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Partial Discharge Activity in PILC Belted Medium Voltage Cable

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Abstract The variation nature of electric field distribution within Medium Voltage (MV) cable insulation results in high sensitivity in Partial Discharge (PD) activity behaviour detection. This paper presented electric field modelling of medium voltage cable containing voids under 3-phase voltage conditions in service. The electric field distribution within a three-phase Paper Insulated Lead Covered (PILC) insulted belted cable containing different void-defect positions is analysed using the COMSOL multiphysics finite element environment. The relationship between the three phase voltages and electric stress amount of different void-defect positions is given. The results will lead to good understanding of PD activity in paper insulated lead covered belted cable.

Keywords: PILC belted cable, Finite Element Method, Electric Field distribution, Partial Discharges.

نشاط التفريغ الجزئي في كابل جهد متوسط ذو عازل ورقي

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الملخص ظروف المجال الكهربائي ضمن عوازل كوابل الجهد المتوسط لها حساسية عالية في الكشف عن سلوك نشاط التفريغ الجزئي. في هذه الورقة، تم تقديم نموذج مجال كهربي للكابل شريطي ارضي ثلاثي الطور معزول بالورق المشبع بالزيت يحتوي على فراغات تحت ظروف التشغيل باستخدام طريقة العناصر المحدودة. حيث تم تحليل توزيع المجال الكهربي داخل الكابل وأعطاء تأثير كل فجوة على نظام العزل. وتم عرض العلاقة بين الفولتية ثلاثية الطور ومقدار الاجهاد الكهربائي لمواضع الفجوات المختلفة. النتائج ستؤدي إلى فهم جيد لنشاط التفريغ الجزئي في الكابل الشريطي المعزول بالورق المشبع بالزيت وطبيعة تباين المجال الكهربائي بهدا الكابل وتأثير الفجوات مختلفة المواضع بة.

الكلمات المفتاحية: الكوابل الشريطية الارضية ثلاثية الطور معزول بالورق المشبع بالزيت، طريقة العناصر المحدودة، توزيع المجال الكهربائي، التفريغ الجزئي الكهربي.

1. Introduction

A significant cause of underground cable failures is the breakdown of electrical insulation between the conductors due to the internal partial discharge activity [1]. Partial discharge is frequently the origin cause of underground cable failure [2]. 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 more than half of underground cable insulation failures are caused by internal defects in particular in the cable accessories [3 and 4]. 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. It should be noted that the combined effect of the different stresses that exist in operating distribution cables, such as mechanical, thermal and electrical stress, will influence the cable insulation life. The combination of the stresses can lead to formation of gas filled voids in the insulation, with temperature being the parameter most likely to affect the aging of the underground cable insulation. 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 a highly

effective prognostic tool for incipient insulation degradation to avoid sudden failures of electrical components and to keep the power network in operation [6]. 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 [7]. It leads to detect incipient faults prior to any detrimental damages [8].
From previously reported investigation of electric field in 3-phase PILC cable under on-line condition [9], it was found that the electric field distribution is complicated and continuously varying over the cable cross-section. In this paper the variation nature of electric field distribution of three phase 11 kV PILC belted cable under three phase voltage conditions in service is studied and the electric stress of void-defect at different positions within PILC insulted cable is analysed. Also, time of maximum electric field over those void-defects is determined.
Figure 1 shows the common construction of the three-phase PILC belted cable type 11 kV. 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.

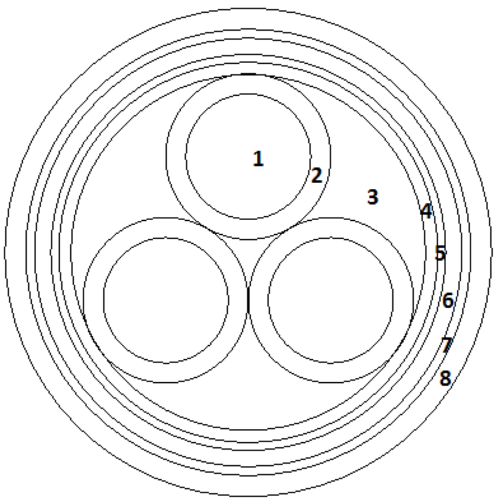

Figure 1. Typical layout of three-core 240mm² PILC cable: (1) copper conductor, (2) mass impregnated paper insulation, (3) Filler, (4) belting insulation, (5) lead sheath, (6) bituminized paper bedding, (7) steel armour, and (8) PVC jacket [9].

2. 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 [9]. The electric field intensity is obtained from the negative gradient scalar potential. The relationship equation of E and V is as follows:

$$E = -\nabla V \quad (1)$$

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

$$D = \varepsilon E \quad (2)$$

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.

$$D = \varepsilon_0 E \quad (3)$$

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

$$\nabla \cdot D = \rho_f \quad (4)$$

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

$$-\nabla \cdot (\varepsilon \nabla V) = -\nabla \cdot (\varepsilon_0 \varepsilon_r \nabla V) = \rho \quad (5)$$

where ρ is the charge density
Due to the application of cable material which has a constant permittivity, ε applied, equation 5 becomes:

$$\nabla^2 V = -\frac{\rho}{\varepsilon} \quad (6)$$

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:

$$\nabla^2 V = 0 \quad (7)$$

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

$$\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} = 0 \quad (8)$$

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.

Boundary conditions:

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

$$n.(D_1 - D_2) = \rho_s \qquad (9)$$

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:

$$n.(D_1 - D_2) = 0 \qquad (10)$$

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.

$$n.D = \rho_s, \; n.(D_1 - D_2) = \rho_s \qquad (11)$$

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:

$$V_{ph1} = V_0 \sin(\omega . t) \qquad (12)$$

$$V_{ph2} = V_0 \sin(\omega .t - 2/3\pi) \qquad (13)$$

$$V_{ph3} = V_0 \sin(\omega .t - 4/3\pi) \qquad (14)$$

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

$$V = 0 \qquad (15)$$

The continuity boundary condition:

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

$$n.(D_1 - D_2) = 0 \qquad (16)$$

2.1 Void Positions

Since, in practice, the existence of spherical void-defect type in insulation material is common [10], air-void in spherical two-dimensional models have been introduced in the PILC cable insulation cross-section.

In this cable of Figure 1, conductor insulation, filler insulation, and belt insulation are made of impregnated paper having the same permittivity 4. In view of this, and to give consideration to the symmetry of cable, the study demonstrates only the list of selected positions of the cable.

The air-filled void defect is located between the ground sheath and conductor position 0, adjacent to a conductor position 1, between the conductors position 3, far away from conductors, positions 2, 4 and 5, respectively, as shown in Figure 2.

Given the symmetry of the cable arrangement, these positions can be related to similar positions around the rest of the region of the cable.

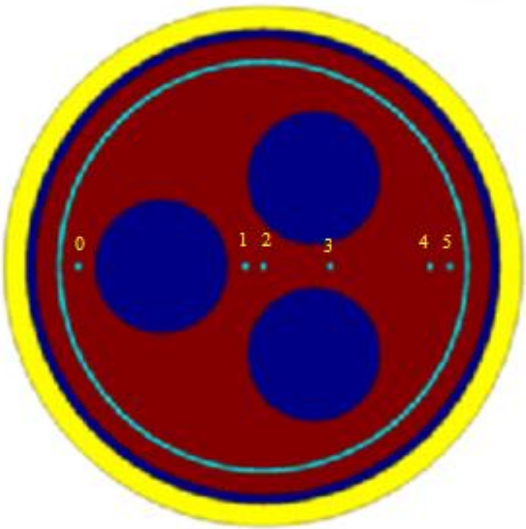

Figure 2: Cross-section view of the PILC cable on x-y plane with air-filled voids in positions 0, 1, 2, 3, 4, and 5.

2.2 PD Inception

A significant cause of insulation failures is the breakdown of electric field due to partial discharge [11]. PD generally occurs when dielectric properties of a cable insulation system under the high potential are not sufficient to withstand applied electrical stress [12]. The discharge is usually originated in cavities such as in air-voids. 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 [13].

When the electric stress according to equation (17), in the air-gap exceeds a certain level, the gas cannot sustain the electrical stress and an electron avalanche is generated in the void [14]. This electron avalanche is the main component of the PD which will occur.

$$E = \Delta V/d \qquad (17)$$

Where

ΔV is the electrical potential differences across the void: $\Delta V = V1-V2$, V1 and V2 are depending on the position of the void

dc = depth of the void

3. Electric field response

Figure 3 shows the applied electric field distribution over the PILC cable cross-section. The symmetrical arrangement of three phase voltage and the structure of lay the paper layers over the PILC cross-section influence the electric field distribution. The upper scheme pointed the positions of 0 to 5 over the PILC cable cross-section and the bottom scheme showed the view of the electric field data along cable cross-section over a 10 ms of 50 Hz AC cycle (0 to 0.01 second). The time period referred to the time of one 50 Hz AC cycle. Concerning the locations pointed in Figure 3, it can be seen that the potential gradient is vertical around the phase at the conductor insulation; that is, positions 0 and 1. The potential gradient level along the position 0

decreases gradually from high level at conductor to minimum level at ground sheath. The potential gradient also decreases linearly from the conductor to cable centre along the position 1. The potential gradient is horizontal between two phases at intersection surfaces of the two conductor insulations (i.e., position 3), which has the highest level of electric field over the AC cycle. Vertical potential gradient distribution at the belting insulation (i.e., 5) between the horizontal and vertical electric fields is circular (i.e., positions 2 and 4) and field is zero at ground sheath and conductor.
The data in Figure 3 demonstrates the symmetry of the three-phase PILC cable arrangement.

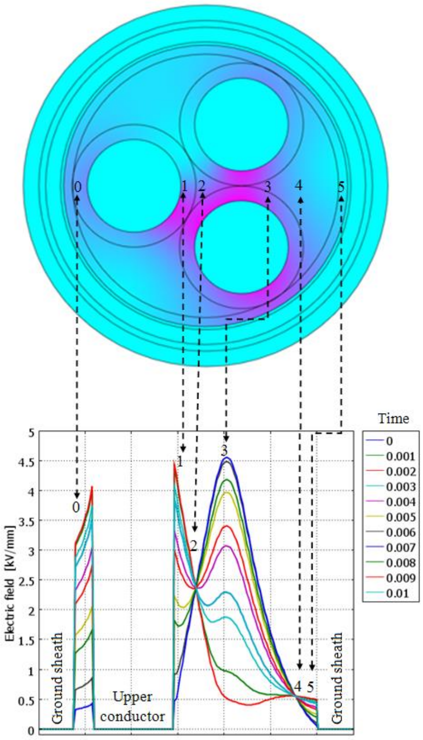

Figure 3. View of the electric field data along PILC cable cross-section at the positions shown. The electric field line variation at the positions indicated over a 10 ms (50 Hz) AC cycle, each line showing the stress at 1 ms intervals.

The electrical stress across air-filled void-defects of size 1 mm was calculated. This calculation was repeated for different voltage levels in the 3-phase cable and for the void locations, illustrated in Figure 2.
Figure 4 represents the results of the effects of void-defect of positions 0, 1, 2, 3, 4, and 5 as considered in Figure 2, with void-defect of size 1 mm. The electric stresses are 5.395 kV/mm in position 0, 5.305 kV/mm in position 1, 3.747 kV/mm in position 2, 6.695 kV/mm in position 3, 0.757 kV/mm in position 4 and 0.726 kV/mm in position 5. The electric field of void defects of positions 0, 1 and 3 are high and decrease gradually over positions 2, 4, and 5, respectively.

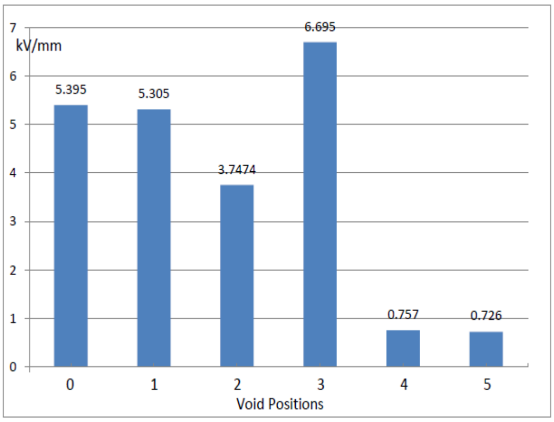

Figure 4: The electric stress over void-defects of positions 0, 1, 2, 3, 4, and 5 as considered in Figure 2.

The electric field magnitudes in the void-defect of positions around the conductors positions 0, 1 and between the conductors (i.e., position 3) are high. The highest magnitude is in position 3. The lowest levels of electric fields are in the void-defect positions far away from conductors, positions 2, 4 and 5, respectively.
The void-defect electric field changes over the positions due to the maximum electric potential difference across those different void-defect positions.
The void-defect electric field is high when maximum electric potential difference across that void is high, and vice versa, according to the equation $E = \Delta V/d$.
The PD usually occurs in a void located at the active electric stress region; that is, around or closer to the conductors according to equation 17 (i.e., positions 1, 3, and 0). There is no probability of PD occurring in the void of 1 mm located at low electric field background of 2, 4, 5 that is far from the PILC conductor. That is because the critical electric field that can cause PD has not been reached.

Table: Results of time of highest Electric Field of Void-Defect of Positions 0, 1, 2, 3, 4, and 5 within Size 1 mm over an AC cycle.

Position	Time of Maximum Electric Field over the Void-Defect (Second)	
0	0.002	0.012
1	0.002	0.012
2	0.001-0.009	0.011-0.019
3	0.007	0.017
4	0.002	0.012
5	0.002	0.012

The times of the highest electric fields are 0.002 and 0.012 seconds in void-defect of position 0 that is between the upper conductor and ground sheath and 1 that is around the upper conductor, and 4, and 5, which are perpendicular to the upper conductor. This is due to the electric potential of the upper conductor that has a maximum voltage value at 0.002 and 0.012 seconds. This has been proved by equations 12,

13, and 14 that apply to right-hand phase, left-hand phase, and upper phase, respectively.
In position 2, the maximum value of void electric field was appeared almost over all the time of AC voltage cycle. This is due to the electric field background at the cable centre which is affected by the three conductors simultaneously.
In position 3, which is between the left-hand and right hand conductors, the times of the highest electric field are 0.007 and 0.017 seconds, mainly due to the electric potentials of both conductors that are at maximum voltage value with an opposite sign at that instance of 0.007 and 0.017 seconds. These also have been proved by equations 12, 13, and 14 that apply to right-hand phase, left-hand phase, and upper phase, respectively.

The three phase voltages influence the electric stress in void-defect position. The time of PD occurrence over different void-defect positions in 3-phase PILC cable insulation is dependent on the time of peak-applied voltage of closer conductor. The PD activities appear relative to time variation of maximum AC voltage cycle.

Conclusion

The electric field modelling of MV cable containing deferent void-defect positions under three phase voltage conditions in service using finite element software was presented. The variation nature of electric field and potential distributions within 11 kV PILC belted cable insulation is studied, and the active defects that may produce PD are shown. Also, the PD activities appear relative to time variation of applied voltage. The time of peak-applied voltage of closer conductor to the void-defect determines the electrical stress amount in that void-defect affecting PD activity.

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