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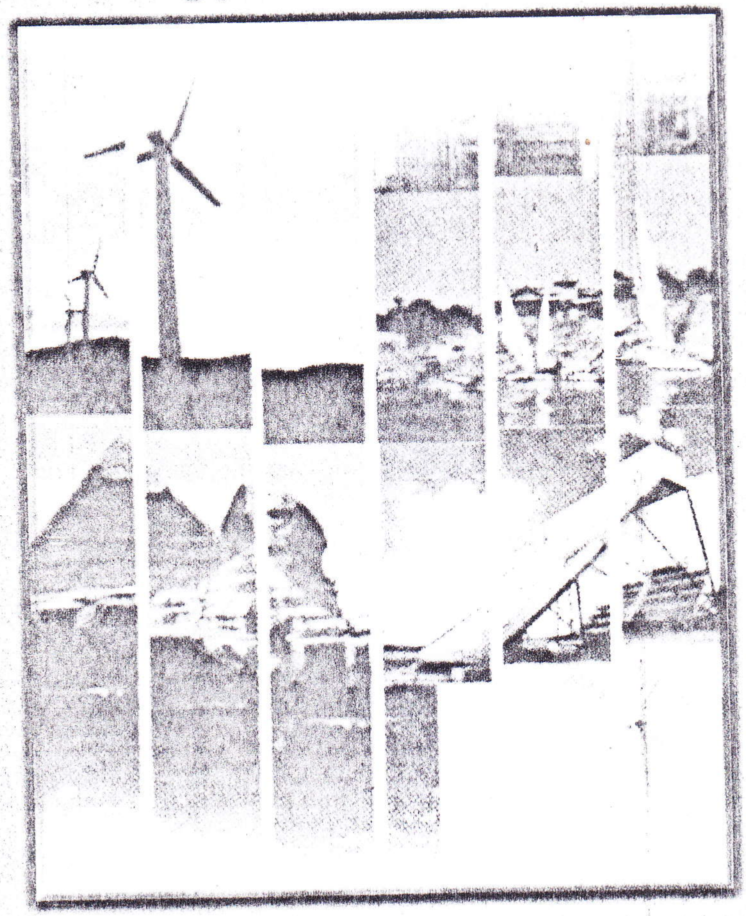

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IMPACTS OF THE ENVIRONMENTAL CONDITIONS ON THE CURRENT-CARRYING-CAPACITY OF OVERHEAD TRANSMISSION LINES

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Abstract
The thermal effects of the flow of the electric current with different intensities through transmission lines have been investigated under the effect of different weather and environment conditions. The actual weather performance of the transmission lines includes the effect of dust accumulation and ice formation on the outer surface is also investigated. A finite element technique was adopted for the two-dimensional transient conduction equation to predict the temperature distribution through stranded conductors at both transient and steady state conditions. The finite element analysis was developed presented for the transformed basic equations using linear triangular elements. The governing differential equations with the appropriate boundary and initial conditions were formulated, using the Galerkin procedure with interpolation functions as a weighted residual to provide the finite element equations. Moreover, measurements of the temperature distribution through the transmission line were carried out at different operating conditions. Also, a comparison between the present experimental and the theoretical results was conducted to check the convergence and validity of the present mathematical model and the method of calculations.

KEYWORDS
Conductor ampacity-Loss of strength-Heat transfer-Thermal rating-Transmission line ratings-Thermal impacts on transmission lines.

1. INTRODUCTION

The maximum load current that can be carried out by the conductor is designated as the conductor ampacity and it is normally determined from a single set of weather conditions and an assumed maximum temperature. A method of calculating the conductor ampacity by simulating the effects of weather and load current on conductor temperatures and determining the loss of strength due to annealing was presented in [1]. The transient current capacity of thick aluminium-clad strands as overhead ground wires for extra-high voltage transmission line was investigated by [2]. In this study a short-circuit current which was simulated as inducing fault current in real transmission lines, was applied and the corresponding temperatures have been measured. Also, a steady state thermal rating procedure, which includes forced convection heat transfer equations taking into account the effect of wind turbulence, wind direction, conductor surface, the proximity of conductors in a bundle and conductor pitch was presented in [3]. In this work, the conductor temperature was obtained directly without resorting to an iterative solution. The solar radiation received by an overhead transmission line was investigated by [4] and it was found that it is dependant on the conductor sag and slope. Also, the effect of the conductor slope on the total radiation was found more significant than that of the solar absorption constant. A method for determining transmission line ratings based on the relationship between the conductor's temperature and its sag is presented in [5]. This method is based on the Ruling span principle and the use of transmission line tension monitoring systems. To calculate the radial current distribution and core loss within a concentrically steel-cored conductor, the magnetic properties of the core must be known. The effects of magnetic field strength, tensile stress and temperature on the modulus, real and imaginary parts of the complex relative permeability, the hysteretic angle, the loss tangent, the total core loss and the hysteresis loss, are illustrated by comprehensive measurements in [6]. The problem of determining the steady state temperature distribution in radial direction of composite overhead transmission lines in steady state was mathematically modelled by [7,8] using the finite difference technique. In the case of transient solution the stranded transmission line was approximated as a solid and lumped body subjected to convective and radiative boundary conditions. Moreover, a test rig was constructed to supply and control a current to the test section of the transmission line and also the temperature of each layer of this section was measured. Also, a comparison between the measurements and theoretical results was carried out and fair agreement was found. This mathematical model gives the radial temperature distribution in each layer of the composite overhead transmission lines at steady-state and can only give the centre line temperature at each time interval at transient condition. The results of this study showed that the core temperature is higher than the surface temperature of the transmission line. The difference between these two temperatures increases with time until it reaches a constant value at steady state. Therefore, the core temperature should be considered as a base for calculating the maximum current carrying capacity corresponding to the maximum permissible temperature of the transmission line. The maximum current capacity for each standard line should be multiplied by a factor called the derating factor, about 0.9, to obtain the safety rating current capacity. This actual value will not cause the temperature of the core of the transmission line to rise over the maximum permissible temperature, to limit damage in the transmission line and to give minimum disruption of electric service.

The present investigation deals with the determination of the transient radial temperature distribution in the transmission lines at different operating conditions. A finite element technique is presented using linear triangular elements for the two dimensional transient conduction equation to predict the temperature distribution through stranded conductors at both transient and steady state conditions. The actual weather performance of the transmission lines include the effect of dust accumulation and ice formation on the outer surface is also investigated.

2. *EXPERIMENTAL INVESTIGATION*

A test rig was constructed to supply and control a current to the test section of a Cardinal model transmission line. The temperature at each layer of the transmission line cross-section was measured via calibrated copper constentan thermocouples. The present transmission line is composed of 7 steel strands surrounded by 54 aluminium strands as shown in Fig.(1). Details of the test rig and the measuring instruments were presented in [7,8].

3. MATHEMATICAL MODEL

In the present analysis the stranded transmission line was analysed as a two dimensional transient conduction problem in x-y plane of coordinates and the following governing equation was applied, [9]:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + q_v = \rho c \frac{\partial T}{\partial t} \qquad (1)$$

Also, the transmission line was subjected to the following boundary and initial conditions as shown in Fig.(2):

a-) Initial conditions

at $t = 0$;

$$T(x,y) = T_0 \qquad (2)$$

b-) Boundary conditions:

1- At the surface Γ_2;

$$q_{conv} = h\,A\,(T - T_\infty) \qquad (3)$$

2- At the conductor axis of symmetry Γ_1;

$$k_x \frac{\partial T}{\partial x} l_x + k_y \frac{\partial T}{\partial y} l_y = 0 \qquad (4)$$

The solution of this system of equations together with its boundary and initial conditions was made through a numerical technique based on the variational methods (Ritz and Galerkin methods) [10-12]. One possible way of discretizing a body is to divide it into a smaller bodies or units, *finite elements*, the assemblage of which represents the original body in one operation. The solution is formulated for each constituent unit, and then combined to obtain the solution for the entire body or structure. A geometrically complex domain of the problem is represented as a collection of geometrically simple subdomains (finite elements) interconnected at nodes as shown in Fig.(2). Over each finite element the approximation function is derived using the basic idea that any continuous function can be represented by a linear combination of algebraic polynomials. The volume of data to be handled is directly proportional to the number of smaller bodies required to discretize the original body. This method can be extended systematically to accept complex and difficult problems involving nonhomogeneous, non-linear behaviour and complicated boundary conditions.

4. FINITE ELEMENT FORMULATION

Because of its capability of dealing with several types of boundary conditions, variation in material properties and also the meshes can be divided and graded according to the region of interest the finite element method was used in the present analysis.

The differential equation, Eq.(1) with its boundary and initial conditions, Eqs.(2) to (4), were formulated using the Galerkin procedure, [10-11], with interpolation functions as a weighted residual to derive the finite-elements equations. The finite element discretization in a two dimensional domain as shown in Fig.(3) is carried out using linear triangular elements as shown in Fig.(4).

The temperature inside any element, can be represented in terms of the nodal temperature by a simple polynomial as follows:

$$T^e = \sum_{m=1}^{3} N_m T_m \qquad (5)$$

Where,

$$N_1 = \frac{1}{2A}(a_1 + b_1 x + c_1 y)$$
$$N_2 = \frac{1}{2A}(a_2 + b_2 x + c_2 y) \qquad (6)$$
$$N_3 = \frac{1}{2A}(a_3 + b_3 x + c_3 y)$$

A = area of the triangle 123 which can be obtained from;

$$A = 1/2 \begin{vmatrix} 1 & x_1 & y_1 \\ 1 & x_2 & y_2 \\ 1 & x_3 & y_3 \end{vmatrix}$$

$$a_1 = x_2 y_3 - x_3 y_2$$
$$b_1 = y_2 - y_3 \qquad (7\text{-a})$$
$$c_1 = x_3 - x_2$$

$$a_2 = x_3 y_1 - x_1 y_3$$
$$b_2 = y_3 - y_1 \qquad (7\text{-b})$$
$$c_2 = x_1 - x_3$$

$$a_3 = x_1 y_2 - x_2 y_1$$
$$b_3 = y_1 - y_2 \qquad (7\text{-c})$$
$$c_3 = x_2 - x_1$$

The problem of finding the solution of Eq.(1), which satisfies the initial and boundary conditions can be written, after a weighted integration over the two dimensional domain and an application of Green's theorem [12], in the equivalent matrix form as follows:

$$[K]^e \{T\}^e + [K_c]^e \{T\}^e = \{F\}^e \qquad (8)$$

Where,

$[K]$ and $[K_c]$ are the element stiffness and capacity matrices, respectively.

$\{F\}$ is the equivalent model influence force vector due to heat generation and the different boundary conditions

The global characteristic-matrices and the global characteristic- force vector can be obtained from an appropriate assembly of Eq.(8), to form the system of equations of the entire domain. The procedure of assembly is based on the requirement of compatibility at the nodes, i.e., at a given node common to a set of elements, the value of the unknown variable is the same for all the elements, which are joined at that node.

When the generalised variables are matched at a common node, the nodal stiffness, capacitance and force for each of the elements, sharing the node are added to obtain the overall stiffness,

capacitance and force vector at that node. The total number of equations on the global level is identical to the number of unknowns. The global characteristic of matrices and vectors can be obtained by algebraic additions.
A popular procedure to solve the time-dependent model equations and to obtain the values of the unknown variables at each point in time, can be obtained by approximation of the time derivatives using a finite difference scheme. The assembled system consists of a set of linear equations and is solved by the Gauss elimination method.

5. *RESULTS AND DISCUSSIONS*

The present theoretical model was tested and evaluated by comparing the theoretical results with the present experimental data at the same operating conditions. Figure (5) shows the experimental observations and the theoretical predictions at 200 A and at the room conditions (U_w=0). It is noticed that, with the increase in the operating time the temperature difference between the transmission line centre and its surface increases approaching a steady state values. The comparison shows a good agreement and assure the validity and reliability of the present theoretical model and the method of calculations.
Figure (6) shows the effect of transmission line loading current on the transient temperature difference between the centre line and surface of the transmission line. The temperature difference increases with the increase in the loading current increases.
The effect of the wind speed on the transmission line performance at a fixed ambient temperature and at different values of the loading currents is shown in Fig.(7). Both the centre line temperature and the outer surface temperature decrease with the increase in the wind speed. Also, the rate of the temperature drop of the transmission line due to the wind effect decreases with further increase in the wind speed. The present prediction for the temperature difference between the core and the outer surface of the transmission line, ΔT, and the loading current, I, were correlated using the least square method and the following correlation was obtained:

$$\Delta T = 10.7 \times 10 \;\; I^{2.19} \qquad {}^{\circ}C \qquad (9)$$

From Eqs.(9) it can be indicated that the temperature difference ΔT is approximately linearly dependant on the rate of heat generated inside the transmission line. Figure (8) shows the model predictions and the correlation Eq.(9) and it was found that Eq.(9) is valid within an accuracy of ± 10%.
The effect of the pollution of the environment and the actual weather performance of the transmission lines include the effect of dust accumulation and ice formation on the outer surface are shown Figs.(9) and (10). Figure (9) shows the results at different values of loading current, different wind speeds and 1 mm dust layer. Also, the effect of dust layer thickness is also investigated within a range up to 4mm for cement pollutants and the results show that the transmission line significantly increases with the increase in the pollutant layer thickness. This in fact due to the thermal insulating effect of the pollutant layers.
For transmission lines that passing through very cold zones at which the ambient temperature drops under zero °C, a layer of ice may be formed around the outer surface of the lines with layer thickness depends on the ambient temperature, moist contents and the wind speed. In the present study a thin ice layer of 1mm thickness was considered and the results are shown in Fig.(10) at different wind speeds and at different loading currents.

Moreover, a comparison between Cardinal and Hen designs for transmission lines at two different operating conditions was performed within the present study. Figure (11-a) shows the results at loading current of 200A for the two different designs. These results show that, at the same loading current the surface temperature of Hen design records a higher value compared with that of the Cardinal design. This may be attributed to the higher value of the heat generated per unit volume for the smaller size, Hen, transmission line compared with that for the Cardinal design. Figure (11-b) shows the comparison between the two designs at the same value of the heat generated per unit volume. A higher value for the surface temperature of the Cardinal design was observed compared with that for the Hen design. This may be attributed to the higher value of the volume co-surface ratio, V/A, for the Cardinal design. This parameter is proportional to the transmission line size and it was simply calculated by, $V/A = D/4$ where V is the transmission line volume, A is the transmission line surface area, and D is the transmission line mean diameter. In fact this parameter (volume co-surface ratio) is a measure of the heating to cooling rate ratio for the transmission lines.

6. CONCLUSIONS

The results of the present study leads to the following conclusions:

1- Through the comparison between the present experimental data and the theoretical results, it can be concluded that the present theoretical model is a satisfactory means for predicting the thermal behaviour of the stranded transmission lines.
2- The effect of the actual weather (dusty and /or very low temperature conditions) is found to be more effective on the transmission line rating especially at high loading capacity.
3- The wind speed is an effective parameter on the transmission line temperature level although, it has no effect on the temperature difference between the centre and surface of the transmission lines.
4- The temperature difference between the centre and surface of the transmission lines is found to be dependent only on the loading current and the transmission line geometry.
5- The comparison between Cardinal and Hen designs for transmission lines at two different operating conditions showed that, at the same loading current the surface temperature of Hen design records a higher value than that for the Cardinal design. Also, at the same value of heat generated per unit volume a higher value for the surface temperature of the Cardinal design was predicted compared with that for the Hen design.
6- The comparison between Cardinal and Hen designs shows the importance of the volume co-surface ratio as an effective parameter in transmission lines design and operation.

7. NOMENCLATURE

SI system of units was applied for the whole parameters used in this paper.

A	element area, TL surface area per unit length
a,b,c	coefficients of interpolation function
C	specific heat
D	TL outer mean diameter
d	strand mean diameter
{F}	force vector matrix
h	convective heat transfer coefficient

Subscripts

0	initial value
1,2,3	triangular element nodes
x	x direction
y	y direction

[K]	stiffness matrix
$[K_C]$	capacity matrix
k	thermal conductivity
l	direction cosine of the outward normal to the element surface
N	interpolation function
q	boundary heat flux due to conduction
q_v	heat generated per unit volume.
T	temperature
T_∞	ambient air temperature
t	time
U_w	wind speed
V	transmission line volume per unit length

Superscripts

e	element number
E	total number of elements

Greek letters

α	thermal diffusivity
Δ	difference
ρ	density
$\Gamma_1, \Gamma_2, \Gamma_3$	domain boundaries

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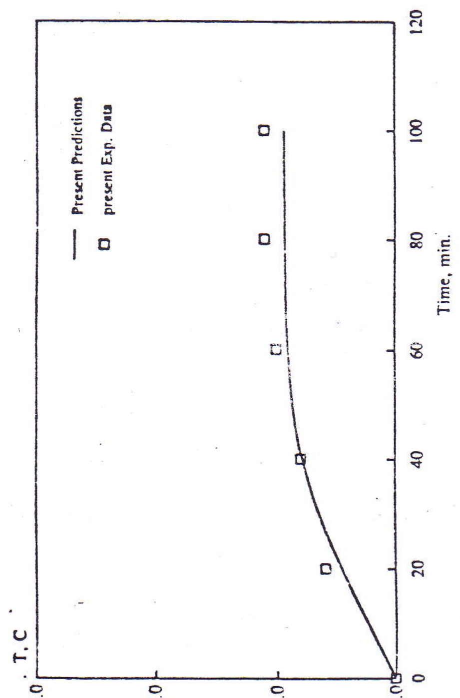


Fig.5. Comparison between the present experimental data and the present predictions.

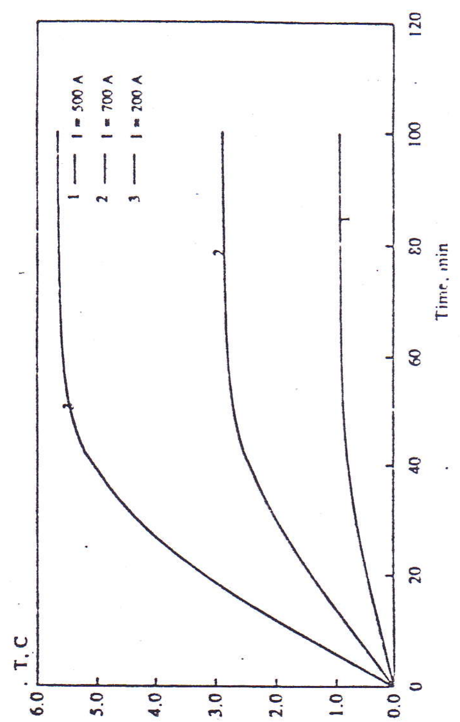


Fig. 6. The effect of transmission line loading current on the transient temperature difference.

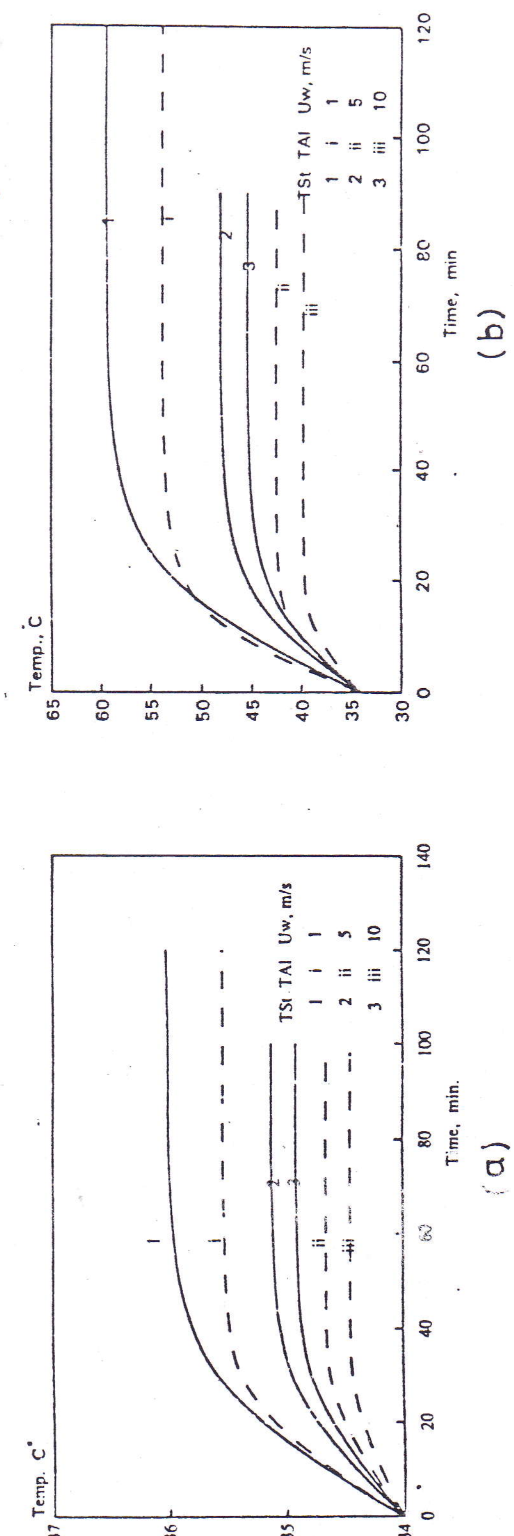


Fig.7. The effect of the wind speed on the transmission line performance at a fixed ambient temperature and at two different values of the loading currents.

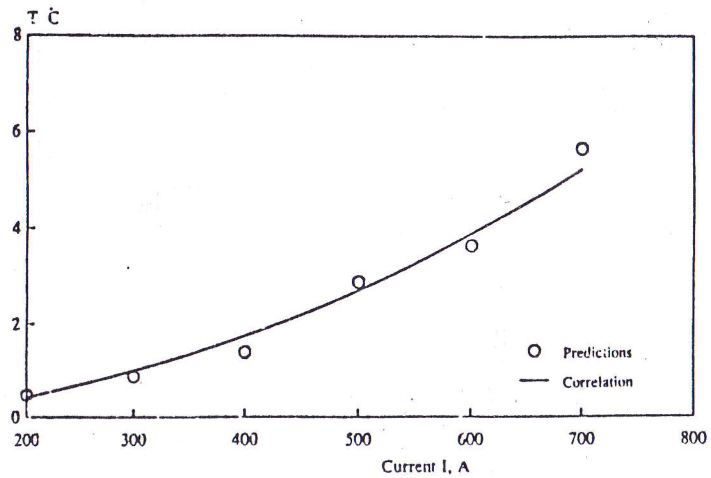


Fig 8. Comparison between the present predictions and the correlation eq.(9).

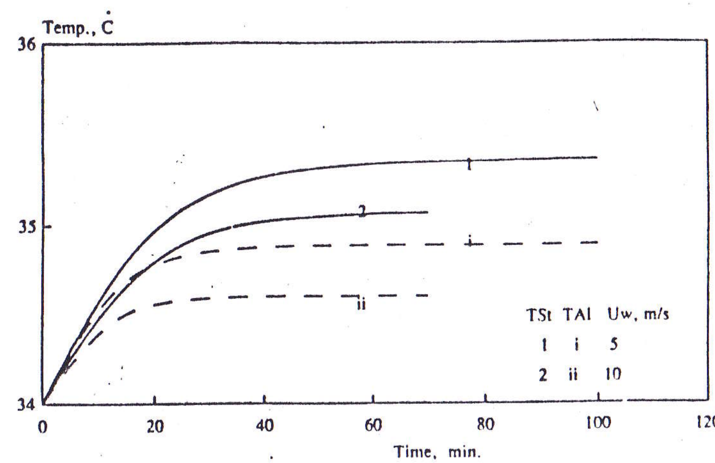
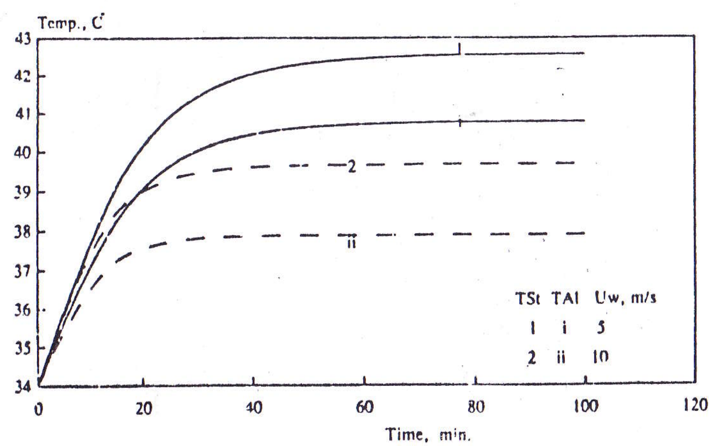
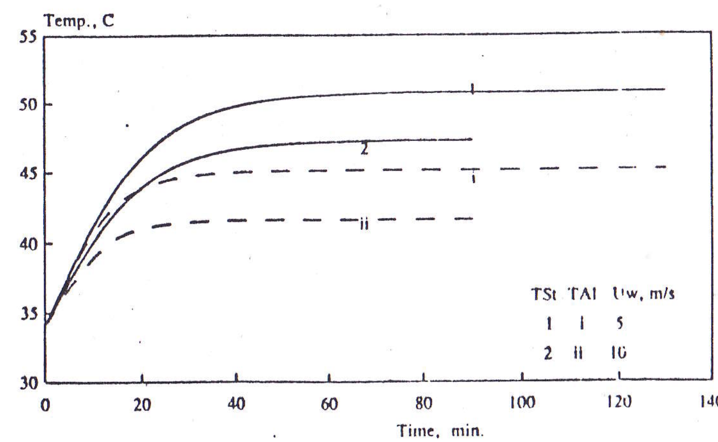


Fig.9: (a)



(b)



(c)

Fig. 9. The transient temperature distribution for 1 mm dust layer at different values of loading current and at different wind speeds.

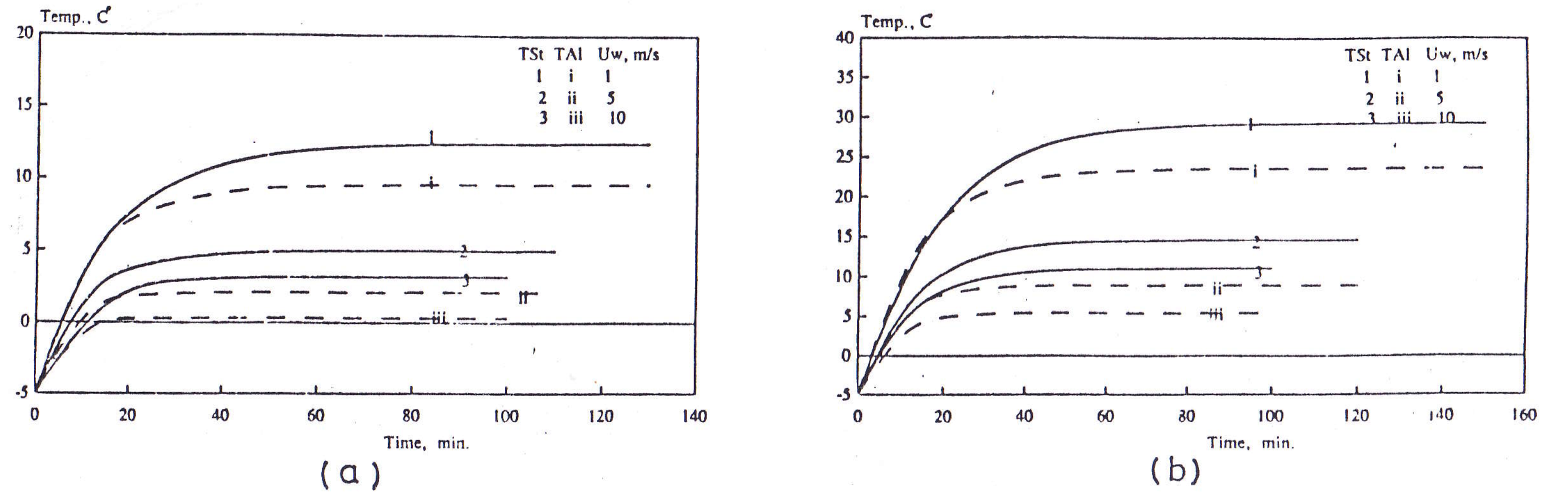


Fig.10. The transient temperature distribution for a thin ice layer of 1mm thickness at different wind speeds and at different loading currents.

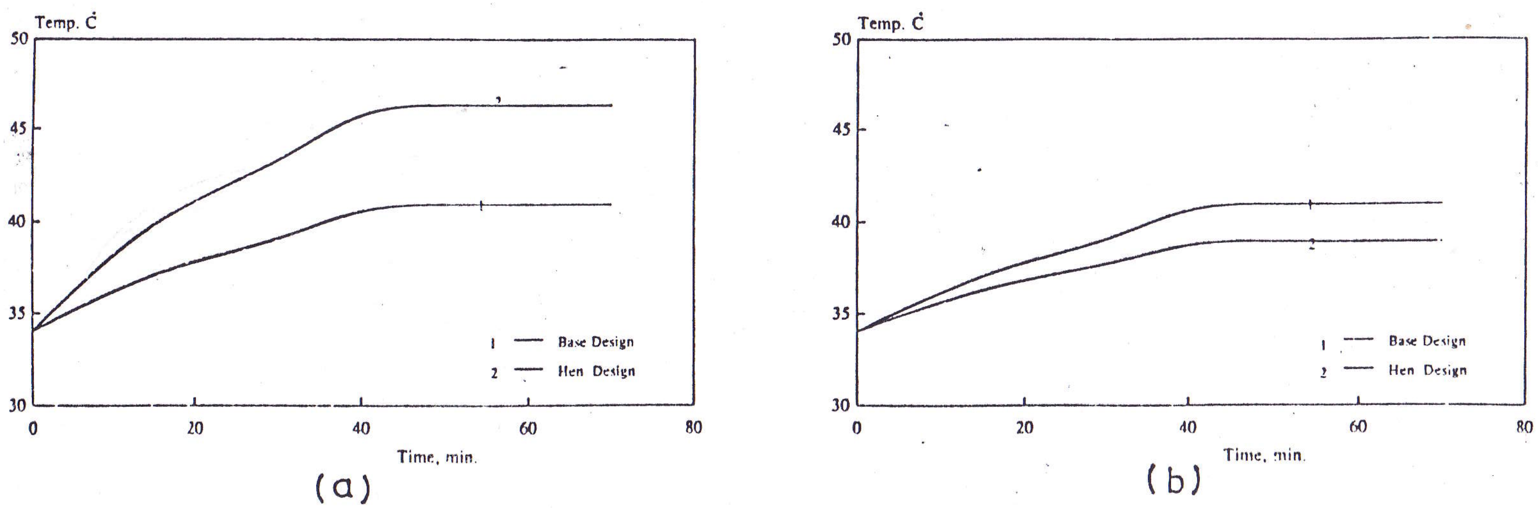


Fig.11. Comparison between Cardinal and Hen designs for transmission lines at two different operating conditions.

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To Whom it May Concern

The paper entitled **"Impacts of The Environmental Condition on The Current-Carrying-Capacity of Overhead Transmission Lines "** by : *M. M. Abdel-Aziz, M. M. Salama, S. A. Abdel-Moneim & M. A. Foda*

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