The Effect of Lightning Impulse and Switching (over voltages) on stress distribution and space charge accumulation of HVDC XLPE cables at load and no load

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Abstract

High voltage direct current (HVDC) power cables are usually exposed to high value of stresses from lightning impulses and switching surges (over voltages) at working under load and no load. In this research used a detail analysis for stresses behavior in the insulation of cable at over voltages and at both modes (load & no load). It also shows the effect of such over voltages (lightning impulse & switching surges) on space charge accumulation in the insulation of the cables at load and no load. The investigated cable is of rated voltage 33Kv insulated by cross-linked polyethylene (XLPE).Electrical field and space charge accumulation are carried out theoretically by the aids of computer programs. The results give an indication of the maximum stresses occurs in the cables insulation at over voltages for both modes (load and no load), and also give an induction of the space charge accumulation at over voltage and at load and no load. The results show that maximum stress occurred by lightning impulse is found much higher than that of switching operation for load and no load but the switching surge has longer period. Also the results show that the space charges accumulation at lightning impulse are more than at switching surges for both modes (load & on load). Both main results (Electrical stresses and space charge accumulation) are found depends on the polarity of the over voltages.

Keywords: HVDC stress distribution at load, XLPE HVDC at load & no load

تأثير نبضات الاندفاعة ونبضات الفتح والغلق على توزيع الاجهادات الكهربائية وتكدس الشحنات في قابلوات الضغط العالي للتيار المستمر ذوات عوازل البولي

اثيلين متقاطع الأواصر في حالة الحمل واللاحمل

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الخلاصة

تتعرض قابلوات التيار المستمر ذات الفولتية العالية عادة لمقادير عالية جدا من الاجهادات الكهربائية الناتجة من تأثيرات ظاهرة الاندفاعة وتأثيرات فولتيات الفتح والغلق (فولتيات المفاتيح)، إذ تعتبر كلا الفولتيتين من الفولتيات العالية عند عمل القابلو في حالة الحمل واللاحمل. في هذا البحث تم استخدام تحليل تفصيلي لسلوك الاجهادات الكهربائية في عازل القابلو وأيضا استخدم تحليل تفصيلي لسلوك ظاهرة تكدس الشحنات في قابلوات الفولتية العالية لكلا الفولتيتين المذكورتين أنفاً في حالة تحميل وعدم تحميل القابلو. كما عنيت الدراسة بصورة حصرية بقابلوات ذات تقنين 33 كيلو فولت وذات عوازل البولي اثيلين متقاطع الأواصر ويرمز له (XLPE). تم حساب نتائج المجال الكهربائي ونتائج ظاهرة تكدس الشحنات بصورة نظرية باستخدام برامج الكومبيوتر وقدمت النتائج المناطق التي يتركز بها أعظم اجهادات كهربائية ومناطق الخطورة لكلا الحالتين الحمل واللاحمل، كما وقدمت الدراسة نتائج واضحة عن ظاهرة تكدس الشحنات وحددت مناطق أعظم تكدس للشحنات وفي كلا الحالتين الحمل واللاحمل. بينت النتائج ان الاجهادات الكهربائية وظاهرة تكدس الشحنات في حالة فولتيات الاندفاعة تكون ذات تأثير كبير جدا مقارنة مع النتائج التي تم الحصول عليها من تأثير فولتيات الفتح والغلق (فولتيات المفاتيح)، لكون هذه الفولتية تكون ذات سعة واسعة وقيمة تأثيرية اقل مقارنة بموجة الاندفاعة ، كما شملت جميع النتائج حالتي القابلو (الحمل واللاحمل). وأخيرا أخذت الدراسة بنظر الاعتبار تأثير القطبية لكلا الفولتيتين العاليتين.

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Introduction:

High voltage cables are considered the most important equipments in the underground power DC transmission systems, especially in our modern life, because the largely and rapidly development in each part of cables. The main properties which are effected on cables behavior are: voltage and current, because any changing in supplied voltage would change the electrical stresses which are exposed on the insulation of cables.[1]

A power cable used for DC transmission has no capacitive leakage currents, and the power transmission is limited by the conductor losses only [2]. How much the cable insulation can withstand in AC operation is normally limited by the maximum voltage stress in service and at impulses over voltages. For DC cables a stress of three to five times that for an AC cable may be used . In AC cables the stress created by the electrical field is distributed in inverse proportion to the capacitance of the cable dielectric. This always gives the highest stresses close to the conductor and the lowest stresses close to the sheath [3]. But in Dc cable the stress distribution is investigated as a function of dielectric conductivity or resistively, which varies with temperature and stress[3]. Voltage distribution is determined by insulation resistance and space charge and is dependent on temperature [4]. In a cold cable the voltage distribution is the same as in AC cables, the highest stresses near the conductor and the lowest stresses near the sheath, but at high conductor to sheath temperature gradient the stress may become highest at the sheath and lowest at conductor as shown in figure(1)[2,3]. Cables are subjected to over voltages from lightning impulse as well as the over voltages from switching operation of the power transmission system. High voltage cables in underground power systems usually tested with lightning impulses according to the applicable (IEC) standard to proof it's capability against lightning over voltage [5].

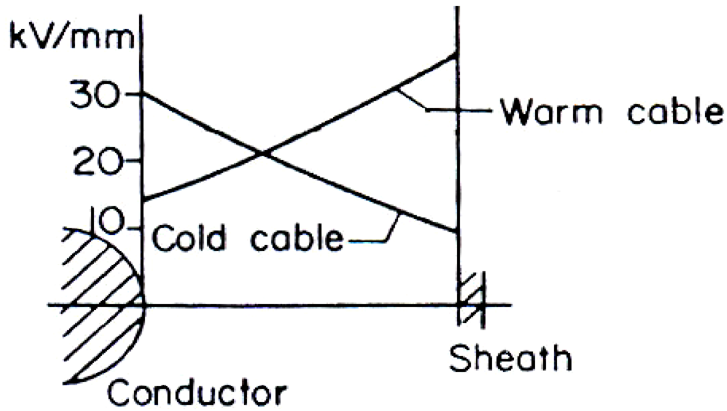


Figure (1) Stress distribution at rated voltage for warm & cold cables

Theoretical Approach:

The investigation is based on previous work[7], studied the effect of stress distribution and space charge accumulation for HVDC cables at rated voltage only and derived the main formula of stress distribution and space charge accumulation, but it neglected the effectiveness of lightning impulse and switching surges. Both over voltages are deeply influenced on stress distribution and space charge accumulation. The theoretical formula of stress distribution at rated voltage is shown by the given equation[6]:

$$E_b = \left[R\left[k_1 + k_2 * \ln\left(\frac{R}{r_c}\right)\right] - \frac{C_1}{\sqrt{R}} \right] \qquad \text{.........} (1)$$

And the theoretical formula of space charge accumulation at rated voltage is shown with the given equation[7]:

$$S_a = \varepsilon\varepsilon_0 * \left(3*k_1 + 2*k_2 + 3*k_2*\ln\frac{R}{r_s} \right) * \left[R*\left(k_1 + k_2*\ln\frac{R}{r_c} \right) - \frac{C_1}{\sqrt{R}} \right] \qquad \text{.........} (2)$$

$$k_1 = \left[\frac{\alpha(\theta_c + \gamma)}{3} + \frac{2*\alpha*\Delta\theta}{9*\ln\frac{r_s}{r_c}} \right] \qquad \text{.........} (3)$$

$$k_2 = -\frac{\alpha*\Delta\theta}{3*\ln\frac{r_s}{r_c}} \qquad \text{.........} (4)$$

$$k_3 = -\frac{r_s^3}{3}\left[\left(k_1 + k_2*\ln\frac{r_s}{r_c} - \frac{k_2}{3} \right)^2 + \frac{k_2^2}{9} \right] + \frac{r_c^3}{3}\left[\left(k_1 - \frac{k_2}{3} \right)^2 + \frac{k_2^2}{9} \right] + V \qquad \text{.........} (5)$$

$$k_4 = -\frac{4}{3}\left[r_s^{3/2}\left(k_2 * \ln\frac{r_s}{r_c} - \frac{2}{3} * k_2 + k_1 \right) \right] - r_c^{3/2}\left[k_1 - \frac{2}{3} * k_2 \right] \qquad \text{......... (6)}$$

$$C_1 = \frac{-k_4 \pm \sqrt{k_4^2 + 4 * k_3 * \ln\frac{r_s}{r_c}}}{2 * \ln\frac{r_s}{r_c}} \qquad \text{......... (7)}$$

E_b = Stress distribution. S_a = Space charge accumulation.

ε = relative permittivity ε_0 = Air permittivity.

V = Rated voltage. R = the distance between the conductor and the sheath.

r_c = conductor radius r_s = sheath radius.

α = temperature coefficient. γ = stress coefficient.

$\Delta\theta$ =change of temperature θ_c =conductor temperature

All above equations were at rated voltage, for adding the effectiveness of over voltages, it has been chosen a single stage impulse generator as shown in figure(2)[8], for producing lightning impulse and switching surges, usually used equation(8)[8,9].

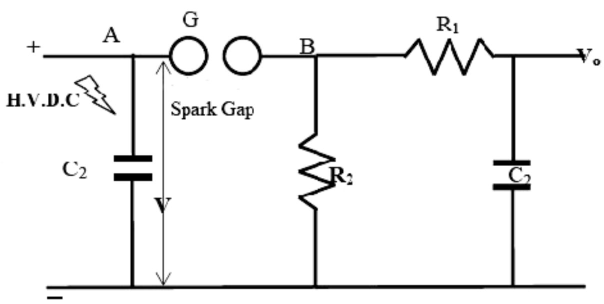


Figure (2) Single stage impulse generator

The waveform of the lightning impulse is shown in figure(3)[9]. The typical lightning impulse produced by equation (8) has two parts, the first is the front of waveform, it could be controlled by the expression (exp(-t/(R_2*C_1)), and the second is the tail of waveform, it also could be controlled by the expression (exp(-t/(R_1*C_2)). By controlling the front and the tail of the lightning impulse waveform it could achieve characteristics of the lightning impulse and switching surges.

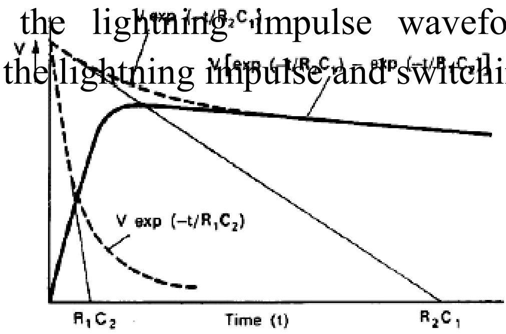


Figure (3)

Lightning impulse waveform

$$V_{imp} = V * \left[\exp\left(\frac{-t}{R_2 * C_1} \right) - \exp\left(\frac{-t}{R_1 * C_2} \right) \right] \qquad \text{......... (8)}$$

The simulation involve used of lightning impulses of 1.2/50 μs (front/tail) and at peak values of 20 limits that of working voltages and at both positive and negative impulses. For switching operation, the waveforms of the surges is at peak value of 4 times that of working voltage and at longer front and tail voltage 20/30 μs, this value is computed by varying the values of the impulse generator parameter (R_1,R_2,C_1,C_2).

The new values of working voltage (VP_{new}) at exposed cables to positive impulse lightning (V_{imp}) and positive switching surges (V_{SW}) are represented by equation (9) and equation (10), respectively. Similarly to the positive, the new value of working voltage (VN_{new}) at exposed cables to negative lightning impulse ($-V_{imp}$) and negative switching surges ($-V_{SW}$) are represented by equation (11), and equation (12) respectively.

$$VP_{new} = V + V_{imp} \quad \text{......... (9)}$$

$$VPS_{new} = V + V_{SW} \quad \text{......... (10)}$$

$$VN_{new} = V - V_{imp} \quad \text{......... (11)}$$

$$VNS_{new} = V - V_{SW} \quad \text{......... (12)}$$

And the electrical stresses and space charge accumulation after exposed cables to lightning impulse are computed from equation (13) and equation (14), respectively.

$$E_{new} = E_b + E_{imp} \quad \text{......... (13)}$$

$$S_{a\ new} = S_a + S_{a\,imp} \quad \text{......... (14)}$$

E_{new} = New electrical stresses after exposed cables to lightning impulse.

E_{imp} = Electrical stresses at lightning impulse.

$S_{a\ new}$ = New space charge accumulation after exposed cables to lightning impulse

$S_{a\ imp}$ =Space charge accumulation at lightning impulse

Similar to lightning impulse equation, the equation of switching surges is computed from the same generator which is shown in figure(2), and same voltage waveform shown in figure(3), but with different peak value, front, and tail time duration. So that the electrical stresses and switching surges are produced from switching surges are computed from equation (15) and equation (16), respectively.

$$ES_{new} = E_b + E_{SW} \quad \text{......... (15)}$$

$$S_{Sa\ new} = S_a + S_{a\,SW} \quad \text{......... (16)}$$

ES_{new} = New electrical stresses after exposed cables to switching surges.

E_{SW} = Electrical stresses at switching surges.

$S_{Sa\ new}$ = New space charge accumulation after exposed cables to switching surges

$S_{a\ SW}$ = Space charge accumulation at switching surges

The simulation of lightning impulse and switching surges is done at two modes load and no load. First mode is done when the cable is warm, according to the previous works which is mention above, and used values of $\theta_c = 80^\circ C$ and $\Delta\theta = 15^\circ C$. And the second mode is done when the cable is cold according reference three [3].

Designed Program:

The theoretical analysis is simulated by designing a computer program. The program used data of high voltage direct current power cables of rated 33Kv. The simulation is done for many modes: the first mode is at rated voltage at load and no load, the second mode is at positive lightning impulse at load and at no load, the third mode is at negative lightning impulse also at load and no load, the fourth mode is at positive switching surges at load and no load, finally the fifth mode is at negative switching surges at load and no load.

All carry out results from program were electrical stresses and space charges accumulation for each mode. The designed computer programs is given by its flow chart shown in figure(5).

Results and Discussion:

In present study has taken the effect of over voltages which are subjected on HVDC power cables at two modes load and no load, these voltages are contained of two main formulas, the first one is the lightning impulse produced form lightning strokes and these are either, positive or negative, and the second one is the switching surges and these also are either, positive or negative..

Simulation of the positive and negative lightning impulse waveform which are chosen and applied in the present study are given in figure(6) which is shown electrical stresses with conductor radius at positive and negative lightning impulse at no load, by similar method, figure(7) is shown positive and negative lightning impulse at load. The obtained results from the field sketching in figure(6) and figure(7) are indicating that the electrical stresses are increased with a large ratio by lightning impulse directly with applied voltage, at both modes (load and no load). Figure(8) shown the electrical stresses at positive and negative switching surges at no load. Similar, figure(9) also shown the electrical stresses at positive and negative

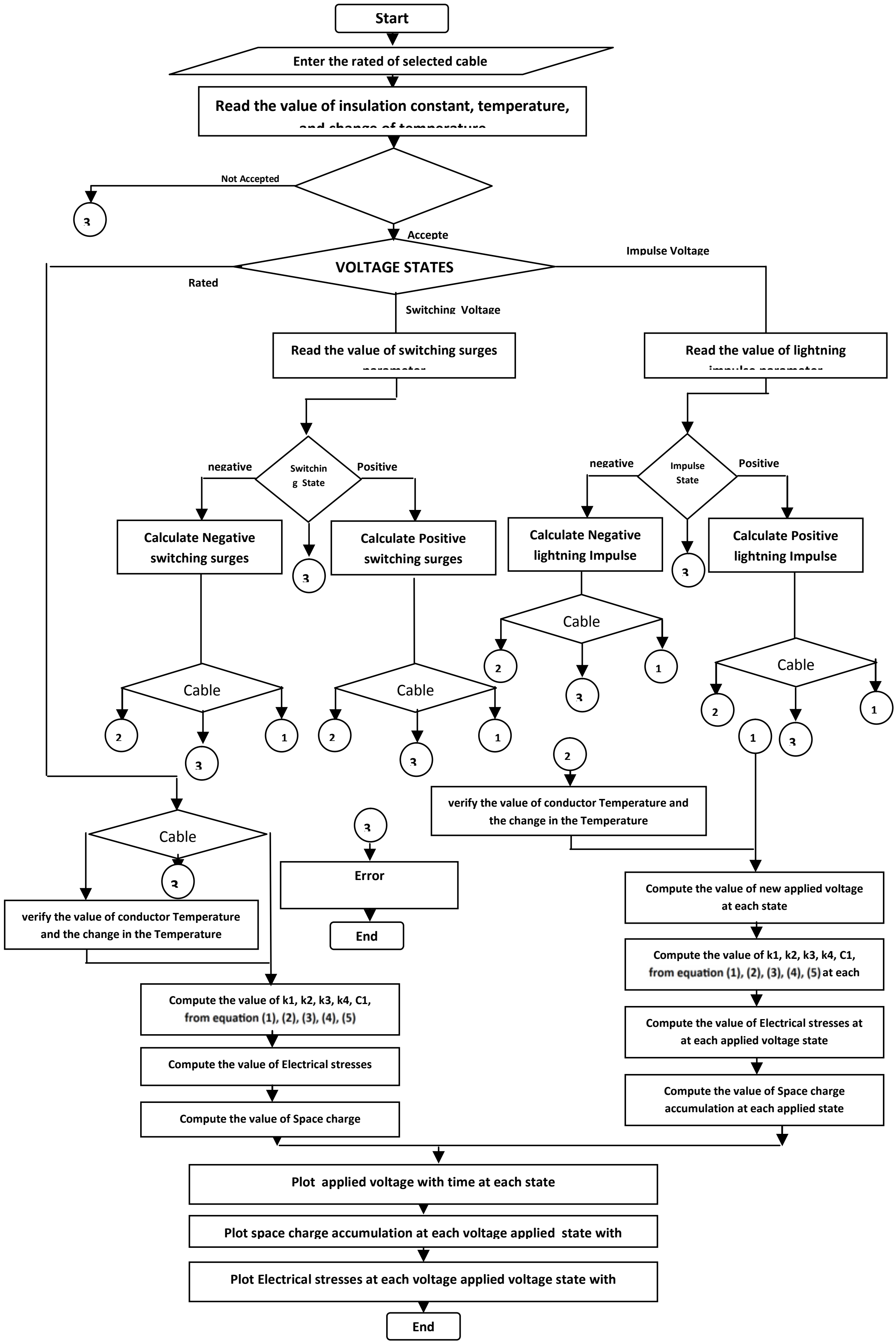
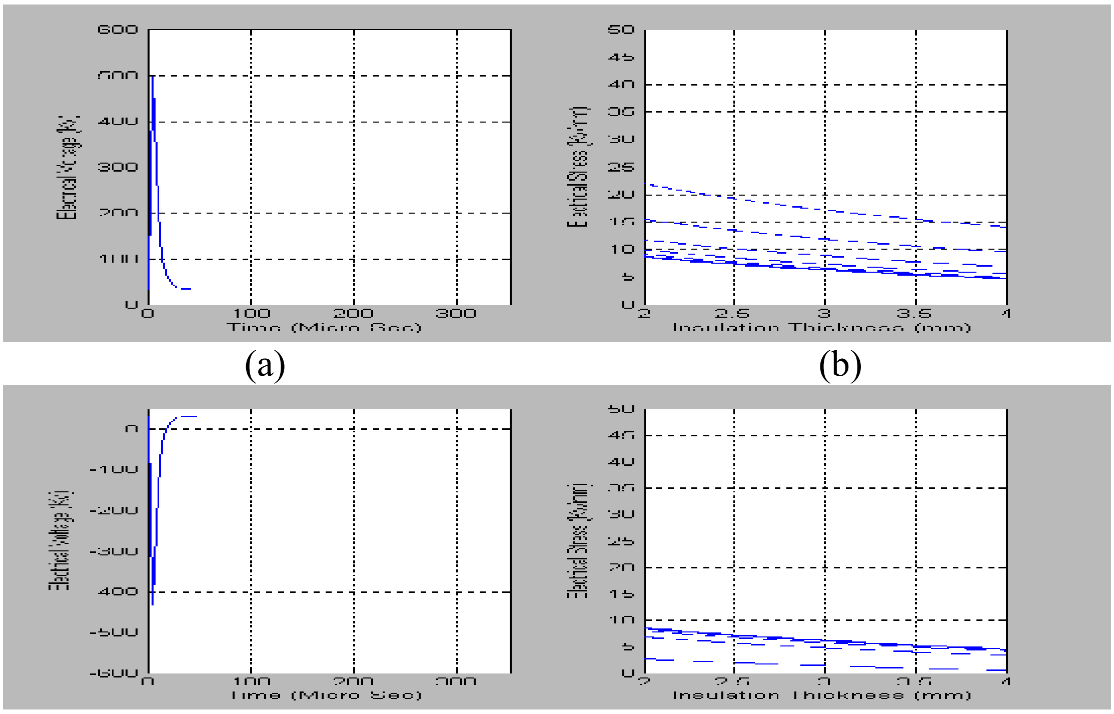

Start
Enter the rated of selected cable
Read the value of insulation constant, temperature,
Not Accepted
Accepte
VOLTAGE STATES
Rated
Impulse Voltage
Switching Voltage
Read the value of switching surges
Read the value of lightning
negative
Switchin g State
Positive
negative
Impulse State
Positive
Calculate Negative switching surges
Calculate Positive switching surges
Calculate Negative lightning Impulse
Calculate Positive lightning Impulse
Cable
verify the value of conductor Temperature and the change in the Temperature
Error
End
Compute the value of new applied voltage at each state
Compute the value of k1, k2, k3, k4, C1, from equation (1), (2), (3), (4), (5) at each
Compute the value of Electrical stresses at at each applied voltage state
Compute the value of Space charge accumulation at each applied state
verify the value of conductor Temperature and the change in the Temperature
Compute the value of k1, k2, k3, k4, C1, from equation (1), (2), (3), (4), (5)
Compute the value of Electrical stresses
Compute the value of Space charge
Plot applied voltage with time at each state
Plot space charge accumulation at each voltage applied state with
Plot Electrical stresses at each voltage applied voltage state with
End

Figure (5) Flowchart of the designed program



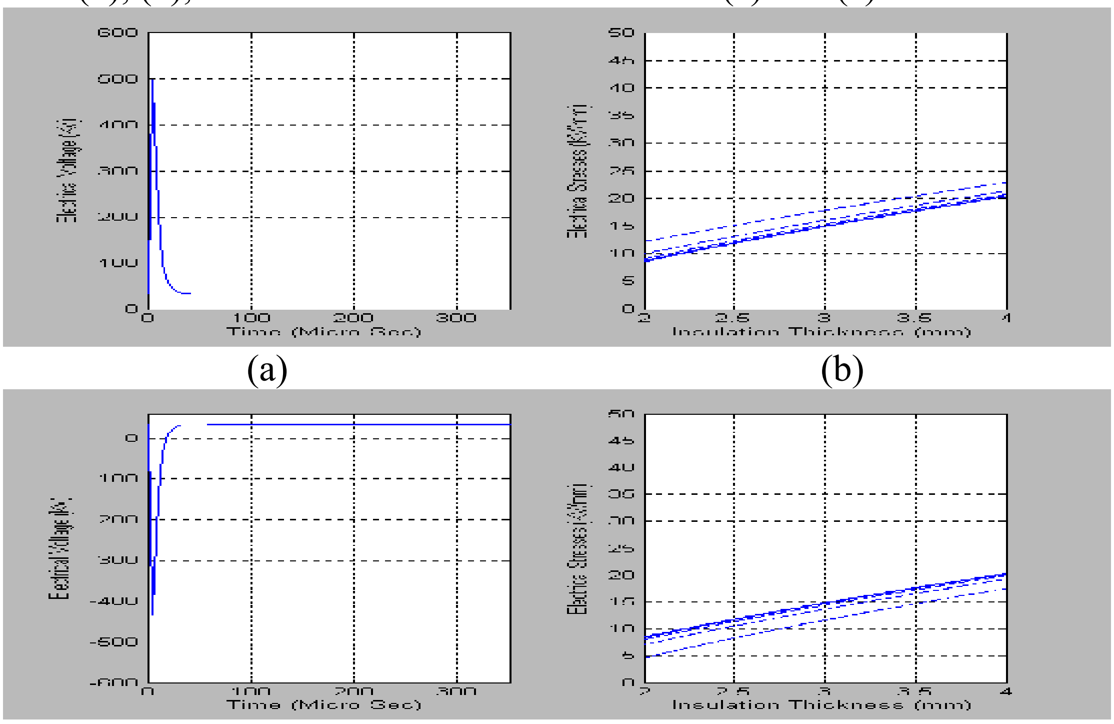
(a) (b)

(c) (d)

Figure (6)

a) Pos. Imp., (c) Neg. Imp., are waveforms of the imposed lightning impulse voltages

(b), (d), are the electrical stresses for cases (a) and (c) at no load



(a) (b)

(c) (d)

Figure (7)

a) Pos. Imp., (c) Neg. Imp., are waveforms of the imposed lightning impulse voltages

(b), (d), are the electrical stresses for cases (a) and (c) at load

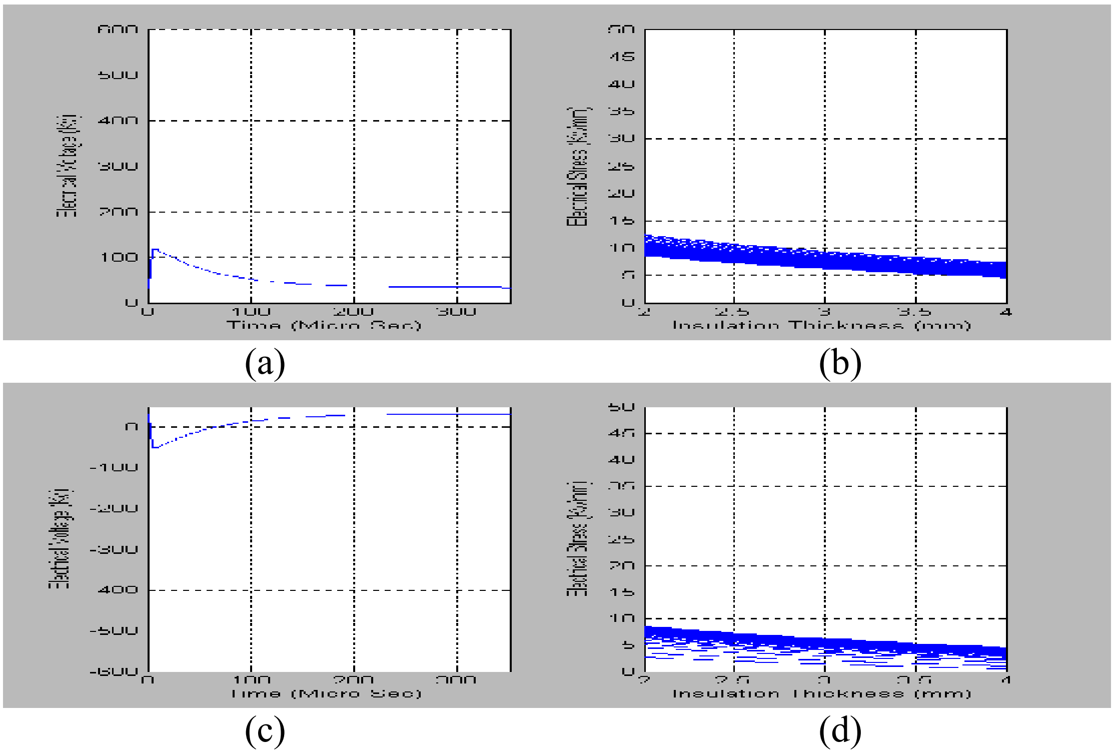


Figure (8)

(a) Pos. Sw., (c) Neg. Sw., are waveforms of the imposed switching surges voltages

(b), (d), are the electrical stresses for cases (a) and (c) at no load

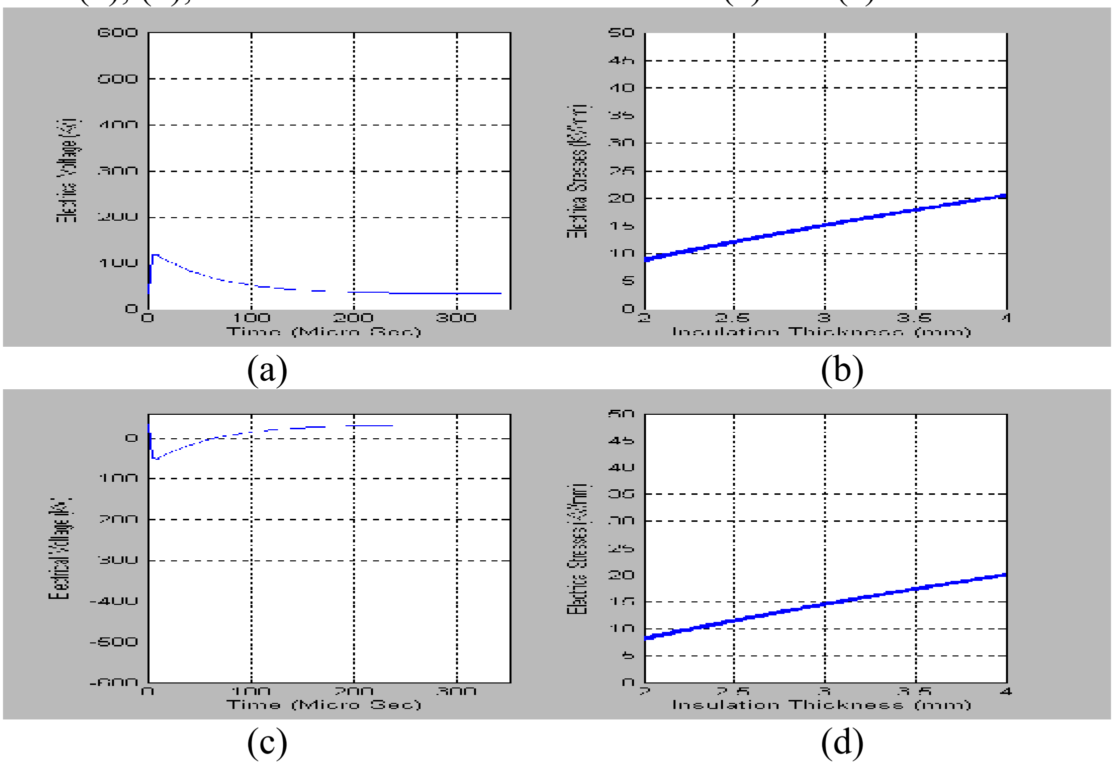


Figure (9)

(a) Pos. Sw., (c) Neg. Sw., are waveforms of the imposed switching surges voltages

(b), (d), are the electrical stresses for cases (a) and (c) at load

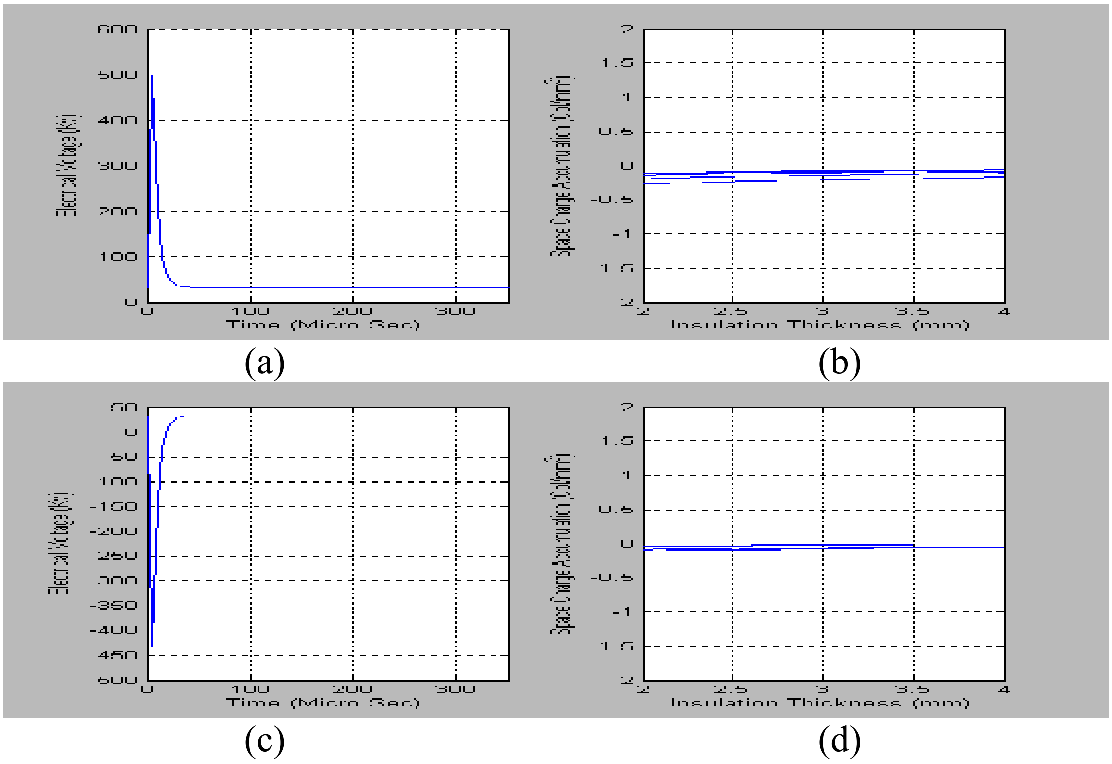


Figure (10)

a) Pos. Imp., (c) Neg. Imp., are waveforms of the imposed lightning impulse voltages

(b), (d), are the space charges accumulation for cases (a) and (c) at no load

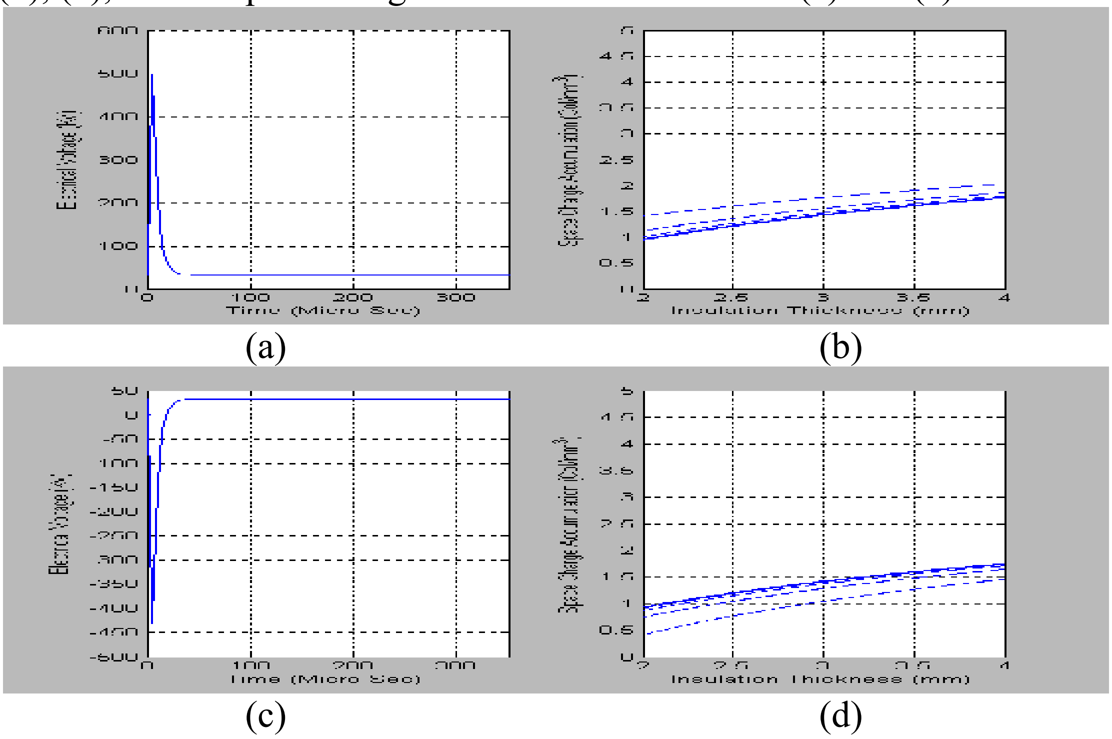


Figure (11)

a) Pos. Imp., (c) Neg. Imp., are waveforms of the imposed lightning impulse voltages

(b), (d), are the space charges accumulation for cases (a) and (c) at load

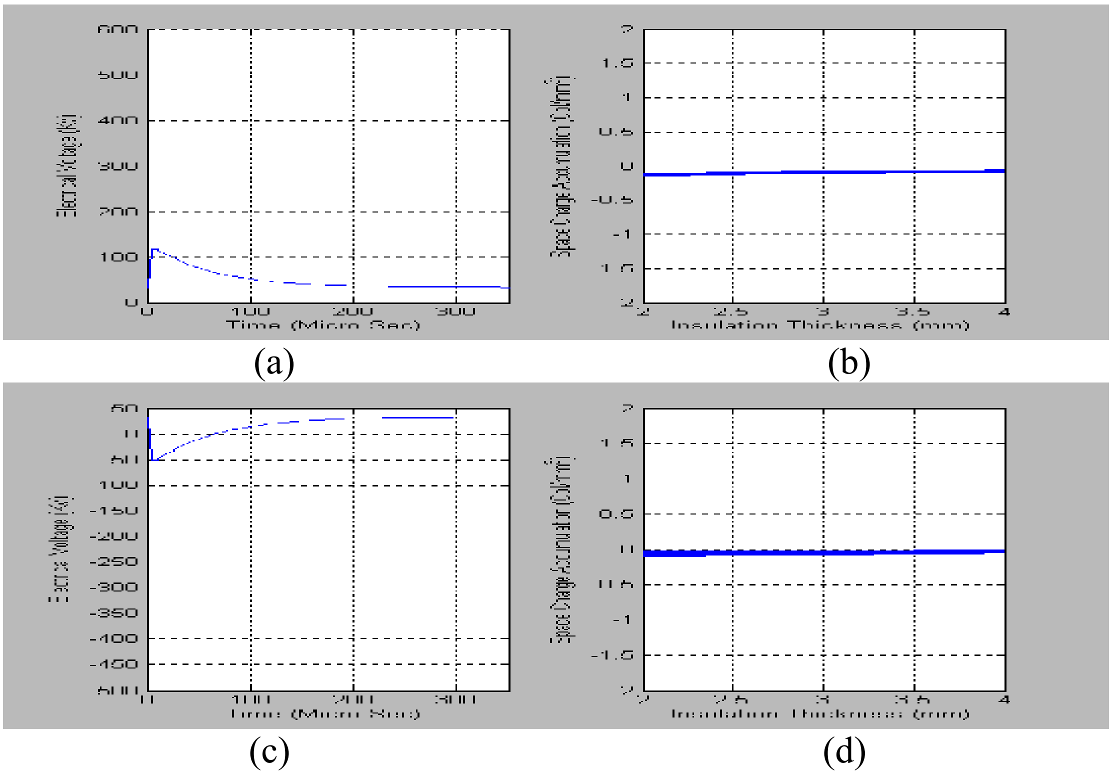


Figure (12)
(a) Pos. Sw., (c) Neg. Sw., are waveforms of the imposed switching surges voltages
(b), (d), are the space charges accumulation for cases (a) and (c) at no load

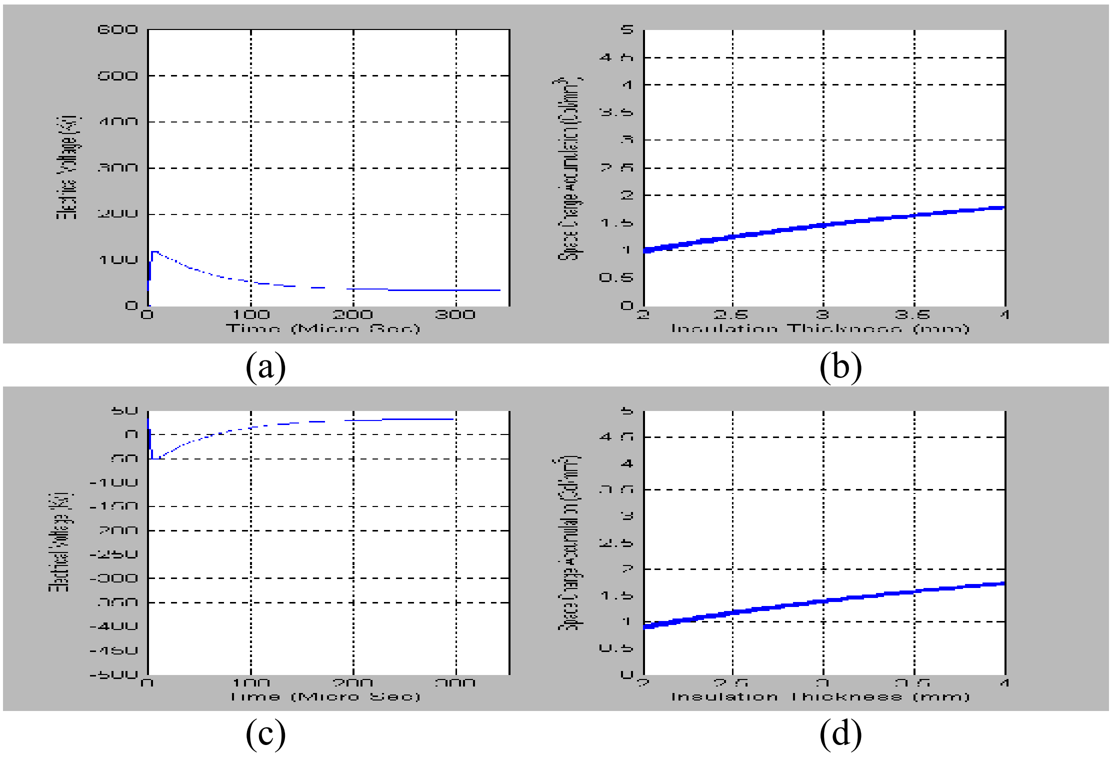


Figure (13)
(a) Pos. Sw., (c) Neg. Sw., are waveforms of the imposed switching surges

voltages

(b), (d), are the space charges accumulation for cases (a) and (c) at load

switching surges but at load. The last figures are indicating that the electrical stresses are increased with small ratio with switching surges at both two modes (load and no load), when it's comparison with the results of lightning impulse which are shown in figure(6) and figure(7).

The obtained results are given in figure (10) which shown space charge accumulation at positive and negative lightning impulse at no load. Similar, figure (11) shown space charge accumulation at positive and negative lightning impulse at load. Both results are indicating that space charge accumulation are changed in small ratio with changed applied voltage. But the results also indicated that space charges accumulation are changed in large ratio with the mode of the cable (load and no load), because the changed in the temperature of the cable.

In additional, figure(12) and figure(13) shown the relationship between positive and negative switching surges with space charges accumulation at no load and load respectively. And both last figures are indicating that space charges accumulation are effected with the mode of cable (load and no load), because the changed in temperature of the cable at each mode.

The comparison between the results of electrical stresses and spaces charges accumulation at lightning impulse, at load and no load, with the results of electrical stresses and spaces charges accumulation at switching surges, also at load and no load, are indicated that the effected of lightning impulse on electrical stresses of HVDC are more than the effected of switching surges on the electrical stresses for the same insulation of cable. And the values of space charge accumulation is mainly depended on the temperature of the cable at imposed over voltages on the insulation of the cable.

Finally all results are shown in the above figures contained two sketches, the first one is the chosen over voltage (applied voltage) which is imposed on the cable for two modes (positive or negative). And the second one is the effected of the given imposed over voltages on the either electrical stresses or space charges accumulation, at load and at no load.

Conclusion:

Electrical stresses which are imposed on the insulation of the high voltage direct current cables are mainly effected on cables behavior because these stresses concentration are changed according to the types of over voltages, which are either lightning impulses or switching surges at positive and negative polarity, and also at load and no load, as shown in the above results, the electrical stresses at lightning impulses may be reached to the double or more than of the value at rated voltage, so that this increasing in electrical stresses is effected deeply on insulation behavior, but in case of switching surges this increasing is limited, so that the effect of electrical stresses at switching surges is also limited.

The values of space charges accumulation are changed according to the mode of cables (load or no load) because at each mode, the values of temperature are changed in the cable, as shown in the Theoretical approach.

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