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Electric Field Investigation in MV PILC Cables with Void Defect

Mohamed A. Alsharif, Peter A. Wallace, Donald M. Hepburn, Chengke Zhou

Abstract**—**Worldwide, most PILC MV underground cables in use are approaching the end of their design life; hence, failures are likely to increase. This paper studies the electric field and potential distributions within the PILC insulted cable containing common void-defect. The finite element model of the performance of the belted PILC MV underground cable is presented. The variation of the electric field stress within the cable using the Finite Element Method (FEM) is concentrated. The effects of the void-defect within the insulation are given. Outcomes will lead to deeper understanding of the modeling of Paper Insulated Lead Covered (PILC) and electric field response of belted PILC insulted cable containing void defect.

Keywords**—**MV PILC cables, Finite Element Method /COMSOL Multiphysics, Electric Field Stress, Partial Discharge Degradation.

I. Introduction

THE Medium Voltage (MV) PILC cables were almost exclusively used in the middle of the twentieth century. With a typical design life of 40 to 70 years, they are approaching or have exceeded their expected operational life [1], [2]. Operation beyond design specification is expected to result in an increased failure rate. With time, operating stresses both thermal and electrical may fail the cable insulation system due to development of Partial Discharge (PD) activity. PD in cable insulation generally results in a degradation phase that may last several years prior to the final catastrophic failure, which results in loss of supply to customers. A significant cause of underground cable failures is the breakdown of electrical insulation between the conductors due to the internal partial discharge [3]. It is well recognized that, no matter the cause, degradation of insulation systems results in partial discharges being generated at the degradation-site(s). Partial discharges are small electrical discharges produced by local enhancement of the electrical field due to the conditions around the fault. PD in the insulation material of cables, therefore, is most likely to occur at the positions in the cable that have had human intervention in construction, i.e. accessories. As joints and terminations are created on site, and so have most human intervention, most of the progressive degradation occurs there. It is reported that the majority of failures occur at the joints in underground cables [4].

M Alsharif is with Physics Department, Faculty of Arts, Sebha University, Libya (corresponding author: phone: + 21871 2632960; fax: + 218712629201; e-mail: m.charif@yahoo.com).

P. A. Wallace, D. M. Hepburn, and C. Zhou are with School of Engineering and Built Environment, Glasgow Caledonian University, Glasgow, Scotland, UK (e-mail: p.wallace@gcal.ac.uk, d.m.hepburn@gcal.ac.uk, c.zhou@gcal.ac.uk).

The characteristics of the electrical signal produced in PD events (magnitude, pulse shape, repetition rate, etc.) are influenced by the materials and electrical conditions at the degradation site. PD in insulation material is usually caused by inhomogeneous electrical fields around voids, bubbles or defects. A gas-filled void has lower electric permittivity and breakdown strength than those of the original insulation material. PD is initiated when the electric field across the cavity exceeds the gas breakdown strength and an initiating electron is present.

Since PD usually occurs in cable insulation before it breaks down completely, PD monitoring provides a warning to remove the power system component from service before catastrophic failure occurs [5]. PD monitoring is becoming an important part of condition-based maintenance (CBM) among utilities. The work presented here is based on Online PD method which widely known as an efficient tool for detecting insulation defects, assessing and monitoring the insulation of high voltage equipment to prevent its in service failure [6].

This paper investigates the electric stress within the PILC insulated cable containing a void-defect under 3-phase voltage conditions in service. The finite element model of the performance of the PILC MV underground cable containing void-defect is developed using the COMSOL multiphysics.

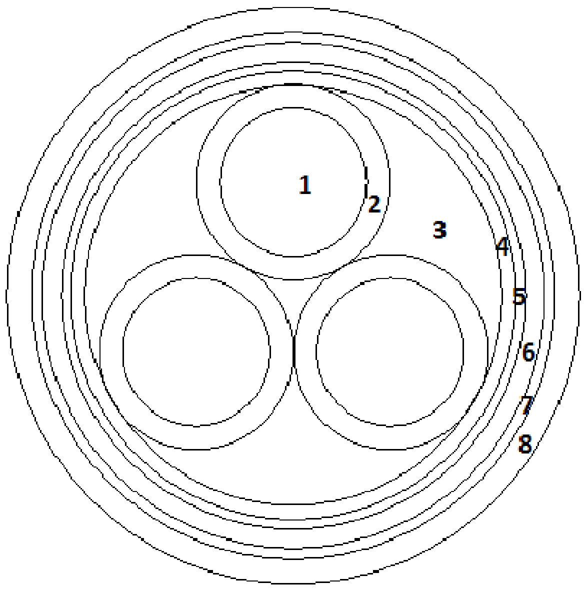

Fig. 1 Typical layout of three-core 240 mm2 PILC cable: (1) copper conductor, (2) mass impregnated paper insulation, (3) Filler, (4) belting insulation, (5) lead sheath, (6) bituminized paper bedding, (7) steel armour, and (8) PVC jacket [7]

Fig. 1 shows the common construction of the three-phase Paper Insulated Lead Covered (PILC) cable type 11 kV. The conductors are made of copper and each is 240 mm^2, the overall diameter of the cable is 67.8 mm. In this type of cable the three conductors are wrapped in oil impregnated paper tape. The three insulated cores are bundled together under another belt of paper insulation and the whole ensemble is covered in a lead sheath which provides a single earth screen for all three phase [7].

II. Electrostatic Model

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

$$E = -\nabla V \tag{1}$$

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 (2). The relationship between the electric field E and electric displacement D in the void or free space is given in (3):

$$D = \varepsilon E \tag{2}$$

where ε is the relative permittivity,

$$\varepsilon = \varepsilon_0 \varepsilon_r$$

ε_r is the relative permittivity of insulation martial; ε_0 is the permittivity of free space; D is the electric displacement of the conductor which is directly proportional to the applied voltage to the conductor.

$$D = \varepsilon_0 E \tag{3}$$

The forms of Gauss' law which involves the free charge and the equation of electric displacement will be represented as;

$$\nabla .\ D = \rho_f \tag{4}$$

where ρ_f is free charge density

By substituting (2) and (4) in (1) and introducing the free charge as charge density Poisson's scalar equation is obtained as:

$$-\nabla \cdot (\varepsilon\ \nabla V) = -\nabla \cdot \left(\varepsilon_0 \varepsilon_r \nabla V\right) = \rho \tag{5}$$

where ρ is the charge density

Due to the application of cable material which has a constant permittivity, ε applied, (5) becomes:

$$\nabla^2\ V = -\ \frac{\rho}{\varepsilon} \tag{6}$$

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 in (7):

$$\nabla^2\ V = 0 \tag{7}$$

The problem is solved regarding the solution of two-dimensional Laplace's equation as in (8):

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = 0 \tag{8}$$

Equation (8) will be used to calculate the electric field in the cable insulation and in the air-filled void-defect by using finite element method in COMSOL software in terms of boundary conditions.

A. Boundary Conditions

The boundary condition of the relationship of interfaces between two different medium for electrostatic model is mathematically express as [8].

$$n.\ (D_1 - D_2) = \rho_s \tag{9}$$

ρ_s is the surface charge; n. D_1 and n. D_2 are the normal component of electric displacement of any two different medium in the model where the surface charges of the same insulation materials in the model are neglected, the boundary condition is continuity and surface charge is zero as:

$$n.\ (D_1 - D_2) = 0 \tag{10}$$

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.

$$n.\ D = \rho_s,\ \ n.\ (D_1 - D_2) = \rho_s \tag{11}$$

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 three-phase potentials of PILC cable are the following:

$$V(t) = V0 \cos(\omega t + 2n\pi/3)\ n = 0, 1,2 \tag{12}$$

The ground boundary condition: The sheath boundary potential is equal to zero.

$$V = 0 \tag{13}$$

The continuity boundary condition: The normal component of the electric displacement is applied continuously across the sheath boundary.

$$n. (D_1 - D_2) = 0 \tag{14}$$

III. Electric Field Response

Fig. 2 shows the electric field and equipotential distribution within the cable at the same point in the AC cycle where the potential of the right hand conductor is at its maximum value. As expected, the maximum electric field value is around the conductor of maximum potential value. The electric field distribution and equipotential distribution around the left-hand phase, and upper phase, are in the same average around each conductor, which is expected due to the symmetry of the cable.

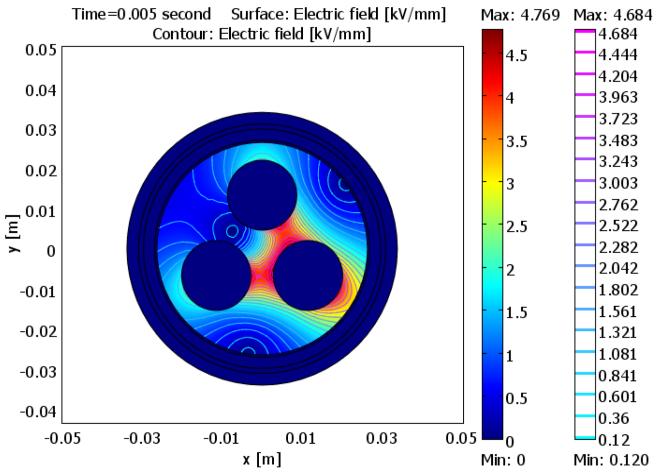

Fig. 2 Electric field and equipotential distribution in PILC cable cross-section

Fig. 3 shows the effect of void-defect of size 1 mm between the upper conductor and ground sheath on electric field distribution at a particular instance where the voltage in the upper conductor is at its maximum value. It shows the distortion of the electric field distribution caused by a void-defect.

In Fig. 4, the dangerously high electric field value of the void-defect in PILC cable insulation cross-section is inside of the defect that is facing the equipotential field distribution and less on other sides. In addition, the highest electric stress occurs across the void-defect from the bottom to top (related to the top of the cable cross-section) where the upper conductor is approximately at its maximum potential value. The PD may occur in PILC cable insulation due to higher electric stress caused by this void-defect.

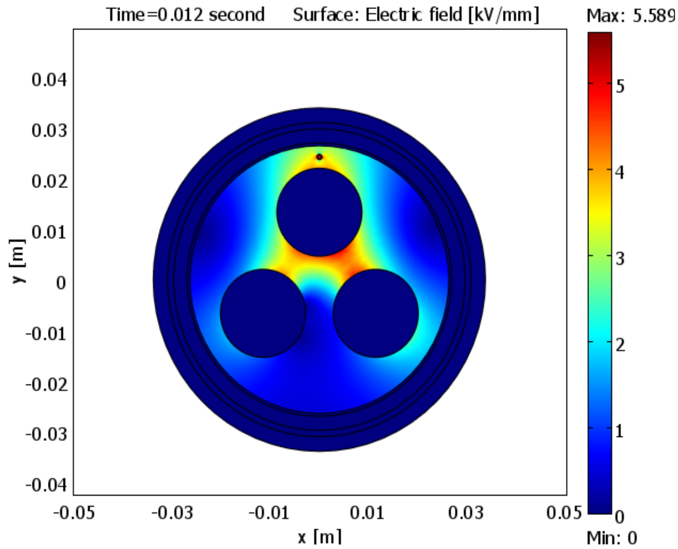

Fig. 3 Effect of void-defect on electric field distribution of PILC cable where upper conductor at its maximum potential value

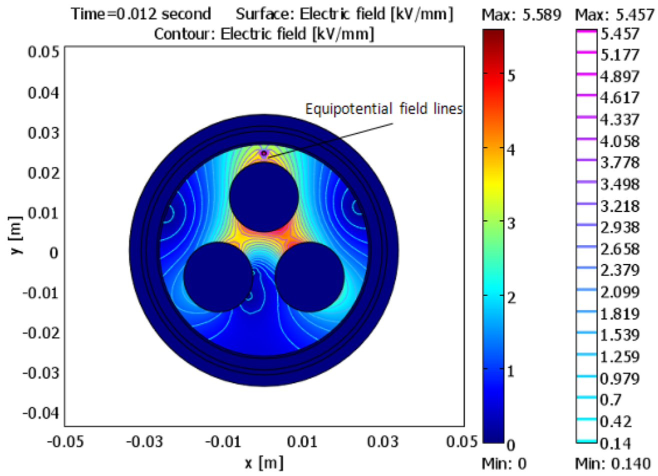

Fig. 4 View effect of void-defect on electric field and equipotential distributions of PILC cable where the upper conductor is at its maximum value

Fig. 5 shows the results of the electric field distribution over the void-defect at a particular instance where the upper conductor is at its maximum potential value.

It was found that the increase of the applied electric stress within the void leads to increase in the discharge void area within the void [9]. The electric field breakdown of an air void of size 1 mm within the insulation material under normal operation working system is about 4.24 kV/mm peak at 1 atmosphere air pressure [10]. When the electric stress in the air-gap exceeds a certain level, the gas cannot sustain the electrical stress and an electron avalanche is generated in the void [11]. Once PD begins, it will erode the insulating materials and cause progressive deterioration.

It can be seen in Fig. 5 that the void-defect electric field is higher than the field of PILC insulation material. The electric field lines are bridging between the surfaces of void that are parallel to the conductor below (upper conductor). The highest amount of electric field stress is 5.6 kV/mm at the bottom of the void-defect. Thus, the electric field void is great enough to produce a PD.

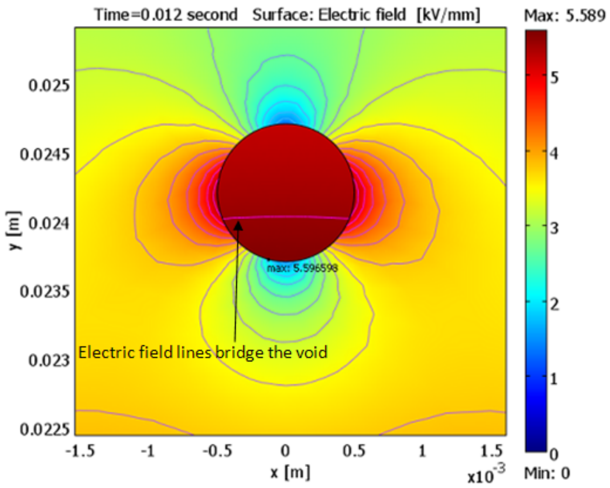

Fig. 5 Electric field distributions over the void-defect in 3-phase 11kV PILC insulation with the highest magnitude of 5.6 kV/mm

IV. Conclusion

A two-dimensional FE model is developed to study the electric field for 3-phase 11 kV PILC cable insulation, continuing air-filled void-defect in COMSOL Multiphysics. The electric field modelling of MV PILC cable containing void-defect under 3-phase voltage condition in service is presented. The electrostatic simulation showed a map of the electric field strength within the PILC cable insulation. The void-defect strongly affect the electrostatic field distribution of 11 kV PILC cable insulation and will affect the electric field stress over that void-defect.

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