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Thermal performance of an overhead transmission line under the influence of dust accumulation

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Abstract

The temperature distribution in the radial direction of a composite overhead transmission line in steady state is the main object of this work when a layer of dust or aluminium oxide is accumulated around the surface of the line. This undesirable dust accumulation will cause an additional rise in temperature of the line. Therefore, the hypothetical lifetime of the line will be reduced. A mathematical model has been developed, when the heat supplied to the dusty transmission line is balanced by the heat dissipated. to give the temperature of each layer of the line in addition to the dust layer temperature. A reduction coefficient of the life time of the line under the influence of dust accumulation is derived. The ampacity of the dusty line should be reduced in order that the temperature of the line doesn't exceed the maximum permissible temperature and to maintain the hypothetical life time of the line. The proposed reduction coefficient of the line ampacity will be, also, deduced.

Keywords: Thermal rating; Transmission line; Conductor ampacity; Temperature distribution; Thermal effect; Life time; Dusty transmission lines

1. Introduction

Transmission line ampacity is normally determined from a single set of weather conditions in addition to an assumed maximum temperature. The thermal rating procedure in steady state has been investigated in Refs. [1,2]. This procedure includes forced convection heat transfer equations, the effect of wind turbulence and wind direction, conductor height above the ground and conductor pitch, in addition to the proximity of the conductors in a bundle.

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The transient current capacity for extra high voltage transmission lines was discussed in Ref. [3]. The temperature distribution in the radial direction of a composite overhead transmission line at steady state and an on line method for evaluation of the line ampacity are investigated in Ref. [4]. The line temperature at each time interval is also presented.

In Ref. [5], a finite element technique was adopted to predict the temperature distribution through stranded lines at both transient and steady state conditions. The actual weather performance of the lines, including the effects of ice and dust accumulation on the outer surface of the lines, is also investigated.

A method for determining the thermal rating of a line based on the relationship between the line temperature and its sag is presented in Ref. [6]. The solar radiation received by an overhead line and the effects of magnetic field strength, tensile stress, total core loss and hysteresis loss for a concentrically steel cored line are discussed in Refs. [7,8].

In practice, the transmission lines extend along very long distances. Therefore, dust of different types, such as sandstone, cement and coal powder, may be accumulated on the outer surface of the lines. Each type of dust has its own mechanical, electrical and thermal properties and behaves as a thermal insulator.

The temperature distribution in the radial direction of a composite line in steady state, when an additional layer of dust or aluminium oxide is accumulated around the outer surface of the line, is presented in this work. The undesirable accumulation of dust will cause an additional rise in the temperature of each layer of the line. This temperature rise will increase the total equivalent resistance of the line and the dissipated power in it. Consequently, the hypothetical life time of the line and the line ampacity will be affected.

2. Mathematical model formulation

The equilibrium heat balance of an overhead transmission line in steady state occurs when the solar, joule, magnetic and corona heating equals the radiative, evaporative and convective cooling. The evaporative cooling effects can be generally neglected, while the radiation loss is usually a small fraction of the total heat loss, especially with forced convection [9,10]. The dusty composite line can be considered as three concentric parallel layers of steel, aluminium and accumulated dust, respectively. The power dissipated in each layer (q_{st}, q_{al} and q_{d}) can be obtained by multiplying the square of the layer current by the corresponding layer resistance, which can be evaluated per unit length by knowing the resistivity of that layer and by calculating the corresponding cross sectional area. The heat generated in the line from the flow of the electric current, which equals the sum of the power dissipated in each layer, will be transferred to the surrounding environment by combined convective and radiative cooling, q_{con} and q_{rad} respectively, as

$$q_{st} + q_{al} + q_{d} = q_{con} + q_{rad} \tag{1}$$

The heat transmitted by convection and radiation from the line surface are given in Refs. [10,11] by the following two equations

$$q_{con} = hA_s(T_s - T_a) \tag{2}$$

and

$$q_{rad} = \varepsilon\sigma A_s(T_s^4 - T_a^4) \quad (3)$$

where h is the heat transfer coefficient (Watt/m^2 °K), can be calculated from the Nusselt, Prandtl and Rayleigh numbers in addition to the thermal conductivity, diffusivity, specific heat, dynamic and kinematic viscosity and the coefficient of thermal expansion of air, A_s is the transmission line surface area (m^2), T_s is the temperature of the surface of the line, T_a is the ambient temperature, ε is the emissivity of the line, which depends on the line surface, ($0.27 \leq \varepsilon \leq 0.95$ or $\varepsilon \cong 0.6$), and σ, the Stefan-Boltzmann constant, $\sigma = 5.67 \times 10^{-8}$ Watt/m^2 °K^4.

Generally, the temperature distribution through the line material is given by the general conduction equation, [10], as follows

$$\frac{\partial}{\partial_r}\left(K\frac{\partial T}{\partial_r}\right) + \dot{q} = \rho c\frac{\partial T}{\partial t} \quad (4)$$

where T is the temperature, K the material thermal conductivity; $\dot{q}$ the rate of heat generated per unit volume (Watt/m^3), ρ and c the density and the specific heat of the material respectively, t is the time and r the radial distance measured from the geometric center of the line.

If the thermophysical properties of the line material are constant and with the approximation to one dimensional steady state conduction, Eq. (4) can be simplified to

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}\left(r\frac{\mathrm{d}T}{\mathrm{d}r}\right) + \frac{\dot{q}}{K} = 0 \quad (5)$$

Three layers of uniform sections can be assumed to overcome the discontinuity of Eq. (5). Then the transmission line can be considered as two concentric layers closed to each other or separated by an air gap, steel layer and aluminium layer, in addition to the layer of accumulated dust, as shown in Fig. 1. The temperature distribution through each layer of the line can be obtained by integrating Eq. (5), taking into account the appropriate boundary conditions.

The mathematical model in Ref. [4] will be extended to include the influence of the accumulated dust around the line surface. First, for the steel layer the following equation is obtained

$$T_{st} = (-\dot{q}_{st}r^2/4K_{st}) + C_1 \ln r + C_2 \quad (6)$$

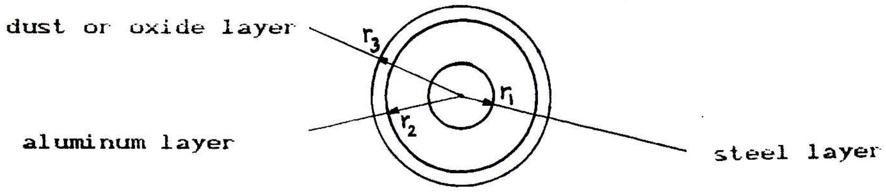

Fig. 1. The composite line surrounded by a dust or aluminium oxide layer.

where T_{st} is the temperature of the steel layer at a radius r, $(0 \leq r \leq r_1)$; r_1, the steel layer radius;$\dot{q}_{st}$, the rate of heat generated in the steel layer per unit volume; and C_1 and C_2, the integration constants. At $r = 0$, $T_{st}=T_c$, $C_1=0$, then $T_c=C_2$ and at $r=r_1$, $T_{st}=T_1$ with T_1 being the temperature at r_1. Then from Eq. (6),the value of C_2 can be deduced to give the temperature (T_c) at the geometric center of the line as

$$T_c = T_1 + (\dot{q}_{st}r_1^2/4K_{st}) \tag{7}$$

Substituting the values of C_1 and C_2 in Eq. (6), the temperature distribution in the steel layer of the line is obtained as follows

$$T_{st} = T_1 + [\dot{q}_{st}(r_1^2 - r^2)/4K_{st}] \tag{8}$$

From Eqs. (7) and (8), T_{st} can be written in terms of T_c as,

$$T_{st} = T_c - (\dot{q}_{st}r^2/4K_{st}) \tag{9}$$

Second, for the aluminium layer of the line, the temperature distribution can also be obtained as follows

$$r(\mathrm{d}T_{al}/\mathrm{d}r) = (-\dot{q}_{al}r^2/2K_{al}) + C_3 \tag{10}$$

Then, at $r=r_1$,

$$(\mathrm{d}T_{al}/\mathrm{d}r) = (-\dot{q}_{al}r_1/2K_{al}) + (C_3/r_1) \tag{11}$$

The flow of heat q_{st} between the steel layer and aluminium layer results in a direction opposite to the temperature gradient. This heat flow can be obtained from the rate of heat generated per unit volume ($\dot{q}_{st}$), as follows

$$q_{st} = \dot{q}_{st}\pi r_1^2 1/2\pi r_1 1 = (1/2)\dot{q}_{st}r_1 \tag{12}$$

However,

$$q_{st} = -K_{al}\frac{\mathrm{d}T_{al}}{\mathrm{d}r} \tag{13}$$

Then from Eqs. (12) and (13), the temperature gradient can be obtained as

$$(\mathrm{d}T_{al}/\mathrm{d}r) = -\dot{q}_{st}r_1/2K_{al} \tag{14}$$

From Eqs. (11) and (14), C_3 can be obtained as

$$C_3 = -r_1^2(\dot{q}_{st} - \dot{q}_{al})/2K_{al} \tag{15}$$

Integrate Eq. (10) to obtain the temperature distribution in the aluminium layer as

$$T_{al} = (-\dot{q}_{al}r_1^2/4K_{al}) + C_3 \ln r + C_4 \tag{16}$$

Substitute C_3 from Eq. (15) and the boundary condition, $r=r_2$, $T_{al}=T_2$, in Eq. (16). With r_2 being the outside radius of the aluminum layer, T_2, the temperature at r_2, can be obtained as

$$T_2 = (-\dot{q}_{al} r_2^2/4K_{al}) - [r_1^2(\dot{q}_{st} - \dot{q}_{al})/2K_{al}]\ln r_2 + C_4 \tag{17}$$

From Eq. (17), C_4 can be deduced as follows

$$C_4 = T_2 + (\dot{q}_{al} r_2^2/4K_{al}) + [r_1^2(\dot{q}_{st} - \dot{q}_{al})/2K_{al}]\ln r_2 \tag{18}$$

Thirdly, by integrating Eq. (10), the temperature distribution in the additional accumulated dust layer around the line will be obtained, after substitution of $r = r_2$, as follows

$$(\mathrm{d}T_{du}/\mathrm{d}r) = (-\dot{q}_{du} r_2/2K_{du}) + (C_5/r_2) \tag{19}$$

The flow of heat q_{al} between the aluminium layer and the dust layer results in a direction opposite to the temperature gradient. This heat flow can be obtained from the rate of heat generated per unit volume, $\dot{q}_{al}$, as follows

$$q_{al} = \dot{q}_{al}\pi r_2^2 1/2\pi r_2 1 = (1/2)\dot{q}_{al} r_2 \tag{20}$$

However,

$$q_{al} = -K_{du}\frac{\mathrm{d}T_{du}}{\mathrm{d}r} \tag{21}$$

Then from Eqs. (20) and (21), the temperature gradient in the dust layer can be obtained as

$$(\mathrm{d}T_{du}/\mathrm{d}r) = -\dot{q}_{al} r_2/2K_{du} \tag{22}$$

From Eqs. (19) and (22), C_5 can be obtained as

$$C_5 = -r_2^2(\dot{q}_{al} - \dot{q}_{du})/2K_{du} \tag{23}$$

Integrate Eq. (19) to obtain the temperature distribution in the dust layer as

$$T_{du} = (-\dot{q}_{du} r^2/4K_{du}) + C_5 \ln r + C_6 \tag{24}$$

Substitute in Eq. (24), the boundary condition, $r = r_3$, $T_{du} = T_s$, with r_3 being the outside radius of the dusty line, then T_s, the temperature of the surface of the line, can be obtained from the following equation

$$T_s = (-\dot{q}_{du} r_3^2/4K_{du}) - [r_2^2(\dot{q}_{al} - \dot{q}_{du})/2K_{du}]\ln r_3 + C_6 \tag{25}$$

From Eq. (25), C_6 can be deduced as follows

$$C_6 = T_s + (\dot{q}_{du} r_3^2/4K_{du}) + [r_2^2(\dot{q}_{al} - \dot{q}_{du})/2K_{du}]\ln r_3 \tag{26}$$

3. Influence of the accumulated dust layer on the hypothetical life time of the line

The energy dissipated (E) in a line during its hypothetical lifetime (T) can be given by

$$E = I^2 R_T T = (I_{st}^2 R_{st} + I_{al}^2 R_{al})T \tag{27}$$

where I, the line current, equals the sum of the two portions, in the steel layer (I_{st}) and in the aluminium layer (I_{al}); R_T, the total equivalent resistance of the two parallel resistances of the two layers, R_{st} and R_{al}.

The convection and radiation of an overhead line will be decreased when an additional layer of dust or aluminium oxide is accumulated around the line surface. According to the electrical and thermal properties of the type of accumulated dust, the temperature of each layer of the line will be raised and leads to an increased value of each layer resistance. Therefore, the hypothetical life time of the line will be affected and reduced to an actual value (T_d). The energy dissipated (E_d) in the line, under the influence of the dust layer and during this actual life time, can be deduced as follows

$$E_d = I^2 R_{Td} T_d = (I_{std}^2 R_{std} + I_{ald}^2 R_{ald} + I_d^2 R_d) T_d \tag{28}$$

where I is the same line current that equals the sum of the three current portions. (I_{std}), (I_{ald}) and (I_d); R_{Td}, the total equivalent resistance of the three parallel resistances (R_{std}), (R_{ald}) and (R_d), where each resistance will be proportional to the temperature rise of each layer; I_d and R_d, the current and resistance of the dust layer, respectively.

For the same value of energy dissipated at the same line current, a ratio (F_r) between the reduced life time of the line and its and hypothetical life time can be calculated from the two Eqs. (27) and (28) as follows

$$F_r = \frac{T_d}{T} = \frac{R_T}{R_{Td}} \tag{29}$$

From Eq. (29), this ratio (F_r) equals the ratio between the total equivalent resistances of the line without and with dust accumulation.

A percentage reduction coefficient (LTRC) of the hypothetical life time of the line due to the thermal influence of the dust accumulation around the line surface can be deduced by the following equation,

$$\%\text{LTRC} = \frac{(T - T_d)}{T} \times 100 = (1 - F_r) \times 100 \tag{30}$$

4. Influence of the accumulated dust layer on the rating current of the line

To take into account the thermal influence of the dust accumulation around the line without reduction in the hypothetical life time of it, the rating current of the line must be modified to a certain reduced value (I_d), such that the energy dissipated in the line remains constant through its hypothetical life time (T) as follows

$$I_d^2 R_{Td} T = I^2 R_T T. \tag{31}$$

The ratio between the suggested modified value of the line current and the rating current can be obtained from Eqs. (31) and (29) as

$$\frac{I_d}{I} = \sqrt{\frac{R_T}{R_{Td}}} = \sqrt{F_r} \quad (32)$$

A percentage reduction coefficient (IRC) of the rating current of the line can be derived as

$$\%\mathrm{IRC} = \frac{(I - I_d)}{I} \times 100 = \left(1 - \sqrt{F_r}\right) \times 100 \quad (33)$$

The ratio between the two reduction coefficients will be obtained from Eqs. (30) and (33)

$$(\mathrm{LTRC}/\mathrm{IRC}) = 1 + \sqrt{F_r} \quad (34)$$

5. Results

The temperature distribution in the transmission line and the integration constants can be evaluated from the proposed mathematical model for each specified value of the line current by knowing the ambient temperature and by calculating the heat generated in the line in addition to the convected and radiated heat from the line surface. Initially, the temperature of the line surface may be assumed and it can be corrected iteratively.

The used transmission line is the so-called Cardinal line with a strands ratio 54/7 and diameter of each strand 3.37 mm. The line is surrounded by an aluminium oxide layer.

Figure 2 shows the steady state temperatures of the line core (T_c), which is obtained, approximately, as the same value as that of the steel layer (T_{st}), versus the line current, at different values of the oxide layer thickness. The temperatures of the aluminium layer (T_{al}) and of the oxide layer (T_d) are shown in Fig. 3 as influenced by the oxide layer thickness. The difference between these two temperatures is insignificant.

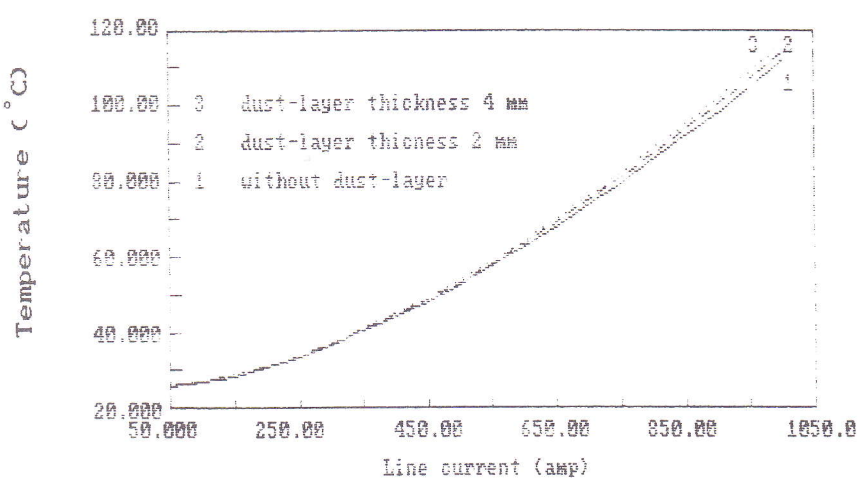

Fig. 2. The temperature of both the line core and steel layer versus line current.

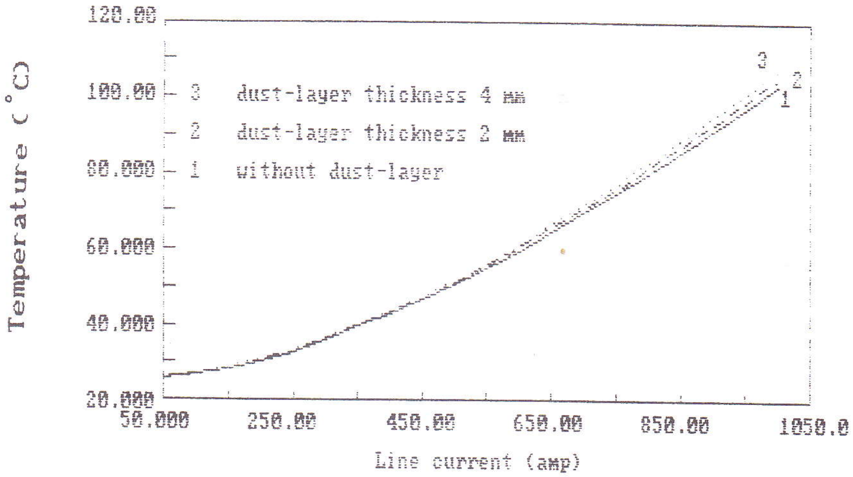

Fig. 3. The temperatures of both the aluminium layer and the oxide layer versus line current.

The difference (ΔT) between the line core temperature and the temperature of the line surface versus the line current is shown in Fig. 4, as influenced by the oxide layer thickness.

Figure 5 shows the equivalent line resistance in μΩ/m, in which each layer resistance is evaluated according to each corresponding layer temperature and layer current, versus the line current, as affected by the oxide layer thickness.

Fig. 6 illustrates that the power dissipated per unit length of the line increases with the increase of line current, which causes rises in the temperature and resistance of each layer of the line.

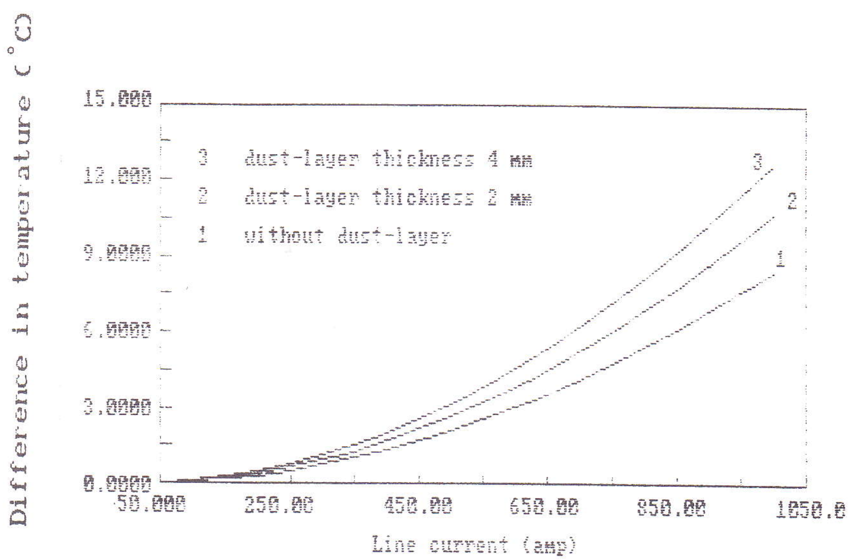

Fig. 4. The difference (ΔT) between the line core and the line surface temperatures versus line current.

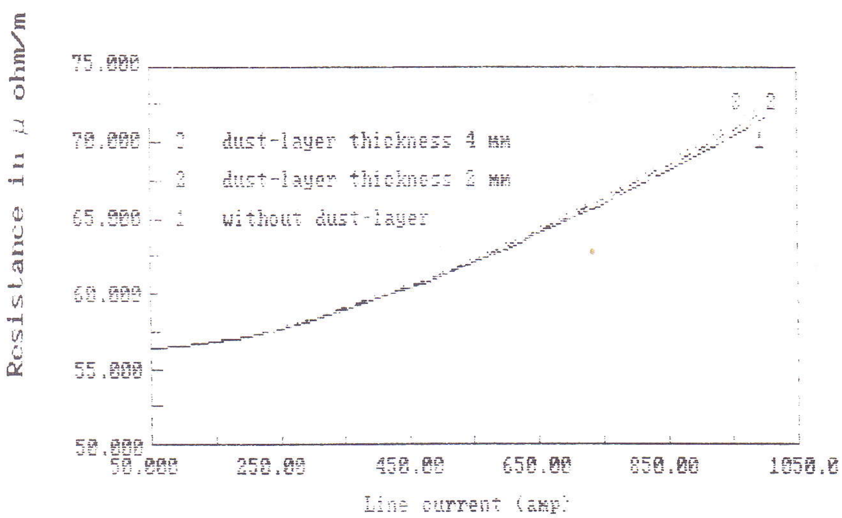

Fig. 5. The equivalent line resistance versus line current.

The ratio (F_r) between the reduced life time and the hypothetical life time of the line versus the line current has been shown in Fig. 7, at two different values of the oxide layer thickness.

The percentage reduction coefficient of the life time of the line (LTRC) and of the rating current of the line (IRC) due to the thermal influence of the oxide layer thickness are plotted versus line current in Fig. 8.

Fig. 9 shows the suggested modified line current, after taking into account the thermal influence of the oxide accumulation around the outer surface of the line versus the rating current of the line, for demonstration, between 820 and 1000 A.

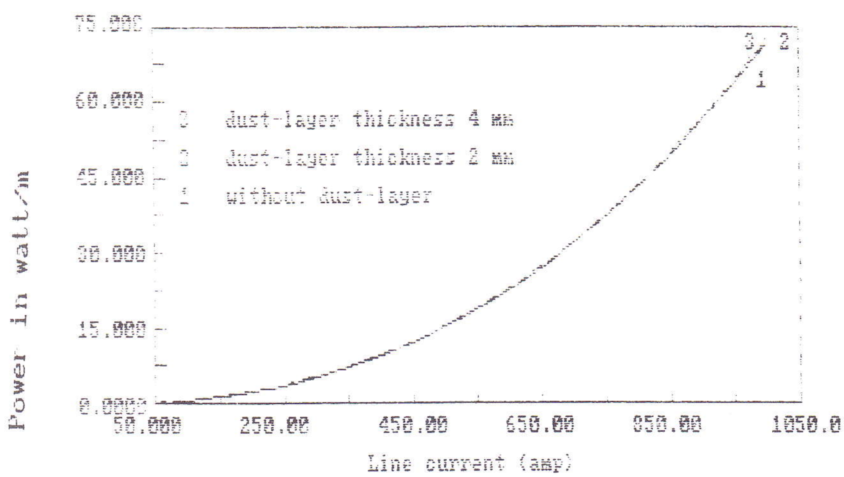

Fig. 6. The power dissipated in the line versus line current.

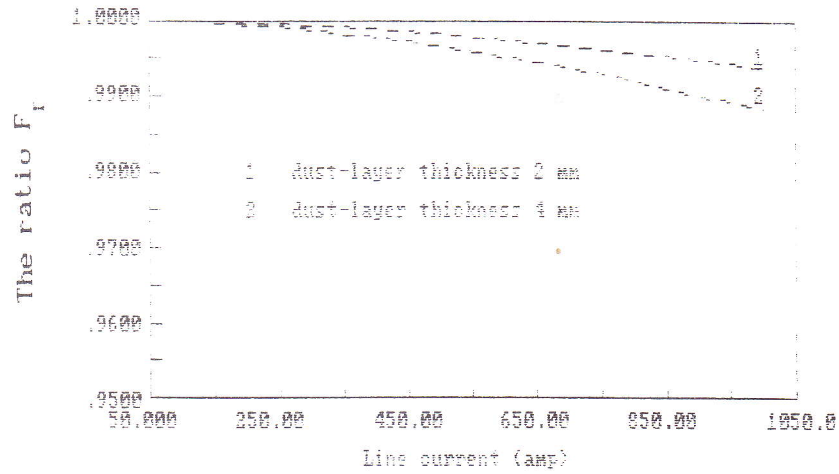

Fig. 7. The ratio between the reduced and hypothetical life times of the line versus line current.

6. Conclusions

The presented mathematical model can give, at steady state, the temperature distribution in each layer of a composite overhead transmission line in addition to the accumulated layer around the line from either dust or aluminium oxide. The increase of thickness of the accumulated layer around the line will raise the temperature of each layer, steel, aluminium and dust, in addition to the line core. The difference between the core and surface temperature will also be increased.

Consequently, the equivalent resistance of the dusty line and the power dissipated in it will be gradually increased at each value of the line current proportional to the temperature rise

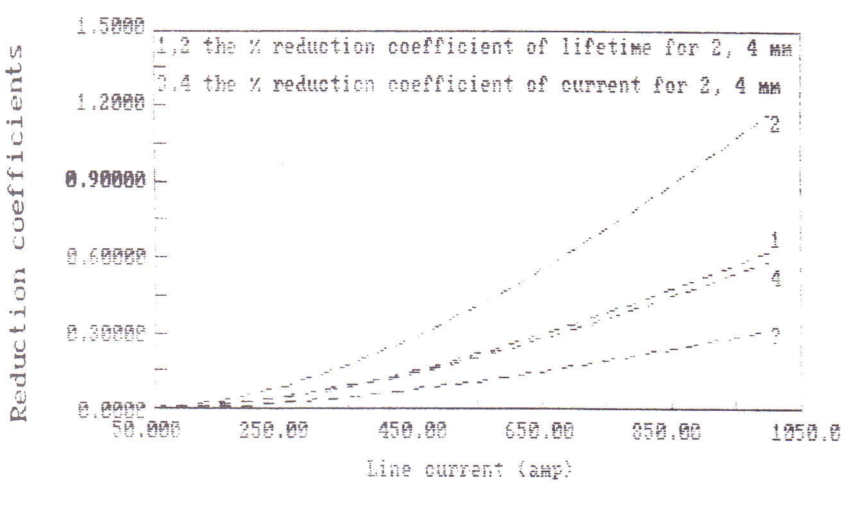

Fig. 8. The percentage reduction coefficients of both life time and rating current of the line versus line current.

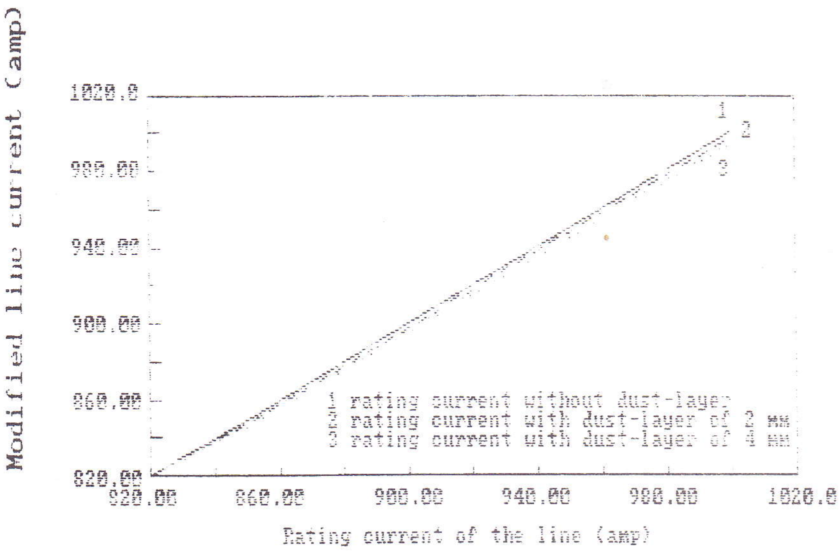

Fig. 9. The suggested modified line current versus the rating current of the line.

and the thickness of the dust layer. The hypothetical lifetime of the line will be reduced by a certain derived reduction coefficient taking into account the thermal influence of the dust layer in addition to its electrical and thermal properties.

The ampacity of the dusty line should be reduced by a certain proposed reduction coefficient to obtain an actual ampacity of the line in order that the temperature of the line doesn't exceed the maximum permissible temperature and for keeping the hypothetical life time of the line to give minimum interruption of electric service.

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