and sparse one at the region that is so far from the cable. Therefore, the calculation will be faster but still insure the high accuracy.
2. Many different configurations of buried cables are presented. So that is the good data for designing and constructing the underground cable system.

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