Investigation on partial discharge activities in cross-linked polyethene power cable using finite element analysis

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Abstract: The nationwide usage of cross-linked polyethylene (XLPE) for medium to high voltage distribution networks are practically common due to its excellent electrical, thermal and mechanical properties and widely installed through existing network of cable line in Malaysia. However, cable exposures to harsh climates coupled with inadvertent damage throughout installation or transportation are influencing the presence of voids inside the insulation leading to the initiation of partial discharges (PD) in the cable line. Therefore, this study is important to investigate the activities of PD due to the manifestation of voids in XLPE cable and how it affects the physical, electrical and mechanical characteristics of the cable. Analysis has been performed using Finite Element Analysis (FEA) tool to simulate the PD activities in a 2D model of a three (3) core-XLPE insulated armoured sheathed cable (500 mm², 11 kV) with several placements of voids. The varied placement and radius of voids is very crucial in order to achieve comprehensive analysis. From the obtained result, it has been established that closest the void to the core yielded higher electric field potential. Additionally, it is verified from the simulation that the larger the size of void, the higher the electric field potential consequently increasing the current density inside the void. This simulation and analysis is quite important to provide better insight pertaining to the behaviour of PD in correspond to the presence of voids which will accelerate ageing failure in insulation framework of the XLPE cable.

1. Introduction

Polyethylene (PE) has a decent electrical properties and furthermore having a low dielectric misfortune factor, which at that point gives a more extensive edge at a lot higher voltages than utilizing PVC links. Cross-linked polyethylene (XLPE) link has a lightweight structure, simple to twist, great electrical properties, heat obstruction, high transmission limit, simple to introduce and a lot more advantages[1]—[3]. The issue notwithstanding, XLPE is a thermoplastic material, which implies that its applications are restricted by warm limitations. Other than that, for a long haul use of XLPE link, it appears that XLPE link will have all the earmarks of being protection maturing in a long running procedure because of the momentum stream, water, heat, mechanical pressure and ecological components, which can result in halfway imperfections that can prompt the weakening of the link's state[1], [4]—[7]. In order to lessen the link's abrupt protection blames, it is fundamental to assess the link state occasionally. The investigations demonstrate that the dielectric misfortune digression and halfway release are two indispensable file of assessing material's protecting properties and they likewise mirror the protection province of XLPE link. At present, a lot of research has focused on the link dielectric misfortune and halfway release; however a particular expository technique to survey the link state is still need. Along these lines, it is imperative to dissect the condition of the link and furthermore specifically the incomplete release and to discover the exercises of the fractional release so as to build up a system to assess and later on keep up the link state[1][8][9]. One of the serious
issue related with the XLPE link is the initiation of fractional releases or PDs [10][11].

Partial discharge (PD) is said to be a localized electrical discharge that not entirely connects the insulation between conduits in accordance to the International Electro-technical Commission (IEC) standard 60270[12]. PD results from local electrical stress concentrations occurred on the surface or on the inside of the insulation which exceeds its critical inception value with duration length of under one second. The PD occurrences which critically seen in high voltage (HV) hardware for instance in the insulation framework, causes an advancement of charge. The charge development will in general lessen the potential between the electrodes until more charge arrives from the supply[4][5][13]–[15].PDs are little releases brought about by solid and assorted electrical fields. The explanation behind such fields could be voids, air pockets, micro-bubbles or imperfections in a protecting material[16]. Early recognition and substitution of a harmed cable line will spare a great deal of superfluous fix costs through attaining proper maintenance schedule for HV cables [17]–[18]. These advantages have driven the PD identification and area methods to turn into a profitable apparatus for condition appraisal of HV systems comprising of cable lines networks [1][4][5][9][13][19]–[20].

Due to the critical importance of PDs early detection it is important to have a comprehensive analysis on XLPE cables in order to fully grasp the understanding of PD activities in reaction of the void parameters such as size of the voids and the locations of each particular void in correspond with current density in each designated area of interest. This paper investigates the electric stress within armored XLPE insulated cable (500 mm$^2$, 11 kV) with the presence of void-defect. The investigation and analysis that has been performed will highlight the electric field potential generated due to voids to provide better insight to activities of PDs in cables.

2. Literature Review
Classifications of partial discharge
Partial discharges fall into three classes [4] depending on their location and mechanism which are internal discharge, surface discharge and the corona discharge. Internal discharge which happens inside the cavities within a solid dielectric material result from high electrical stress across a small void or air gap causing ionization of gas in the void. When the gas or air in cavity is overly stressed, the discharge will occur either in the form of electrical tree or cavity discharge [21].

Corona discharge is a product of non-consistency of electric field on sharp edges of the transmitter. For this sort of discharge, the insulation provided is either fluid, air, or gas where it will appears for lengthy duration around the bare conductor. Corona discharge will not significantly affect the insulation framework since it is just the backhanded action of ozone framed by corona deteriorates insulating materials utilized.

Surface discharge commonly takes place on interfaces of dielectric material or outside the power equipment. Typical occurrences such as in underground cable, overhead lines terminals, bushing or any point on insulator surface between electrodes. Numerous factors contribute to these phenomena including the voltage distribution between the conductors, permittivity of the dielectric material used, or the properties of the insulating medium. Partial discharge produce by leaning trees on MV lines is categorized as surface discharge.

XLPE cable insulation degradation is heavily linked to PD activities as a consequence of the enhancement of electrical field due to the local stress concentrations or low dielectric strength media resulting deterioration of the dielectric materials over time which eventually lead to a complete insulation breakdown. Therefore, PD location and estimation is subsequently vital and important to anticipate the insurance life in HV control hardware[14][22].
Factors affecting the dielectric strength of the XLPE cable

There are a few essentials necessities for the insulating materials utilized for high voltage cable. The primary necessity that should to be taken into account is that the dielectric quality and the insulation resistance of the material ought to be high. The insulating material must also have great mechanical properties. Furthermore, the materials need to withstand the effect of different chemicals. Several factors affecting the dielectric quality of the materials which are spacing between the electrodes, temperature, and the nearness of impurity[23][24].

The capacity of the insulation relies upon its operating temperature. At the point when the temperature is rising, the level of degradation will also rises hence will reduce the lifespan of the insulating materials. Subsequently, temperature has an undesirable impact on the dielectric quality of the insulating material and relies on the sorts of materials utilized in the high voltage control gear. The power hardware operation temperature is in charge of degradation of insulating material utilized. The characteristics of the quality of the material utilized and the temperature at which gear operates is, in this way, conversely proportional.

The breakdown quality of the insulation relies on its electrode shape, width, and the material utilized for insulation. The shape and size of the electrodes are in charge of deciding the volume of medium exposed to high electrical stress. The pollution content particles rises with increases in volumes. A large substance of pollution particles will bring down the breakdown voltage of the space among electrodes and the nearness of contamination has an immediate impact on the insulating material which is utilized on the power hardware. The quality of the dielectric fluid utilized in HV gear decreases to 70% as an outcome of polluting influence substance, for example, metal particles. Contamination incorporates strong particles like cellulose fiber, wax, carbon and acids. In addition, pollution content creates blemishes on the insulation district. The dielectric quality of insulating material which is utilized in power hardware is also affected by different factors, for example the thickness of the example and the dimension of stickiness. The thickness of the example is legitimately proportional to the dielectric quality of the insulating material, where as a surface condition like mugginess is contrarily proportional to the dielectric quality of the material[14].

At the point when a strong or a fluid electrical insulation framework is under high voltage stress, a small segment of the framework may experience a procedure of dielectric breakdown known as partial discharge. The partial discharges inside an insulation framework may or may not traceable, as the discharge occasions will in general have a progressively sporadic character. The impacts of partial discharge inside cables and other high voltage gear can lead to final breakdown and in this manner ought not to be treated lightly. PD can potentially cause difficult issues amongst HV gear. The PD phenomenon usually initiates inside the voids, cracks, in rises inside fluid dielectrics or consideration inside the strong insulating medium. In addition, it also happen at the boundaries between the distinctive insulating materials, poor conduit profiles, contamination and floating metal-work in the gear. The electrical PD detection techniques are based on the form of the partial discharge flow or voltage beat across the test item or large high voltage control apparatus.

3. Method

A software design of three (3) core - XLPE insulated armoured sheathed cable (400 mm², 11 kV) is implemented and test data for simulation is analyzed. This proposed cable design was simulated using Finite Element Analysis (FEM) tool to obtain the electrical properties.

Work flow

In the initial phase, the designs of the XLPE cable were created in two dimensional (2D) in order to better analyze the activities of the surface. The parameters of the cable sizes that being design is abide by the standard cable size obtained from one of the local cable and wire manufacturing company which conform to the . Next, simulation on thermal and electric field has been performed to obtain the activities of the PD. The resulting data will be analyzed in the final phase and further recommendation to minimize the effect of PD activities in such cables will be proposed based on simulation data.
**XLPE Design Model**

**Electrostatic Model**

In a typical cable construction, the electrical field distribution is described by two-dimensional field models. As a base for further analysis, the model is solved for a non-degraded system configuration. Furthermore, in order to investigate the effect of void presence on the XLPE electrical field insulation system, an air-filled void is introduced into the model cable insulation. The mathematical field model for electrical field distribution in the air-filled voids is created in respect of the single-phase XLPE cable field model. The electric field intensity is attained from the negative gradient scalar potential. The relationship equation of $E$ and $V$ is as equation 1:

$$E = -\nabla V$$

The equation of the constitutive relationship between the electric field $E$ and electric displacement $D$ for the insulation material, in terms of the relative permittivity of the insulation and free space, are given in equation 2. The relationship between the electric field $E$ and electric displacement $D$ in the void or free space is given,

$$D = \varepsilon E$$

Relative permittivity of insulation material given as $\varepsilon = \varepsilon_0 \varepsilon_r$, where $\varepsilon_0$ is the permittivity of free space while $\varepsilon_r$ is the relative permittivity of insulation material. $D$ is the electric displacement of the conductor which is directly proportional to the applied voltage to the conductor $D = \varepsilon_0 E$.

The forms of Gauss’ law which involves the free charge and the equation of electric displacement will be represented as; $\nabla \cdot D = \rho_f$, where $\rho_f$ is free charge density. Introducing the free charge as charge density Poisson’s scalar equation is obtained as:

$$-\nabla \cdot (\varepsilon \nabla V) = -\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla V = \rho)$$

Due to the application of cable material which has a constant permittivity, $\varepsilon$ applied, equation 3 becomes:

$$\nabla^2 V = -\frac{\rho}{\varepsilon}$$

The charge density in insulation is neglected due to its small amount as well as in the void due to its small size in comparison to size of the cable insulation. Therefore, the electric field is expressed by Laplace’s equation as:

$$\nabla^2 V = 0$$

The problem is solved regarding the solution of two-dimensional Laplace’s equation:

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = 0$$

Equation 6 will be used to calculate the electric field in the cable insulation and in the air-filled void-defect by using finite element tool in terms of boundary conditions.

**Boundary Conditions**

The boundary condition of the relationship of interfaces between two different medium for electrostatic model is mathematically express as:

$$n \cdot (D_1 - D_2) = \rho_e$$
where, $\rho_s$ is the surface charge and $n \cdot D_1$ and $n \cdot D_2$ are the normal component of electric displacement of any two different medium in the model respectively. When the surface charges of the same insulation materials in the model are neglected, the boundary condition is continuity and surface charge is zero as:

$$n \cdot (D_1 - D_2) = 0$$

(8)

At boundary between two different mediums, the normal component of electric displacement does not equal zero. It is infinite due to change in the permittivity.

$$n \cdot D = \rho_s, \quad n \cdot (D_1 - D_2) = \rho_s$$

(9)

The conditions of $V$ and $E$ are applied continuously.

The electric-potential boundary condition:
Due to the cable application, the applied voltage is sinusoidal. The single-phase potential of XLPE cable is as the following:

$$V_{p\phi l} = V_0 \sin(\omega t)$$

(10)

The ground boundary condition: The sheath boundary potential is equal to zero, $V = 0$.

The continuity boundary condition: The normal component of the electric displacement is applied continuously across the sheath boundary similarly as equation (8).

**FEA Model Design**

Figure 1 shows the 2D cross-section model of three (3) core - XLPE insulated armoured sheathed cable(400 mm², 11 kV) designed via FEM tool. Included in the designed were the placement of six (6) spherical voids with varied radius and positioning from the copper core for simulating the effect of electrical field distribution in order to tabulate the simulation data. The radius and positioning of each void is as shown in Table 1.

![Cross-section layout of three (3) core XLPE insulated armoured sheathed cable](image)

**Table 1. Radius and position of the void**

| Void | Radius (mm) | Position of void (mm) |
|------|-------------|-----------------------|
|      |             | x-axis | y-axis |
| 1    | 0.8         | 1.1    | 63.4   |
| 2    | 0.8         | -5.0   | 60.0   |
| 3    | 0.8         | -44.0  | 38.0   |
| 4    | 1.6         | -29.0  | 22.5   |
| 5    | 1.0         | -47.6  | -47.8  |
| 6    | 0.8         | -23.8  | -66.1  |
4. Simulation Result and Discussion

For the first part of the simulation, the 2D model of three core XLPE insulated armored sheath cable has been designed with their respective material and respective parameters. Next simulation of electrical field has been performed to investigate the electric distribution of the void defects. The electric field distribution within the cable captured during the AC cycle when the conductor potential is at its maximum value is as shown in Figure 2.

Figure 2. Surface electric potential distribution through XLPE cable cross-section at time=0.005s.

Figure 3. A close-up view of surface electric potential due to void defect in one of the core region (varied distance from core).

Figure 3 shows the electric potential stress of XLPE insulation material with the presence of two voids (both are 0.1 mm in radius). The electrical potential is captured when the conductor is at its maximum value (t=0.005 s). Based on the equipotential lines, the concentration of electrical field is higher around one of the void (distance of 12 mm from core) compared to the other one (distance of 18.7 mm from core).

Figure 4. The graph of the electric field distribution of void with varied distance from core (12mm and 18.7 mm)

Based on the graph in Figure 4, the electrical field distribution is lessen when the voids are farther away from the core indicated by the two PD spike occurrences. This simulation demonstrated that the distribution of electrical field have a higher concentration around the vicinity of void much closer to the core based on the perceived equipotential lines and electrical field norm distribution.
Based on Figure 5, the electrical field and equipotential distribution is affected by varied size of spherical voids around the core. The electrical stress is much higher within the void with larger radius (1.6mm) as shown in Figure 5(a) compared to the smaller voids (0.8 mm in radius) based on the observe equipotential lines. The corresponding electrical field distribution is represented in Figure 6 proved that the total magnitude of electrical stress is increase under larger void size based on PD spike occurrence along the arc line of 13.7 mm of arc line compared to the spike resulting from a smaller void 58.6 mm along the arc line.

5. Conclusion

A model of PD activities in a cross section of XLPE cable has been successfully designed using Finite Element Analysis (FEA) tools. A two-dimensional model being used to simulate PD event for two parameter which are void sizes and location of the void from the core. Simulation of discharge occurrences within the void in the presence of non-uniform electric field distribution has been investigated.

Based on the analysis on the electric field distribution, it was found that the distribution of electrical field have a higher concentration around the vicinity of void much closer to the core based on the perceived equipotential lines and electrical field norm distribution. Finally, from measurements under varied void sizes, it was established that the PD occurrences per cycle and total magnitude of charge
per cycle are higher under larger void size due of higher generation rate of electrons in the void. The magnitude of total charge and maximum charge increase as the void radius was increased, which might be due to larger development of the avalanche head within large size of the void. The minimum discharge magnitude does not depend on the void size.

Further studies can be implemented to build upon the this information such as the effect of different void geometry or by using different type of cable or material in order to fully grasp the understanding of PD effect in XLPE cable.

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