Stress Distribution In Two Layers Of H.V.D.C Cable Insulation For Cooling Outer Conductor

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Abstract

In DC transmission, Stress inversion is a complex phenomena occurring in 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 new proposed power cable with two insulation layers (XLPE and oil) with forced coolant oil has been analyzed under DC voltage to improve the performance of DC cables.

The new proposed cooling method increase the ampacity of the cable, reducing space charge affection and reducing the radial temperature drop which is in turn causing less variation in DC stress distribution.

Keywords: Cooling, DC Power Cable, Electrical Stress.

توزيع الاجهاد ضمن طبقتين من عازل قابلوات الضغط العالي ذات التيار المستمر ذات التبريد الخارجي للموصل

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الخلاصة

إن تصميم قابلوات نقل الطاقة الكهربائية ذات التيار المستمر تلاقي صعوبة حقيقية بسبب التغير الكبير في توزيع الجهد الكهربائي على العازل. حيث ان توصيلية العازل تتغير اعتمادا على التوزيع الحراري للعازل والذي يؤدي الى تغير توزيع الجهد الكهربائي قطريا. تم في هذا البحث دراسة القابلو المقترح والذي يتكون عازله من طبقتين (XLPE والزيت) حيث يتم ضخ الزيت ليبرّد القابلو.

الطريقة الجديدة المقترحة في تبريد القابلو تزيد من القدرة المنقولة وتقليل تأثير شحنة الفراغ كما تقلل من التدرج الحراري للعازل قطريا والذي بدوره يؤدي إلى تقليل تغير الجهد الكهربائي.

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1. Introduction:

Transmission at high DC voltage diminishes the losses and costs and needs less space compared to AC transmission. This holds for both power lines and cables. HVDC makes it possible to transmit electric power through long cables. It also makes it possible to connect systems with different frequency, synchronicity or voltage.

The calculation of electric fields in an HVDC cable system depends on many factors, like insulation resistivity, stress coefficients of resistivity, temperature coefficients of resistivity, time and voltage shape. Only at a theoretical infinite amount of time, one can talk about a stable resistive DC field [1].

A large number of literatures exist on the theory of the stress distribution in the insulation [2-4]. While the others dealing with the effects of space charge and/or water tree on the stress distribution [5-7].

In this work, a simulation of the HVDC power cable has been built based on the numerical equations, which have been solved and simulated by MATLAB 7.6 based M-File. A new method of internally forced cool has used in HVDC power cables. The oil has used as insulation and coolant, which was in turn, changed the performance of power cable.

2. Construction of New Proposed Cable:

Figure (1) explains the construction of the internal oil cooled outside the conductor. The insulation is constructing of two layers insulation which are oil and XLPE. The oil is forced flow to be a coolant fluid. The electrical stress distributed along coolant oil and XLPE. The conductor fixed by the spacers with aerodynamic shape to reduce its effect on fluid motion.

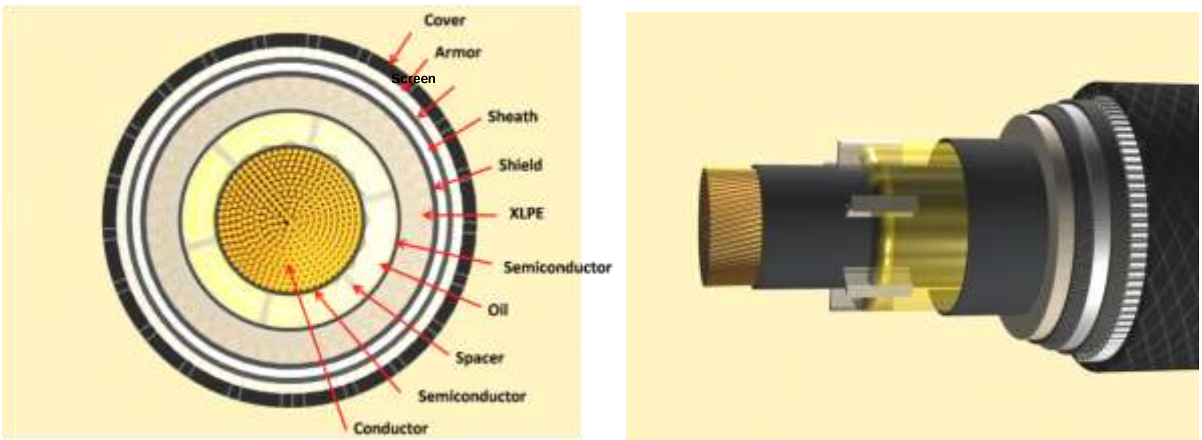

Figure (1): The Construction of Internal Oil Cooled Outside The Conductor.

3. Analysis of the New DC Power Cable:

The analysis for this type of cables is explained as bellow with the following assumptions:

1. Neglecting the effect of the spacers on the coolant oil flow.
2. Neglecting the heat generated from friction flow of the coolant.
3. Neglecting the expansion in coolant oil caused by increasing temperature.

4.1 Laminar and turbulent flow in circular tubes:

Flow in a tube can be laminar or turbulent, depending on the flow conditions. Fluid flow is streamlined and thus laminar at low velocities, but turns turbulent as the velocity increased beyond a critical value. Reynolds discovered that the flow regime depends mainly on the ratio of the inertia forces to viscous forces in the fluid. This ratio is called the Reynolds number, which is a dimensionless quantity. For flow in a circular tube, if Mean fluid velocity $\mathcal{V}_m$ (m/sec), Hydraulic diameter of the tube D_h (m) and Kinematic viscosity of the fluid v_K (m^2/sec) then the Reynolds number $\mathcal{R}e$ is defined as [8]:

$$\mathcal{R}e = \frac{\mathcal{V}_m D_h}{v_K} \qquad \text{... (1)}$$

4.2 Flow through concentric annulus:

The steady axial laminar flow in the annular space between two concentric cylinders has no slip at the inner $(r = r_c)$, outer radius $(r = r_o)$, Flow pressure $\mathcal{P}$ (N/m^2), Gravity g (m/sec^2), Height z (m), Fluid density ξ (kg/m^2) and Dynamic viscosity μ (kg/m.sec).

As shown in Figure (2), the velocity $\mathcal{V}(r)$ of flow is a function of radius and the Reynolds number will have the following expression as follow [9, 10]:

$$\mathcal{V}(r) = \frac{1}{4\mu}\left[-\frac{d}{dx}(\mathcal{P} + \xi g z)\right]\left[r_o^2 - r^2 + \frac{r_o^2 - r_c^2}{\ln\frac{r_c}{r_o}}\ln\frac{r_o}{r}\right] \qquad \text{... (2)}$$

$$\mathcal{R}e_{eff} = \frac{1}{\mathfrak{S}}\mathcal{R}e \qquad \text{... (3)}$$

$$\mathfrak{S} = \frac{(r_o - r_c)^2 (r_o^2 - r_c^2)}{r_o^4 - r_c^4 - (r_o^2 - r_c^2)^2 / \ln\left(\frac{r_o}{r_c}\right)} \qquad \text{... (4)}$$

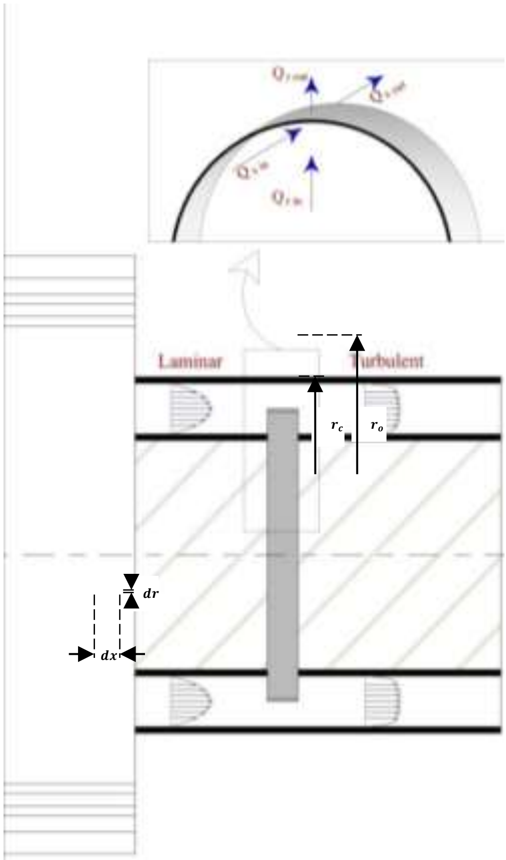

Figure (2): The Free Body Diagram of a Cylindrical Fluid Element of Radius r, Thickness dr, and Length dx Oriented coaxially with a Concentric Annulus Steady Flow.

4.3 Cable losses:

The effective power loss in DC cables is conductor loss while the other losses are negligible. The conductor current I (Amp.) and conductor DC resistance R_{DC} (Ω/m) producing power loss P_{c-loss} (W/m) in conductor as [10]:

$$P_{c-loss} = I^2 R_{DC} \qquad \text{... (5)}$$

4.4 The power equation:

The power equation can obtain by applying the power balance to a differential volume element. Reconsider steady laminar flow of a fluid in a circular tube of radius r_o. The fluid flows along the *x*-axis with velocity $\mathcal{V}$ (m/sec). The flow is fully developed so that $\mathcal{V}$ is independent of x and thus $\mathcal{V} = \mathcal{V}(r)$. Noting that energy is transferred by mass in the *x*-direction, and by conduction in the r-direction, (heat conduction in the *x*-direction is assumed negligible), the steady-flow energy balance for a cylindrical shell element of thickness dr and length dx as shown in Figure (2) can be expressed as [8]:

$$\sum \mathcal{Q}_{in} + P_{loss} = \sum \mathcal{Q}_{out} \quad \text{... (6)}$$

Assuming that heat transferred from x to $x + \Delta x$ and from r to $r + \Delta r$, in addition, insulation loss is negligible ($P_{loss} = 0$) in DC power cables.

$$\mathcal{Q}_x + \mathcal{Q}_r = \mathcal{Q}_{x+\Delta x} + \mathcal{Q}_{r+\Delta r} \quad \text{... (7)}$$

$$\mathcal{Q}_x = \dot{m}\mathcal{C}_p\theta_x \quad , \quad \mathcal{Q}_{x+\Delta x} = \dot{m}\mathcal{C}_p\theta_{x+\Delta x} \quad \text{... (8)}$$

$$\dot{m} = \xi\, \mathcal{V}(r)A_x \quad \text{... (9)}$$

$$\mathcal{Q}_r = \mathcal{K}A_r\frac{\theta_{r-\Delta r} - \theta_r}{\Delta r} \quad , \quad \mathcal{Q}_{r+\Delta r} = \mathcal{K}A_{r+\Delta r}\frac{\theta_r - \theta_{r+\Delta r}}{\Delta r} \quad \text{... (10)}$$

Where $\dot{m}$ is mass flow rate (kg/sec), $\mathcal{C}_p$ is specific heat (W.sec/kg ºC), ξ is fluid density (kg/m^3), A_x is cross sectional area in *x* direction (m^2), $\theta_x, \theta_{x+\Delta x}$ are fluid temperature at x and $x + \Delta x$ respectively (ºC), $\mathcal{K}$ is thermal conductivity of fluid (W/m ºC), $A_r, A_{r+\Delta r}$ are cross sectional area in r direction (m^2) and $\theta_{r-\Delta r}$, θ_r, $\theta_{r+\Delta r}$ are fluid temperature at positions $r - \Delta r$, r and $r + \Delta r$ respectively (ºC). Noting that $\xi, \mathcal{C}_p$ and $\mathcal{K}$ are a function of temperature as shown in Appendix A [11, 12].

4.5 The power equation for turbulent flow:

For turbulent flow, the balance equation applied to shell of thickness equal to coolant oil channel as follows [8]:

$$\mathcal{Q}_x + P_{c-loss} = \mathcal{Q}_{out} + \mathcal{Q}_{x+\Delta x} \quad \text{... (11)}$$

Where $\mathcal{Q}_{out}$ is the heat transferred from Oil to XLPE.

4.6 Calculation of DC stress distribution:

The general equation used to find the DC electrical stress at any radius point r_x is [1, 13]:

$$\ln E_{r_x} + \beta E_{r_x} + Y = 0 \quad \text{... (12)}$$

$$Y = \ln\frac{r_x}{r_c E_{r_c}} + \alpha\left(\theta_{r_x} - \theta_{r_c}\right) - \beta E_{r_c} \quad \text{... (13)}$$

Where E_{r_x} is electrical stress at radius r_x (kV/mm), E_{r_c} is electrical stress at conductor radius r_c (kV/mm), θ_{r_c} is insulation temperature at conductor radius r_c (°C), θ_{r_x} is insulation temperature at radius r_x (°C), α is temperature coefficient of electrical conductivity (1/°C) and β is stress coefficient of electrical conductivity (mm/kV).

In the case of polarity reverse or transient surges the stress distribution has two components, the first one is the stress calculated from the previous condition (before polarity reverse or switching surge). The second component is the stress caused by transient from polarity reverse, which is calculated as the AC stress distribution.

4.7 Flowchart of the DC power cable programs:

The program produce the results of the cable analysis for certain parameters (voltage, cooling method, oil velocity, cable dimensions … etc) to determine

the temperature distribution, suitable length of cooling section and stress distribution. Figure (3) explains the Flowchart of the program.

4. Results of Simulation:

The parameters of the new proposed power cable are given in Appendix B.

5.1 The temperature distributions

The conductor temperature variations versus distance for both laminar and turbulent flow when conductor current equal 3.3 kA are shown in Figure (4). The total heat generated in DC power cables is represented by conductor loss.

The other losses are very small and could be neglected. The total heat generated in DC power cable, the heat dissipated to cooling oil and the total heat dissipated to ambient

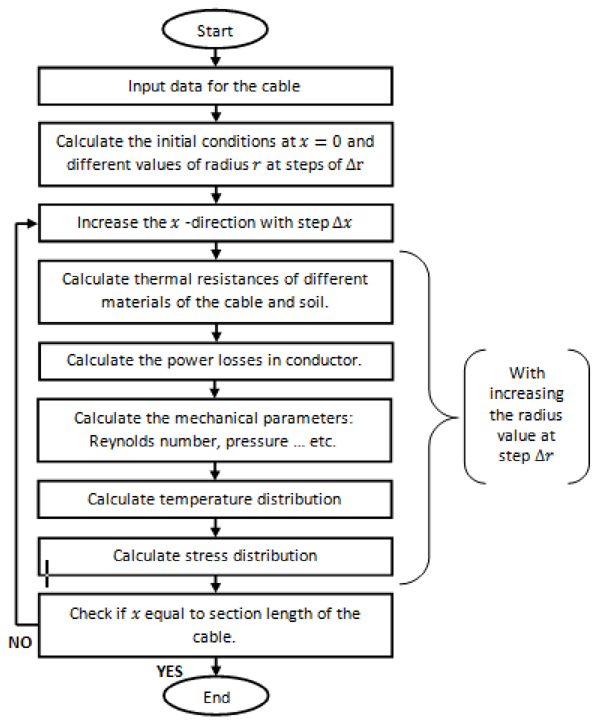

Figure (3): Flowchart for DC power Cable Analysis Program

versus distance for laminar flow (dark lines) and turbulent flow (light lines) are shown in Figure (5).

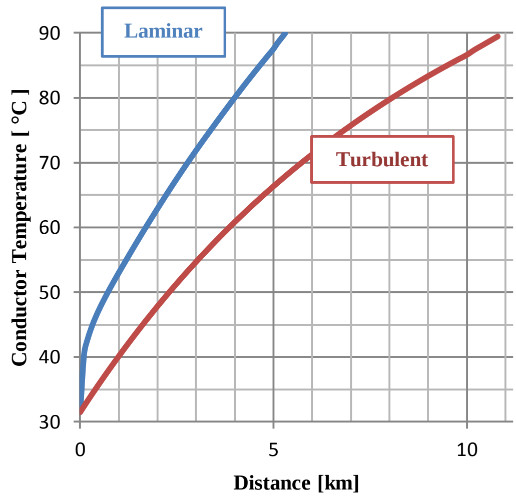

Figure (4): The Increasing in Conductor Temperature versus Distance for 500 kV 3320 A DC Power Cable

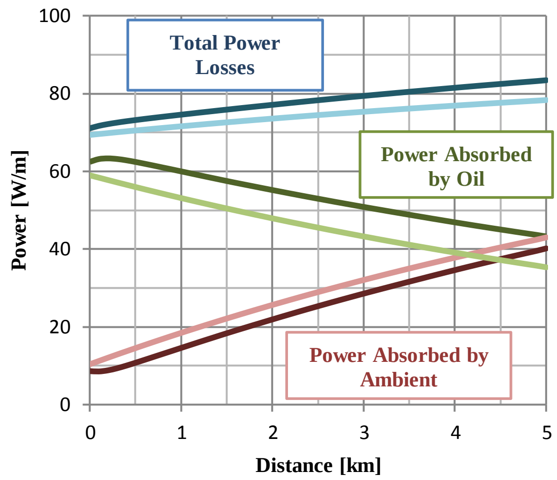

Figure (5): The Division of Heat Generated in 500 kV DC Power Cable between Ambient and Cooling Oil versus Distance.

The radial temperature distribution at different distances for laminar and turbulent flow are shown in Figures (6) and (7) respectively at conductor current equal 3320 A.

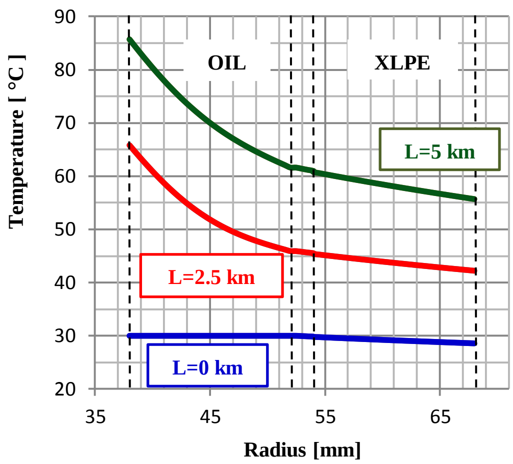

Figure (6): The Temperature Distribution versus Radius for Laminar Flow 500 kV, 3320 A DC Power Cable.

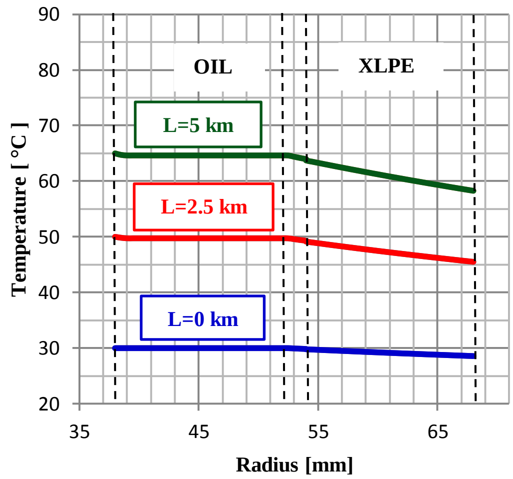

Figure (7): The Temperature Distribution versus Radius for Turbulent Flow 500 kV, 3320 A DC Power Cable.

5.2 Conductor current and cooling section length:

The DC power cable can loaded by high current causing shorter cooling section length as shown in Figure (8). The radial temperature distribution at the end of cooling section (conductor temperature equal 90 °C) for high conductor currents, laminar and turbulent flow are shown in Figures (9) and (10) respectively. The radial heat flow has one direction in DC power cable even in high currents which is from conductor to oil and then to ambient.

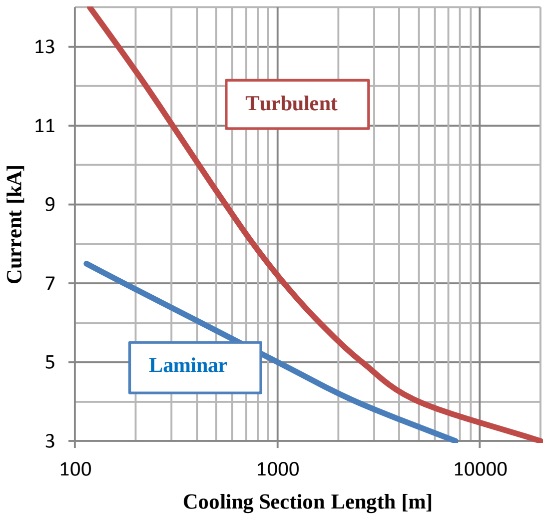

Figure (8): Cable Current versus Cooling Section Length for 500 kV DC Power Cable

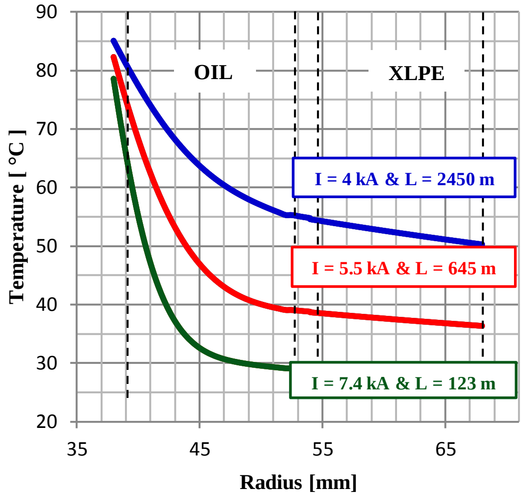

Figure (9): The Radial Temperature Distribution at the End of Cooling Section for 500 kV DC Power Cable, Laminar Flow and Different Conductor Current.

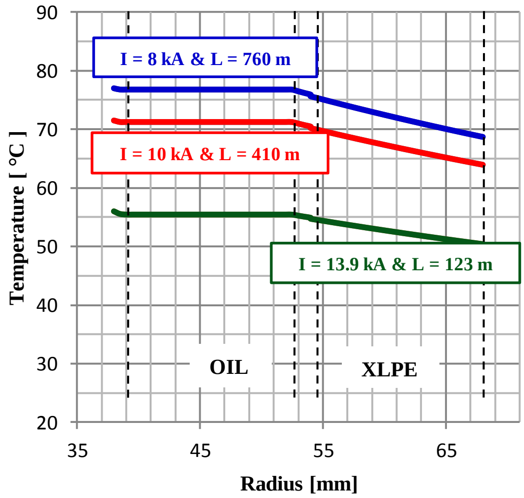

Figure (10): The Radial Temperature Distribution at the End of Cooling Section for 500 kV DC Power Cable, Turbulent Flow and Different Conductor Current.

5.3 Electric stress distribution:

The performances of new design DC power cable when the coolant oil flow is turbulent, better than it when flow is laminar. Thus, the DC electrical stress distribution will be studied for turbulent flow.

When the DC voltage applied suddenly to insulation, the electric stress distributes **immediately under AC stress conditions. After few hours of transient, the electrical stress converted to distribute gradually under the conditions of insulation conductivity (depending on the electrical stress and temperature distributions). This is meaning that**

the DC electric stress has transient period which about 24 hours [2]. The coolant oil passing through the power cable within approximately 1.5 hours, thus the coolant oil will not reach the case of stress distribution depending on insulation conductivity. Figure (11) explains the steady state electric stress distribution versus radius at different distances of cooling section +500 kV 4010 A (full load) turbulent flow DC power cable and 5 km cooling section length.

Figure (12) shows the steady state electrical stress for +500 kV 4010 A at full load and no load turbulent flow two layers insulation (oil and XLPE) DC power cable at the end of cooling section, in addition, the Figure shows the steady state electrical stress for +500 kV 2700 A for XLPE insulation at full load and no load. It can be seen that the difference between the no load and full load steady state electrical stresses is 5.56 kV/mm at the conductor and 4.72 kV/mm at the sheath for XLPE insulation DC power cable, while the difference is 2.53 kV/mm at the coolant oil and 2.17 kV/mm at the sheath for two layers insulation (oil and XLPE) DC power cable.

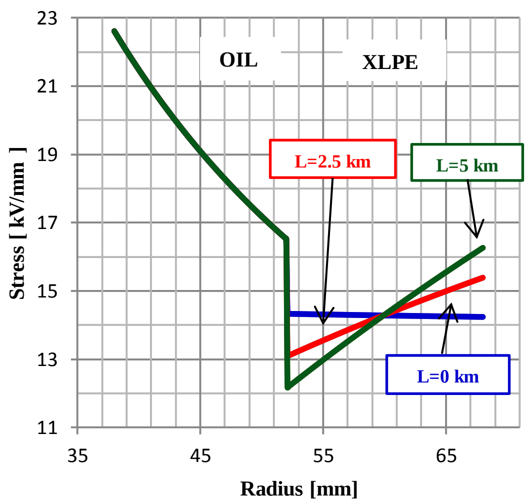

Figure (11): The Steady State Electric Stress Distribution versus Radius at Different Distances of Cooling Section +500 kV 4010 A Turbulent Flow DC Power Cable.

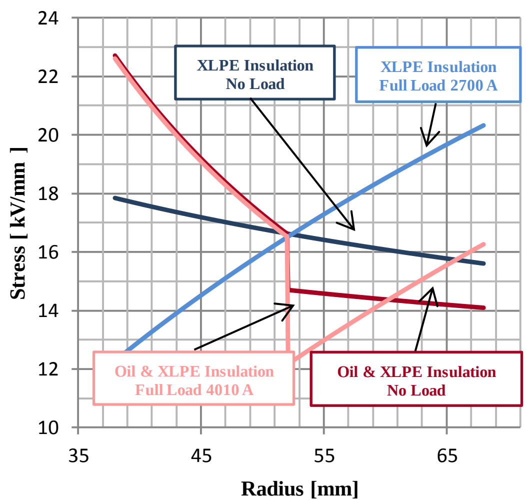

Figure (12): The Steady State Electrica Stress for +500 kV 4010 A Turbulent Flow Two Layers Insulation (Oil and XLPE) at the end of cooling section and +500 kV 2700 A XLPE Insulation at Full Load and No Load DC Power

The stress distribution at the moment immediately follows a polarity reverse has two component, the first one is the stress distribution before the change in voltage which is depending on the insulation conductivity, the second component is the stress distribution depending on the permittivity of the insulation. The coolant oil has no stress distribution depending on the insulation conductivity thus, it has one component. Figures (13) and (14) explain the electric stress distributions before and after reverse polarity for both XLPE insulation and two layers insulation (oil and XLPE) at the end of cooling section for +500 kV no load and full load respectively. In addition, the Figures show the electric stress differences between electric stress before and after polarity reverse for no load and full load. It is clear from the Figures that the electric stress difference in case of two layers insulation (oil and XLPE) is always lower than it in XLPE insulation.

5.4 Space charge:

The low charge carrier mobility and charge trapping within the polymer give rise to space charge, resulting in localized electric stress enhancement. This is particularly true in the case where XLPE is used as DC power cable insulation [6]. The space charge accumulation increased due to the temperature gradient and charge injection from the electrodes. The space charge under isothermal conditions less accumulates in the insulation bulk if compared to the situation in which the temperature drop is applied [5].

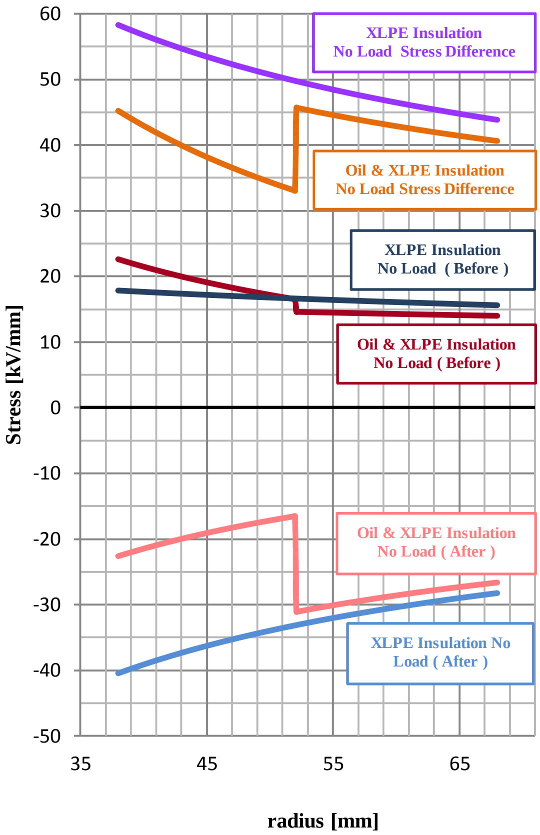

Figure (13): The Electric Stress Distribution Before and After Reverse Polarity and The Difference Between Them for both XLPE Insulation and Two Layer Insulation (Oil and XLPE) at the end of cooling section for 500 kV No Load DC Power Cables.

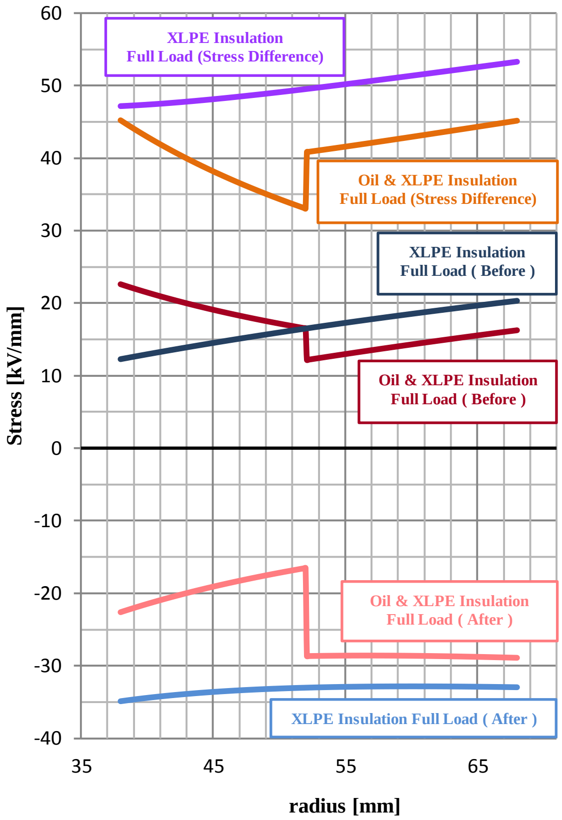

Figure (14): The Electric Stress Distribution Before and After Reverse Polarity and The Difference Between Them for both XLPE Insulation and Two Layer Insulation (Oil and XLPE) at the end of cooling section for 500 kV Full Load DC Power Cables.

The new design (two layers insulation) DC power cable has temperature drop across XLPE insulation (equal to 9.21 °C at the end of cooling section) less than conventional XLPE insulation (equal to 17.86 °C) DC power cables at full load as shown in Figure (15). This is producing less space charge accumulation in new design DC power cable. In addition, the relative high speed of the coolant oil (comparing with the time of space charge mobility) leads to swipe space charge out the cable.

The use of semiconductor layers outside the XLPE insulation can reduce the space charge accumulation in the XLPE insulation. Charge accumulation in coolant oil can be dissipated at each cooling station.

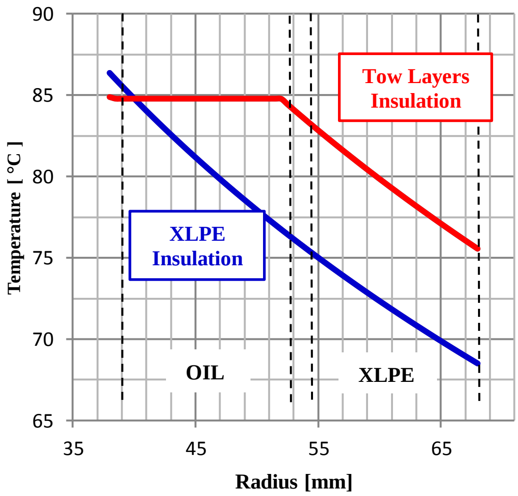

Figure (15): The Temperature Drop versus Radius for 500 kV 4010 A Turbulent Flow Two Layers Insulation (Oil and XLPE) and 500 kV 2700 A XLPE Insulation at Full Load DC Power Cable.

5. Conclusions:

A two layers insulation of high voltage DC power cable has been proposed and studied in the present work. The conclusions could be outlined as follows:

- The rate of conductor current increase in new proposed design to the conductor current in conventional XLPE power cable is up to 148.5 % for ± 500 kV when cooling section length equal 5 km.
- The turbulent flow of the coolant oil increase conductor current capacity to about 120.8 % of laminar flow conductor current.
- In the new proposed design, the coolant oil has AC stress distribution (depending on permittivity) while XLPE has DC stress distribution (depending on conductivity). This is producing the following benefits:

1. The maximum difference of XLPE steady state stress in new proposed design between no load and full load is 45.4 % of the maximum difference in XLPE conventional DC power cable.
2. The maximum difference between the XLPE electrical stresses before and after reverse polarity in new proposed design are 78.38 % and 84.75 % at no load and full load respectively, of the maximum difference in XLPE stresses of conventional DC power cable.
3. The maximum XLPE steady state electrical stress in new proposed design is about 80 % of the maximum steady state electrical stress in conventional XLPE DC power cable. This is reducing the expected space charge accumulation in new proposed power cable.

- The new proposed design has radial temperature drop across cable insulation (at the end of cooling section) equal to 51.57 % of the radial temperature drop in conventional XLPE DC power cable at full load. Less temperature drop across insulation is meaning reduction in space charge accumulation in DC power cable.

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Appendix A: Oil Parameters [12, 13]

Temperature θ [°C]	Density ξ [kg/m^3]	Specific Heat C_p [W.sec/kg °C]	Thermal Conductivity ρ_{th} [W/m °C]	$\tan\delta$	Kinematic Viscosity υ_K e^{-6} [m^2/sec]	Relative Permittivity ϵ_r
20	881.5	1847.5	0.1314	0.0002	35	2.3
30	876	1890	0.13065	0.0003	22	2.28
40	870	1930	0.1299	0.00045	14.1	2.25
50	864	1973	0.1291	0.0007	9.6	2.2
60	858	2017	0.12835	0.001	7.2	2.15
70	852	2060	0.1276	0.0014	5.4	2.1
80	846.5	2100	0.1268	0.0018	4.22	2.05
90	841	2140	0.12604	0.0023	3.52	2
100	835	2180	0.12534	0.0029	3	2

Appendix B: DC Power Cable Parameters

Cable Parameters	Values
Cable Voltage (kV)	± 500
Conductor Current I (A)	4010
Coolant Oil thickness (m)	$14e^{-3}$
XLPE thickness (m)	$14e^{-3}$
Outer radius of Cable r_{out} (m)	$81e^{-3}$
Distance between Cables [$2r_{out} + 0.07$] (m)	0.232
Conductor DC resistance (Ω/m)	$6e^{-6}$
Sheath Thickness t_{sh} (m)	$4e^{-3}$
Conductor radius r_c (m)	$36e^{-3}$
Semiconductor thickness (m)	$2e^{-3}$
Covering thickness (m)	$7e^{-3}$
Main Coolant oil velocity (m/sec)	1
Temperature of coolant oil input to cable (°C)	30
Soil temperature (°C)	20
XLPE thermal resistivity (°C.m/W)	3.5
Cover thermal resistivity (°C.m/W)	2.5
Soil thermal resistivity (°C.m/W)	1
Depth of cable laying (m)	1
Convection heat transfer coefficient for coolant oil h_{oil} (W/m^2.C)	11130
Stress coefficient of electrical conductivity β_{XLPE} (mm/V)	$0.2e^{-3}$
Temperature coefficient α_{XLPE} of electrical conductivity (1/°C)	0.15

The work was carried out at the college of Engineering. University of Mosul