Investigation and Analysis of Inception Voltage and Field Distribution in Power Cables with Internal Cavities in Dielectric

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ABSTRACT

Partial discharge (P.D.) in micro cavities in the insulation of H.V. power cables drastically affect the performance, the field distribution and hence the rating of these cables. It is well known that, P.D. deteriorates power cables and lead to its complete failure. This has adverse effects on the reliability and maintainability of power supply, which affects directly the production of industrial factories.

In this work a study and investigation of the effect of partial discharges in cavities in the solid insulation of H.V. power cables is carried out. The field distribution along that part of the conductor which lies within the triangle formed by joining the conductor centers will give the closest representation of the cable, and hence the rating of these cables were determined by modeling and simulation of these P.D.

Cables three core power were tested and investigated at different voltages at low voltage, medium voltage and high voltage under alternating voltage at room temperature.

The cavity shapes, spherical and cylindrical, with different sizes were tried. The insulation thickness was varied. The location of the micro cavity in the insulation was changed at different angles.

The position of maximum electric stress in cables was determined.

A developed simulation program using boundary element method was applied. The inception voltage was calculated and the applied voltage was changed as a function of the inception voltage. The discharge inception voltage was minimum at the conductor/insulation interface due to the high stress at this region. The result showed that cylindrical cavities are more severe than spherical ones. The simulation results are in good agreement with the experimental findings and the practical experience. This shows the effectiveness of this study as a non-destructive method of cables evaluation.

1-INTRODUCTION

Insulating systems contain some micro cavities or voids within the insulation or at boundaries between the dielectric and the conductors. In case of cables, cavities are formed by the differential expansion and contraction of the cable material under cyclic loading conditions. The cavities being effectively pockets of low pressure electrically weak and will ionize at quite low electric stresses. The ionization and occurrence of partial discharges within the cavities would cause erosion and local deterioration of the insulation eventually leading to a complete failure of the cable. Thus knowledge of the inception voltage is important for the proper design [1].

Methods of calculating the discharge inception voltage in voids for single core and for three-core belted type cables have been proposed [2-4].

For the optimization of the insulation design for three-core power cables, it is fundamental to know the location and the magnitude of the maximum field stress as a function of the cable dimensions.

The present paper describes the application of the boundary element method [5] to accurately determine the stress in three-core cables. The electric field is determined as a function of the location in the three-core cables. The maximum field in the cable which is used to calculate the voltage rating of the cable for a discharge inception at voids created during the manufactures of and/or operation of the cable is calculated.

The phase voltage in a three-core belted cable which is capable to initiate partial discharges anywhere in the cable is determined. The voltage is calculated for different locations of the void and as a function of the void thickness and shape.

2- THREE-CORE BELTED CABLE

Fig. (1) shows the cross section of the three-core belted cable having the following parameters: d the diameter of each core conductor, T the conductor electrical insulation thickness, t the belt insulation thickness, $S = (2T+d)/\sqrt{3}$ the distance between the conductor and the cable center, and $R = S+d/2+T+t$ the inner radius of the metallic sheath. The insulation consists of three main parts; conductor insulation, belt insulation and the filling material in the interstices between the cores.

3- SIMULATION TECHNIQUE

In order to calculate an electric field distribution, one has to solve Laplace's partial differential equation with boundary conditions prescribed over the boundary. When complicated geometries are encountered, as in the case of HV engineering applications, numerical techniques are generally the only viable approach [5].

In this work Boundary element method is used to calculate the electric field distribution and the maximum field stress within a cavity embedded in a dielectric material in the three-core belted cable. The electric field distributions within the dielectric are studied as a function of applied voltage, cavity shape, (spherical and cylindrical), with different sizes, insulation thickness and location of the micro cavity in the insulation. The position of the maximum electric stress in cable was determined.

Thus, the method can be directly related to superposition of charge contributions to yield potential distributions.

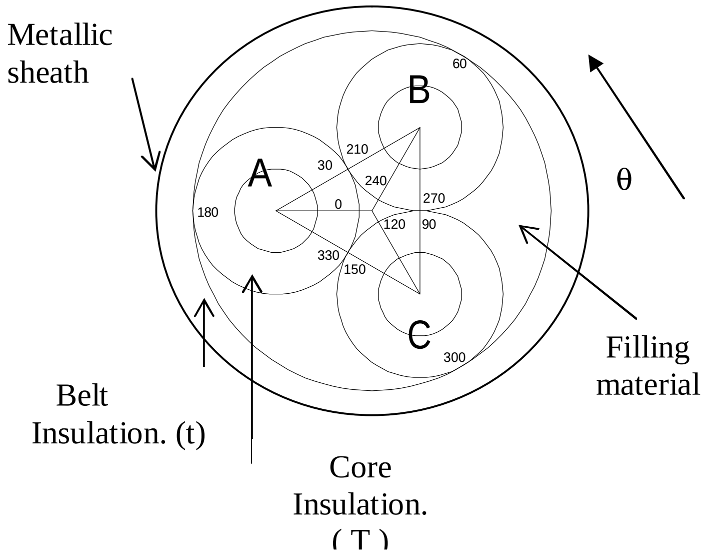


Fig (1) Three core cable

A more complex and fruitful generalization involves the use of strip charges, divide the cable cores and dielectric boundaries into individual strips over each the charge density is approximated as constant. Values of the strip charges re determined by satisfying the boundary conditions at a selected number of contour points. Once the values of simulation charge are known, the potential and field distribution anywhere in the region can be computed easily.

4- BOUNDARY ELEMENT METHOD.

The boundary element method does not rely upon fictitious charges; instead it seeks to calculate charges distributed over boundaries. Then, approximating the real charge distribution rather than assigning values to nonphysical ones. The electric potential due to a surface charge density is written as in [6]

$$\phi(r) = \frac{1}{2\pi\alpha\varepsilon_0} \int_{\Gamma} \rho_s(r')\phi^*(r,r')d\Gamma(r') \qquad (1)$$

Where Φ (r): represents potential at location r

α: is a constant and equal to 1 or 2 for two or three dimensional problems respectively.

$\rho_s(r')$: is the surface charge density at location r'

Γ : denotes the boundary between different regions

r : denotes a field point and r' denotes a source point

$\Phi^*(r, r')$: is the fundamental solution of the potential problem.

Equation (1) is the basic equation of the source formulation of the boundary element method. A system of boundary conditions is required for determining the unknown charge density. After successive simplification [6], a set of linear equations to satisfy Dirichlet boundary conditions on energized conductors and flux continuity through dielectric boundaries are obtained and expressed by:

$$[A].[\rho_s] = [\phi] \qquad (2)$$

Where: [A] is a known vector potential-coefficient matrix.

[ρ] is the unknown surface charge density vector matrix.

[Φ] is the potential vector matrix

By solving this system of equations we can find the unknown values of charge density. Consequently, using this charge distribution, potential and electric field values can be calculated.

5- DISCHARGE INCEPTION VOLTAGE.

Consider a gas filled cavity of spherical shape having a diameter r within the solid insulation present at a location θ in degree anywhere within the tree-core cable. The origin is the center of the cable. The conductor voltage V_i which causes a discharge inside the cavity is to be determined. Knowledge of this voltage is important for a satisfactory design, manufacture and a proper operation of electric power cables.

The electric field E_r in solid dielectric just outside the gaseous cavity at a location θ is calculated by using the boundary element method.

It has been shown that the electric field inside a spherical cavity within dielectric is given by [3]

$$(\mathrm{E_c})_\theta = 3\varepsilon_r/(1+2\varepsilon_r)(E_r)_\theta \qquad (3)$$

And for a cylindrical cavity

$$(E_c)_\theta = \varepsilon_r (E_r)_\theta \qquad (4)$$

Where $(E_C)_\theta$ is the electric field (in p.u) inside the cavity at a location θ and $(E_r)_\theta$ is the electrical field in (p.u) in the dielectric at location θ. ε_r is the relative permittivity of the solid dielectric used to insulate the cable.

The derivation of Eqns. (3) and (4) is based on the assumption that the electric field strength of an air cavity within a solid insulation material is approximately the same as that between a pair of matel electrodes of the same gap length and the linear dimension of the cavity [5].

The inception voltage for a discharge in the cavity can be calculated as follows:

$$[(\mathrm{V_i})_r]_\theta = [(\mathrm{E_g})_r]/(\mathrm{E_c})_\theta \qquad (5)$$

Where $[(V_i)_r]_\theta$ is the magnitude of the normalized inception voltage, i.e., the voltage of the conductor whose insulation contains a cavity of thickness r, and this voltage shall be sufficient to cause a discharge inside the cavity and $[(E_g)_r]$ is the magnitude of the electric strength of the entrained gas inside the cavity having a thickness r at pressure p.

The inception voltage Vi is calculated from Equ. (5) for a given cavity of thickness r and gas pressure p. The value of $[(Eg)_r]_p$ are obtained from Table I[7]. For completeness $(E_C)_\theta$ is computed using Equ.(3) for a spherical cavity and Equ.(4) for a cylindrical cavity. $(E_r)_\theta$ is calculated using Boundary element method.

Table I: the maximum electrical field E_g of a cavity inside a solid insulator for different air pressures and cavity thickness.

1 bar		0.1 bar		0.01 bar	
r (mm)	E_g (kv/cm)	r (mm)	E_g (kv/cm)	r (mm)	E_g (kv/cm)
0.005	700	0.02	300	0.09	500
0.01	375	0.025	200	0.1	350
0.02	230	0.036	100	0.12	200
0.05	140	0.05	65	0.14	100
0.1	100	0.1	35	0.17	50
0.2	75	0.2	23	0.2	30
0.5	55	0.5	14	0.23	20
1	45	1	10	1	3.5
2	40	2	7.5	2	2.2

6- RESULTS AND DISCUSSION

For the purpose of calculations, the following parameters are considered:

The voltages on the three cores of the cable are absolutely symmetrical and sinusoidal.

Fig. (2) Shows the variation of resultant stress E_θ around all three conductors and the sheath corresponding to (wt= 90 and 150) respectively as a function of stress location θ.
It is clear that, the maximum stress in dielectric is around the conductor of highest potential, the field variation at the surfaces of other conductors is about the same while the stress at the sheath is lower. The normal component of the electric field at the sheath surface pulsates according to the variation of the applied voltage at the conductor with time.

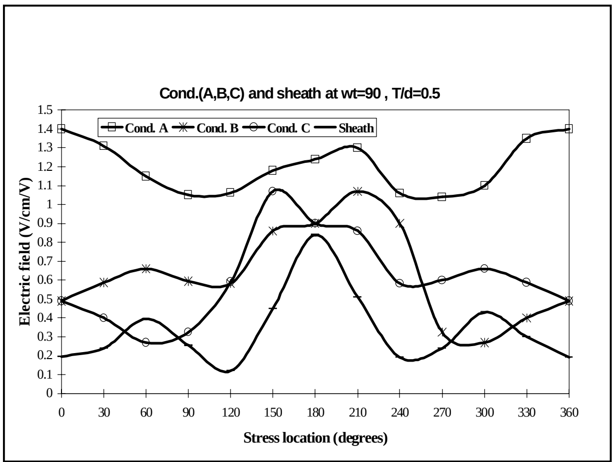


Fig. (2-a) Electric field around conductors of cores A, B and C and sheath

Fig. (2-a) the instantaneous values of the phase voltages at wt = 90 on the three conductors are V_A = 1, VB = -0.5 and V_C =-0.5 p.u.

For each conductor θ is measured from its center in counterclockwise direction. It is clear that, the field stress around the conductor A which has a peak potential is of higher value than conductors C and B. when the stress location θ is near conductor A, there is a maximum stress for conductor B and C at the points of touch with conductor A (i.e. θ = 210) for conductor B and θ = 150 for conductor C. The stress values at location θ =0 and θ = 360 for conductors B and C are of the same values. The sheath stress is pulsating and its maximum value occurs at θ = 180 which is between the two maximum point of B and C.

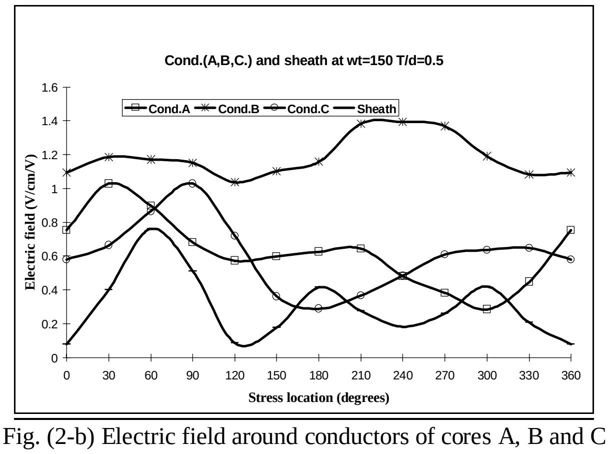


Fig. (2-b) Electric field around conductors of cores A, B and C and sheath

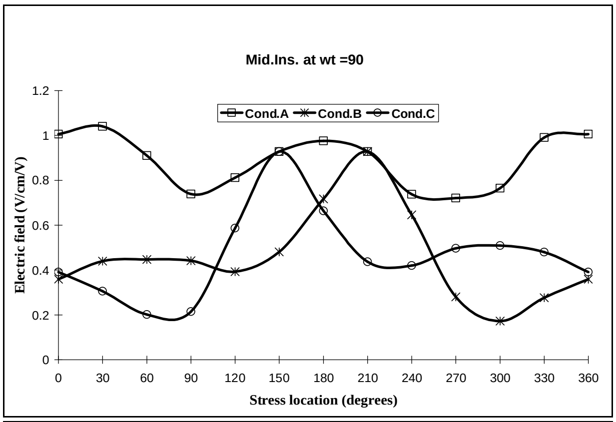
Fig. (2-b) The instantaneous values of the phase voltages at wt = 150 on three conductors are V_B=-1, V_A= 0.5 and V_C =0.5 p.u.
It is clear that for conductor A the maximum stress occurs at θ= 30 and for conductor C at θ= 90. It will be observed that the field values at the surfaces of the conductors A and C are about the same while at B is high.

Generally, the field stress around the conductor which has a peak potential is higher than other two conductors. The maximum stress for the other two conductors is at the points of touch with the peak potential conductor. As expected the stress distribution becomes more and more non uniform as the conductors are brought nearer each other.

Fig. (3) Shows the variation of middle insulation stress for all three conductors corresponding to wt= 90 and 150 respectively, as a function of stress location θ.

The middle insulation stress for a conductor which has a peak potential is lower than the conductor surface stress and is higher than the sheath stress. The middle insulation stress for other conductors is nearly the same, and is maximum at the points of touch with the conductor having the peak potential.

Fig. (3-a) It is clear that, the insulation stress on conductor A which has peak potential is lower than the conductor stress and higher than the sheath stress. The maximum insulation stress which occurs at θ=210 for conductor B and θ=150 for conductor C are the same with the insulation stress of conductor A.



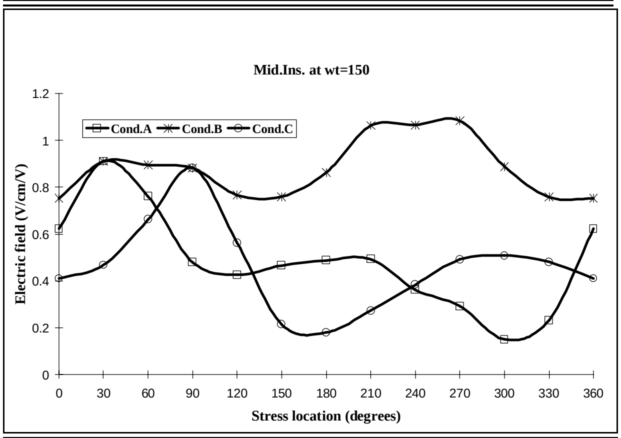
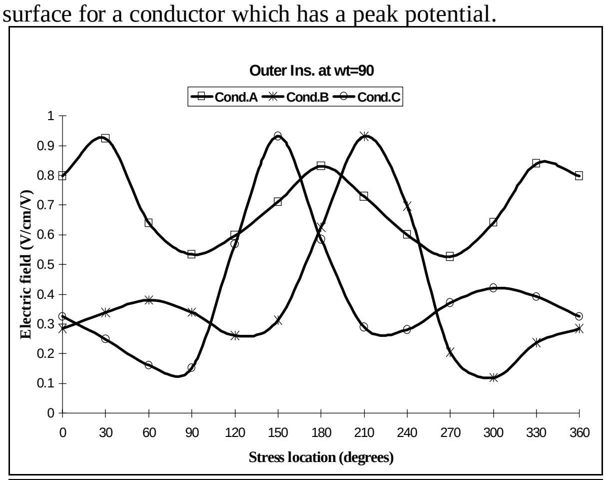


Fig. (3-a, b) Electric field at middle insulation of A, B and C

The same results can be obtained from Fig. (3-b) where wt=150.

Figs. (4 –a, b) illustrate the variation of sheath stress with stress location θ at different values of wt. namely, wt= 90, 150,.

It is observed that the field distribution is more non uniform and this is due to interference between fields for three sheath surfaces. For the points at which the conductor insulations touch each other there is a maximum field stress at sheath surface. These values are higher than the field in sheath surface for a conductor which has a peak potential.



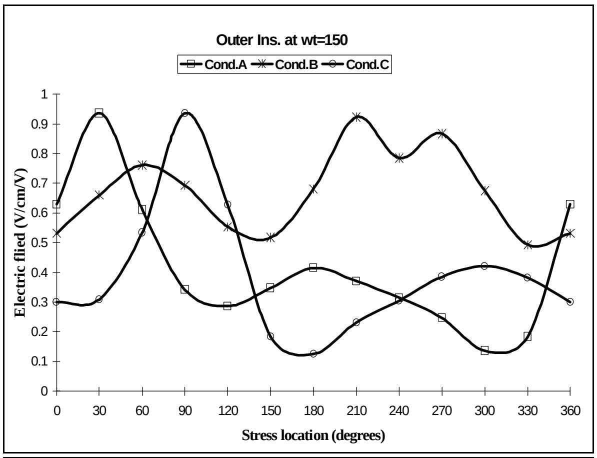


Fig. (4-a,b) Electric field at outer insulation of A,B and C

Fig. (5-a) shows the variation of stress around conductor, inside insulation and on the sheath for conductors A and C at wt=0. Thus the instantaneous values of the phase voltages at wt=0 (V_A=0, V_B=0.866 and V_C= -0.866).

It is shown that for conductor C the electrical field is maximum value around conductor and decreased inside the insulation and its minimum value is at the sheath.

For conductor A, in the zone between θ = 120 and 240 there is nearly minimum potential so, there is a minimum field stress on it. The field stress in this zone is almost the same for conductor A, inside insulation and at sheath. For the zone between θ = (0-120) and θ = (240-360) where the conductor A stress is nearly same as the two conductors B and C. The field stress is increased in the different cases.

It is clear that, in conductor A the stress in the first and end zones is opposite in conductor C while the field in sheath is larger than in the insulation around the conductors.

The same results can be obtained when wt=120, (V_A=0.866, V_B=-0.866 and VC= 0)

Fig. (5-b) at wt=30, (V_A=0.5, V_B=0.5 and V_C=-1) It is illustrated that the stress around conductor C is of high value and decreases toward the insulation. For conductor A the stress around conductor is higher than inside insulation and the sheath but this field is smaller than the stress for conductor C. The same results can be obtained when wt=90, (V_A=1, V_B=-0.5 and VC=-0.5).

Fig. (5-c) at wt =60, (V_A=0.866, V_B=0 and V_C =-0.866). Because the potential on conductors A and C are equal there is a distortion and interference between the stress on the two

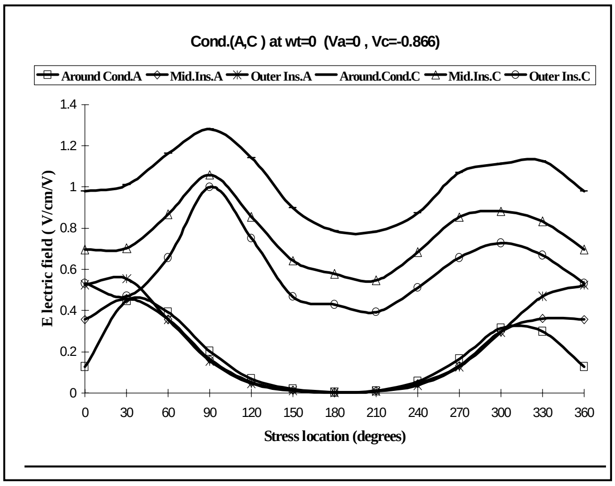


Fig. (5-a)

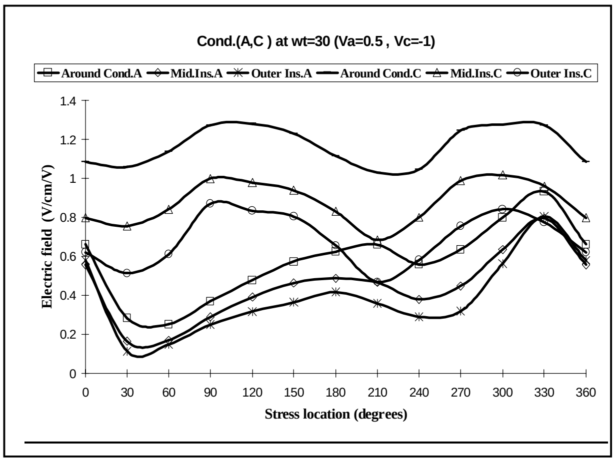


Fig. (5-b)

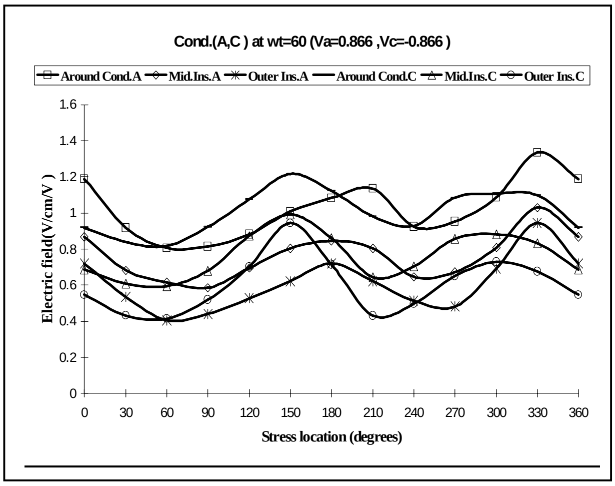


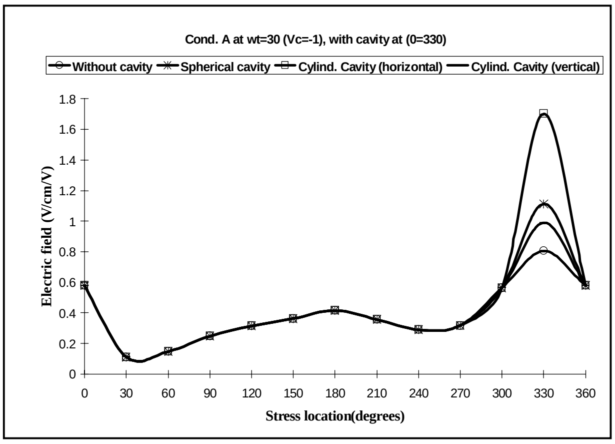
Fig. (5-c)

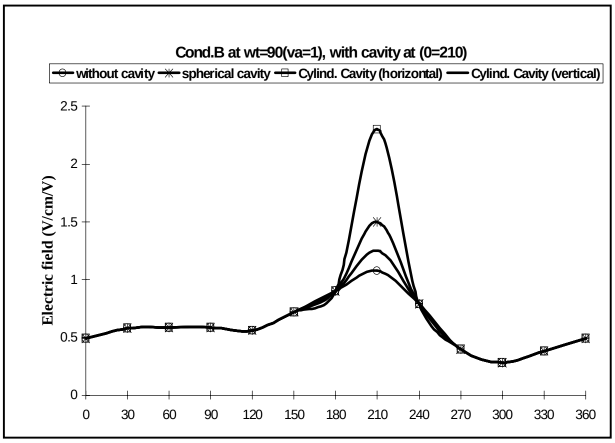
Fig.(5) variation of stress around conductor inside insulation and at the sheath for conductors A and C.

conductors A and C. The stress around conductor is of maximum value and decreases inside insulation and on the sheath. The same results can be obtained when wt=150 (V_A=0.5, V_B=-1 and VC=0.5).

INCEPTION VOLTAGE

Fig. (6-a, b, c) Shows the relation between the electrical field distribution around conductors A, B and C at wt = 30, 90,150 respectively. With different cavities namely, spherical and cylindrical (vertical and horizontal) which are located at θ =330,210 and 90 respectively as a function of field location θ. It is clear from the figures that, the maximum value of stress occurs at cavity in all cases. It is also clear that in the case of horizontal cavity the stress has the highest value and in case of insulation without cavity it is of the lowest value .The field distribution in the rest of the insulation is almost constant and equal to the designed value.





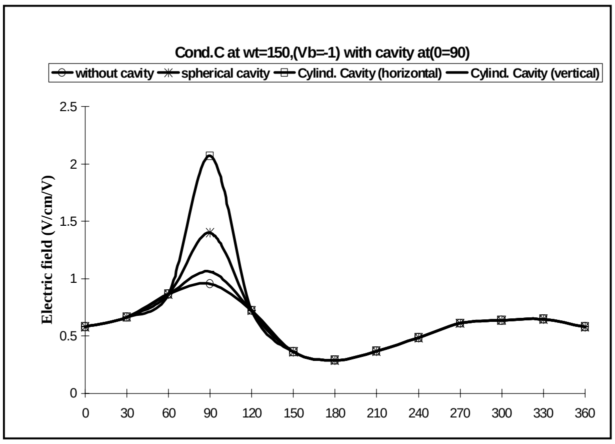


Fig. (6-a, b, c) Electric field distribution around Cond. A, B, C with and without cavity

Fig.(7) show the influence of the shape, size and location of the cavity as well as the gas pressure inside the cavity, on the inception voltage of a belted power cable. It is clear that for

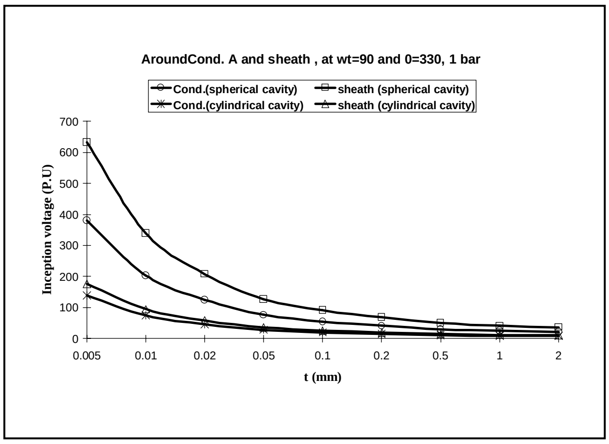


Fig (7) Inception voltage for a conductor A and sheath at different shape cavity

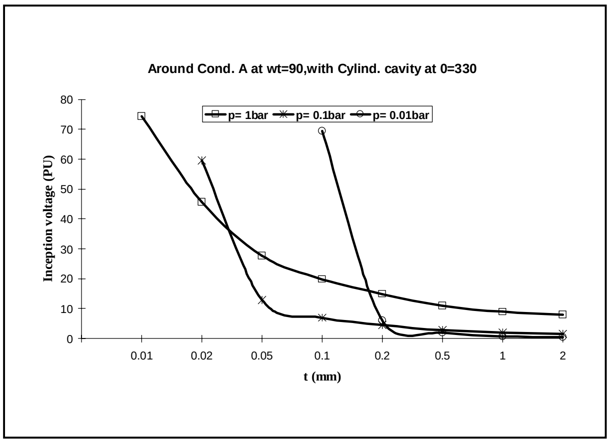


Fig.(8) Inception voltage for a conductor A at different gas pressure inside the cavity

a constant pressure at 1bar, V_i decreases as t is increased. Due to the remnant charge on the walls of the cavity. Moreover, spherical cavities have higher inception voltage when compared to the cylindrical ones. For given cable and cavity parameters, V_i is lowest when the cavity is located at the conductor surface where E_{max} has the highest value. However, the cavities at the sheath are significantly larger than those in the conductor insulation.

Fig.(8) Shows the relation between inception voltage and thickness of cavity for conductor A at $\omega t = 90^0$ at different gas pressure inside the cavity. It is clear that, with increasing the thickness of cavity the inception voltage decreases and partial discharge increased. Therefore voltage rating of belted cables is decided by discharge inception in cavities present in the filler material or at the sheath interior.

7- CONCULSIONS

- For an accurate stress analysis of three-core belted type cables boundary element method can be used.
- The field stress around the conductor which has a peak potential is higher than the other two conductors.
- The maximum stress in the middle of insulation for the other conductors occurs at the touch with the conductor that has the peak potential and equal to that at the middle of insulation for a conductor which has the peak potential.

- Compared to spherical voids, cylindrical shaped voids are much more vunrable to partial discharges.
- The inception voltage is a function of the location of the void in the insulation of the cable.
- Increasing the thickness of the cylindrical cavity the inception voltage decreases and partial discharges increase.

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