Calculation of electrical stress distribution using analytical computations.

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Abstract- The electrical conduction in insulating materials is a complex process and several theories have been suggested in the literature. Many phenomenological empirical models are in use in the dc cable literature. However, the impact of using different models for cable insulation has not been investigated until now, but for the claims of relative accuracy. The steady state electrical field in the dc cable insulation is known to be a strong function of dc conductivity. The dc conductivity, in turn, is a complex function of electric field and temperature. As a result, under certain conditions, the stress at cable screen is higher than that at the conductor boundary. The paper presents detailed investigation on using different empirical conductivity models suggested in the literature for HV DC cable applications. It has been expressly shown that certain models give rise to erroneous results in electric field and temperature computations. It is pointed out that the use of these models in the design or evaluation of cables will lead to errors.

I. INTRODUCTION

Stress inversion is a complex phenomena occurring in the matrix of the cable insulation seriously hampering the design of HVDC cables. Radial variation of the temperature dependent dc conductivity, forces the stress inversion under certain conditions. A large body of literature exists on the theory of the stress distribution in the insulation [1-7]. Significant contributions reported in the recent past indicate that the stress distribution in the stable state is nearly a linear function of the radius. The predominant linearity, found to be a consequence of electric field dependence of the further developments in analytical arena. A global understanding is always made possible when non-linear systems are linearized within acceptable limits and this is a common practice in many branches of engineering design. Fortunately, the stress distributions in the steady state stable operating conditions, being almost always linear, provide a natural tool in hand. During the early period of DC cable research the analytic approximations received due consideration compared to the recent bias towards numerical computations due to the advent of digital computers. Analytical theories, albeit approximations, are always found to give deeperinsights into the research problems. For example, the thermal instability and the existence of double solutions of stress distributions at a given voltage, in the dc cable could only be observed in the analytical computations [1, 3] until now.

Keeping in view these aspects the Authors develop the theory further taking linear stress distribution as the basis. Some of the facts which did not receive attention have been covered in this work. A compelling need is felt to introduce certain parameters affecting the stress inversion which are useful in the assessment of operating conditions of the cable. Further these can also be used for a suitable design of the dc cable. The theory of linear stress distribution is found to match with accurate theories developed earlier and the comparisons are in close conformity within certain limits.

II. DC CONDUCTIVITY MODELS

The stress and temperature dependent dc conductivity, σ, in general, may be expressed in the following form,

$$\sigma = \sigma_{\circ} \, x \, f(T) \, x \, g(E) \, , \qquad (1)$$

For some functions f and g of temperature T and stress E respectively. Here σ, is a material related constant.

The following semi-empirical dc conductivity models are of frequent use in the literature of the dc cables [1-7]:

$$\sigma = \sigma_{\circ} \times e^{-b/T} \times e^{aE} \qquad (2)$$

$$\sigma = A \times e^{-b/T} \times \sinh(a'E) \,/\, |E| \qquad (3)$$

$$\sigma = \sigma_{\circ} \times e^{\alpha T} \times e^{\beta T} \qquad (4)$$

Where;

$\sigma_{\circ}$, A are material related constants

a,a′,β are called stress coefficients

b,b′,α are called temperature coefficients

The authors have worked on all the models above a critical analysis is presented later in this work

III. POINT OF CROSSOVER IN LINEAR STRESS:

Assume that the steady-state potential distribution, $\emptyset(r)$, at a radial position r in the body of insulation, be expressed as (a consequence of the linearity assumption of stress distribution),

$$\emptyset(r) \quad = \alpha_{\circ} + \alpha_1 r + \alpha_2 r^2 \qquad (5)$$

where, $\sigma_{\circ}, \sigma_1, \sigma_2$ are arbitrary constants to be determined by boundary conditions .

The stress distribution, E(r),results in,

$$E(r) = -\ \alpha_1\ -2\sigma_2 r \qquad (6)$$

If a potential V is applied to conductor (r_1) and sheath (r_2) is at ground potential, then,

$$\emptyset(r_2) - \emptyset(r_1) = -v = \alpha_1(r_2-r_1) + \alpha_2(r_2-r_1)^2 \qquad (7)$$

Or,

$$\frac{V}{r_2-r_1} = -\alpha_1 - \alpha_2(r_2 + r_1) = E \,\big|\, (r_1 + r_2/2) = E_{\circ} \qquad (8)$$

This implies that stress is invariant exactly at the central region of the insulation and its magnitude is equal to the mean insulation stress, E0. Therefore, for a given applied voltage, all steady-state stress curves must cross each other at the middle of the insulation irrespective of thermal boundary conditions and material properties.

IV. ELECTRIC FIELD

Knowing a point in a linear stress curve, the only other requirement for its complete description is its slope, m, which can be found as follows:

It follows from continuity of charge across the insulation, that,

$$I = 2\pi r_1\sigma(r_1)E_1 = 2\pi r_2\sigma(r_2)E_2 \qquad (9)$$

Where, E1 and E2 are stresses at r_1 and r_2 respectively using(1),and rearranging

$$\frac{E_2}{E_1}\frac{g(E_2)}{g(E_1)} = \frac{r_1}{r_2}\frac{f(T_1)}{f(T_2)} \qquad (10)$$

Since, f and g are monotonically increasing functions of T and E, respectively, if temperature is uniform across the dielectric, E2 < El. However, due to gradient in temperature, the right hand side tends to increase, resulting in E2 ≥ E1, in certain conditions. Since the ratio $f(T_1)$ /$f(T_2)$ is the factor which forces the stress inversion we name it 'inverting factor', for ease of understanding and denote it by $\boldsymbol{\tau}$(≥ 1, always).

Expressing El and E2 in terms of E0 and m, after simplification,

$$\left(\frac{1+\xi}{1-\xi}\right)\frac{g(E_{\circ}[1+\xi])}{g(E_{\circ}[1-\xi])} = \frac{r_1}{r_2} \times \tau \qquad (11)$$

Where,

$$\xi = \frac{m\,(r_2-r_1)}{2E_{\circ}} = \frac{\Delta E}{E_{\circ}} \qquad (12)$$

Which is equal to the per unit increment in electric stress over its average value ($\Delta E = |E_1 - E_{\circ}| = |E_2 - E_{\circ}|$) and is an important parameter assessing magnitude of stress increment.

Since $\xi$is a representative of a true measure of stress inversion, it is named here the 'coefficient of stress inversion', for convenience. The exact value of 4 can be computed solving the above equation numerically using Newton's or Secant method. However for most conductivity models, an analytical estimate can always be obtained, with sufficient degree of accuracy, for example, with the conductivity model (2), Fig. 1, it can be shown that,

$$\xi \approx \frac{b\left(\frac{1}{T_2} - \frac{1}{T_1}\right) - \ln\left(\frac{r_2}{r_1}\right)}{2(1+aE_{\circ})} \qquad (13)$$

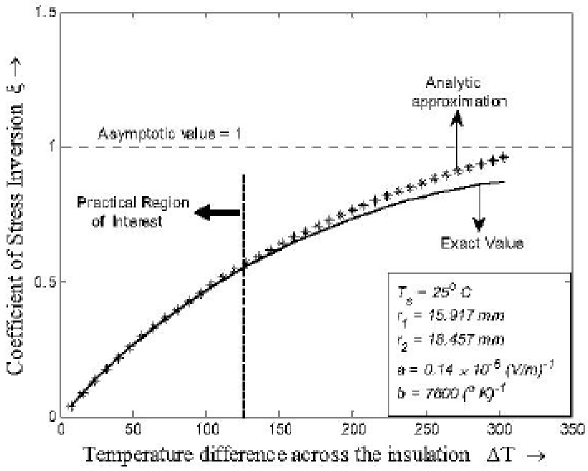

Fig. 1 Comparison of Analytical and Numerical Estimation of 4 at 100 kV

Knowing the value of 4 the slope m and hence stress distribution can be obtained, thus:

$$E(r) = E_{\circ} + m\left(r - \frac{r_1 - r_2}{2}\right) \qquad (14)$$

V. DISCUSSION

The Authors identify three important parameters of design interest; the inverting factor, T, the slope parameter, m, and the coefficient of stress inversion 4. Under uniform temperature regime, the inverting factor assumes unity while m and 4 assume negative values. For a given maximum design insulation temperature, T is a constant while m and 4 depend on the geometry of the cable apart from design voltage. The parameter m is closely associated with intrinsic space charge accumulation and 4 is a measure of maximum electric stress in the insulation.

The factors affecting these parameters are many, for example, the stress coefficient, temperature coefficient (or thermal activation energy), choice of r1, the thickness of the insulation, applied voltage, load current, and the boundary temperatures or the thermal boundary conditions. Therefore simultaneous treatment of all the factors renders to a multi dimensional (7- dimensional) problem. An understanding of the influence of these factors is possible making appropriate choice of factors in a given situation.

As a first case consider a DC cable with the parameters given in Table I. The influence of thermal boundary conditions on 4 can now be studied.

Table 1

PARAMETERS OF AN EXAMPLE CABLES

Parameter	Value
r 1	22.5 mm
r2	44.2 mm
a	0.142×10^{-6} $(V/M)^{1}$
b	7600K
V	600 kV
R,	17.6μΩ/m
k	0.34 W/m K

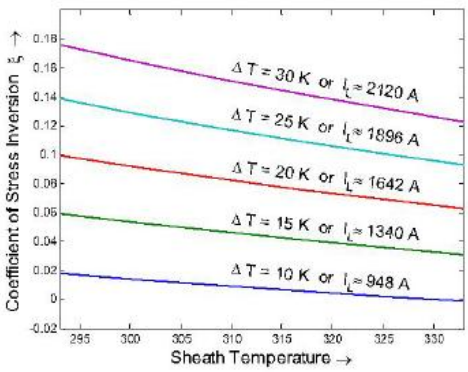

Fig-2 : Variation of coefficient of stress inversion with the sheath temperature

The coefficient of stress inversion vs sheath temperature is shown in Fig. 2, with ΔT or load current as a parameter.Thisis shown, also, in Fig. 3, differently, in order to clearly show the tendencies. For a given sheath temperature 4 sharply increases with AT or load current. This can further be seen in stress curves plotted in Fig. 4.

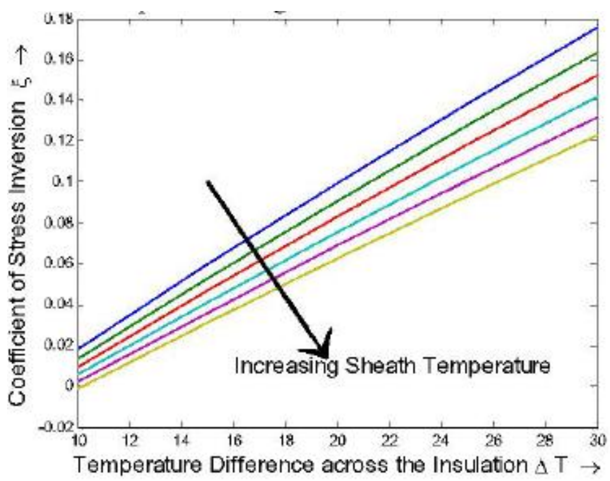

Fig-3 : Variation of coefficient of stress inversion with temperature difference

across the insulation

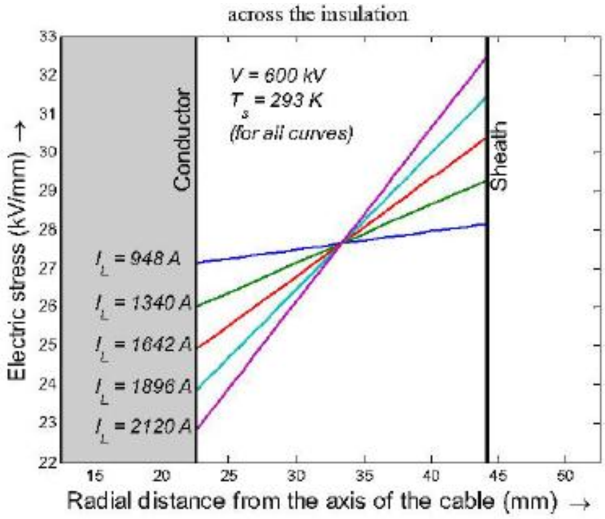

Fig-4 :Electric field distribution across the insulation

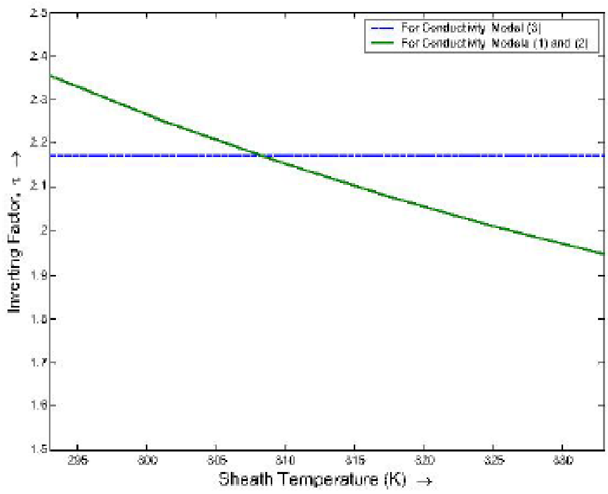

Fig-5 : Variation of the Inverting Factor with sheath temperature

It can be noted here that, for a given AT or a constant load current, the 4 decreases, marginally, with sheath temperature. This interesting feature, however, can not be observed with less accurate conductivity model (4). A further investigation into this aspect led to the fact that, in case of model (4), the inverting factor T, is insensitive to the sheath temperature, Fig 5, contrary to the Boltzmann temperature dependence in the other two models.

VI. CONCLUSIONS

In conclusion it is strongly recommended to use Boltzmann temperature dependent conductivity models for estimation of stress distribution in HV DC Cables.

Future work:-The dc conductivity of the cable is strong function of electrical field and temperature due to homic losses of the conductor and Electrical field itself function of the radius of the cable. But in practice the dielectric coated stranded conductor surface is not really smooth and some amount of eccentricity exist.

If include geometry of cable and leakage current then the total problem becoming non- linear so by using analytical method we can’t deal non-linear problems.by using numerical method we can deal non-linear problem very simply

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