BEHAVIOUR OF PD IN IMPULSE AGED INSULATION: A THEORETICAL STUDY

M. M.C. Mampane[1*] and C. Nyamupangedengu[1]
[1]School of Electrical and Information Engineering,
University of the Witwatersrand, Johannesburg, Private Bag 3, Wits, 2050, South Africa
*Email: makanyane.mampane@students.wits.ac.za

Abstract: It is known that insulation in high voltage equipment can be exposed to impulse electric stress. Impulse voltage sources include lightning, switching surges and power electronics. Literature shows that exposure of insulation to impulse voltages alters the intrinsic characteristics of the insulation such as dielectric strength, loss tangent and relative permittivity. In addition to impulse voltage induced ageing, the insulation could develop defects which give rise to partial discharge (PD) activity. The PD induced degradation of the insulation and progression to total failure depends on the electrical properties of the insulation. It follows that PD phenomena may be influenced by sustained exposure of insulation to impulse voltages. The relationship can be synergistic and therefore accelerate insulation failure. This paper identifies and analyses how electrical insulation parameters can be affected by sustained exposure to voltage impulses. Furthermore, the analysis includes how the changes can influence the behaviour of partial discharges that may be initiated in the impulse aged insulation.

1 INTRODUCTION

An insulator is a non-conducting material that isolates high voltage systems from the surrounding environment. Polymer insulation is widely used in electrical equipment such as power cables and rotating machines (generators and motors). An intrinsic disadvantage of polymer insulation is its vulnerability to partial discharge (PD) induced degradation. Electrical breakdown of insulation may result in serious consequences such as power blackouts, fire and explosions [1].

Partial discharges are defined as localised small electric sparks or discharges. The discharges do not bridge the insulation between conductors. They occur in defects in the insulation, or at interfaces, between insulating materials or surfaces, or between a conductor and a floating metal component (not connected electrically to the high voltage conductor nor to the ground conductor) or between floating metal components [2]. PD defects can develop in insulation. They may be a consequence of insulation condition deterioration or improper installation, faulty design or poor workmanship (in the case of cable joints and terminations). PDs are an essential activity in high voltage insulation condition diagnosis. PD measurements are used in insulation diagnosis to check the reliability of insulation systems, classify insulation defects, evaluate failure threats and prediction of equipment remaining life [3].

PD activity is an important high voltage research area, which has span over decades. There has been varying progress regarding types of electrical equipment and discharge behavioural aspects being studied. Common areas include: types of discharges, detection sensitivity, degradation phenomena of insulation exposed to PD, discharge pulse quantities and pulse pattern recognition. Furthermore, significant development has been achieved in understanding PD regimes and corresponding methods for quantitative numerical simulation [4]. A lot of work has been done to understand partial discharge mechanisms in polymer insulation under sinusoidal stress conditions. The same however, cannot be said about partial discharge mechanisms under impulse voltages in polymer insulation [5, 6].

An impulse voltage is a unidirectional voltage that rises rapidly to a peak value and decays relatively slowly to zero. There are two types of impulse voltages, namely; lightning and switching overvoltages. A lightning discharge can induce travelling voltage surges in electrical systems. Switching impulses are always related to the operating voltage and the shape is influenced by the impedances of the system as well as the switching conditions [7].

In this study interest is in lightning voltage impulse and its effect on medium voltage (MV) power cable insulation. Power cable insulation can develop defects that give rise to PD. PD induced insulation degradation depends on the electrical properties of the insulation. It follows therefore that PDs could be influenced by how impulse voltages change the insulation properties. This research aims at investigating PD behaviour in polymer insulation and seeks to address questions such as:

- How can PDs in un-aged insulation differ from those in impulse aged insulation?
- If the insulation condition history is not known, can one deduce from PD measurements whether the insulation has been exposed to impulses or not?

This paper presents a theoretical study of the behaviour of partial discharges in impulse-aged polymer insulation. It contributes to knowledge on further understanding of mechanisms by which impulse voltages contribute to the ageing of insulation under PD activity. The paper first analyses and discusses mechanisms of impulse ageing in polymer insulation. Cavity PD mechanisms in polymer insulation are then analysed in the context of how the mechanisms can be influenced by impulse ageing of the insulation. The effect of impulse-ageing on PD mechanisms is postulated through identifying and relating insulation parameters that are affected by both impulse and PD induced ageing.

2 INSULATION IMPULSE AGEING MECHANISMS

The mechanisms of impulse ageing within insulation can be classified into physical and electrical effects, and these are mutually related. Lightning impulse's impact on insulation often manifests as surface flashovers. Although insulation breakdown can be abrupt, lightning impulses can initiate considerable long term degradation. The physical manifestations of the impulse damage range from minor to substantial erosion and may include burn marks. These roughen the insulation texture and distort the uniformity of the surrounding insulation electric field; which in turn has implications on breakdown characteristics [5].

Literature shows that the following electrical parameters have been identified to respond to impulse damage of polymeric insulation, namely; dielectric loss, dielectric strength, space charge and insulation capacitance. In power cables, research has shown that aged samples are lossier than un-aged ones. Increased conduction losses imply that the aged insulating material experiences increased temperatures when subjected to the same electrical stress as un-aged ones [8].

Lightning impulses in insulation may generate excited electrons with high energy that penetrate the bulk dielectric. These electrons can cause bond scission and create charge trapping centres. The traps enhance charge build up and alter the breakdown strength of the sample. Alternatively, the space charge may only be present in the vicinity of the surface of the sample, which may dissipate overtime or the lightning impulse may only provide thermal energy elevating the sample temperature [9, 10].

Space charge measurements show that space charge profiles change as a function of impulse ageing. It has been shown that after sustained exposure to impulse voltages, the electric field strength of dielectrics is weakened, the material becomes more conductive and space charge injection is more efficient [8].

The insulation defect of interest in this research is the gas cavity as it is the commonly encountered defect type in most equipment. In power cables gas bubbles are trapped in the insulation as a result of poor workmanship during assemble of cable terminations and joints. Though rare, gas bubbles can also be trapped in the main cable insulation during the manufacturing process.

The parameters of an insulation cavity that can characterise PD mechanism are given in Table 1.

Table 1: Generalized gas void parameters and the controlling factors [3]

Category	Parameter	Symbol
Geometry	Applied field (V/m) Defect dimensions (m)	E_o l and r
Bulk substance attributes	Permittivity (F/m) Pressure (Pa) Gas ionization constants	ε_r p $(E/p)_c r$, B, η, γ
Cavity surface	Surface conductivity (S)	k_s

The parameters can be classified into; geometry, bulk substance attributes and cavity surface categories. The first category pertains to the depth (l) and radius (r) in the direction of the surrounding field (E_o). The second category is the bulk attributes of the polymer and gaseous substances trapped in the PD activity. These consist of the relative permittivity ε_r of the solid dielectric, the kind of gas and its pressure p, and the parameters $(E/p)_{cr}$, B, n, γ which are the classical gas ionisation constants and represent the ionisation characteristics of the gas or gas-surface interface. $(E/p)_{cr}$ is the pressure reduced critical field, B is a constant, η is the attachment co-efficient and γ is a dimensionless proportionality factor.

The last category of parameters pertains to cavity surface boundary conditions involved in the PD. The cavity surface conditions influence the variations of the gas ionisation features by surface conductivity, charge release from surfaces and charge motion along surfaces [11].

3 CAVITY PD MECHANISM REVIEW

Figure 1 below illustrates the recurrence of PDs and assumes an ideal cavity enclosed within polymer insulation that is subjected to a sinusoidal wave voltage. When a free electron is available and the voltage across the cavity attains its breakdown value (E_{inc+} or E_{inc-}), a PD occurs. In turn, the voltage across the cavity decreases rapidly either to zero or to a relatively small residual value. The PD appears as a pulse superimposed on the power frequency voltage sine wave.

Subsequent to pulse extinction, the voltage across the cavity rises until it attains a breakdown value and a new PD initiates. This occurs many times on the rising and falling regions of the applied voltage as illustrated in Figure 1. The resulting PD pulses exhibit stochastic behaviour characterised by intermittency and rapid fluctuations. This is caused by randomness in the statistical time lag [4, 11].

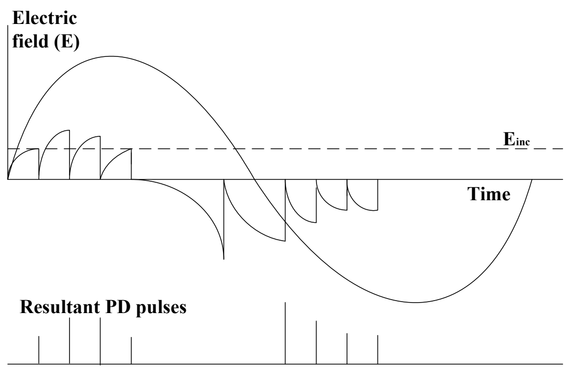

Figure 1: An illustration of PD recurrence [11]

In the following sections PD parameters such as inception voltage, apparent magnitude and phase resolved patterns are analysed and discussed with regard to how they can be influenced by impulse ageing of the insulation.

4 PD INCEPTION AND HOW IT CAN BE INFLUENCED BY IMPULSE AGEING

In order for a PD to occur, two pre-requisites must be fulfilled, namely, an initial electron must be present to start an ionization avalanche and the field (*E*) in the void must exceed the discharge inception voltage E_{inc} (streamer criterion). The initial electron is the primary driver of the PD process statistical characteristics such as inception delay, frequency of occurrence and phase distribution. Initial electrons are generated by two distinct processes: volume and surface processes. Volume generation processes are driven by radiative gas ionization due to energetic photons and field detachment from negative ions. Surface processes include the production of electrons from void surfaces where they have been trapped in a preceding PD [3].

The streamer criterion is fulfilled if the electric stress in the cavity equals or exceeds the streamer inception stress level as shown in Equation 1 [3]:

$$E_{inc} = E_{str} = E\left[1 + \frac{B}{\sqrt{2ap}}\right] \qquad (1)$$

Where:

B is a gas property (Pa.m)
p is the gas pressure (Pa)
a is the cavity radius (m)

In a gas void, the stress enhancement occurs within the void and if the stress is higher than the breakdown strength of air, a discharge is initiated. The electric field enhancement factor varies with cavity dimensions, location and alignment. The electric field enhancement factor is defined by Equation 2 below [12]:

$$E_f = \frac{E_c}{E_d} \qquad (2)$$

Where:

E_f is the electric field enhancement factor (dimensionless)
E_c is the electric stress within the cavity (V/m)
E_d is the stress within the dielectric (V/m)

For a spherical void the stress enhancement factor is as expressed in Equation 3 [12]

$$E_f = 3\varepsilon/(2\varepsilon + 1) \qquad (3)$$

In a coaxial cable the PD inception voltage is expressed as given in Equation 4 [13]:

$$V_c = 24.2p\left\{rIn\frac{R_o}{R_i}\right\}\left\{\frac{2\varepsilon_r + 1}{3\varepsilon_r}\right\}\left\{\frac{9.6}{\sqrt{2ap}} + 1\right\} \qquad (4)$$

Where:

P is the pressure of the air within the cavity (Pa)
r is the radial position of the cavity (m)
R_i is the radius of the conductor semicon-dielectric interface (m)
R_o is the radius of the dielectric-ground semicon interface (m)
a is the radius of the cavity (m)
ε_r is the relative dielectric constant of the insulation (dimensionless)

Impulses alter the dielectric properties of insulation such as the relative permittivity. The electric field enhancement factor which is key to PD initiation is mainly governed by the relative permittivity as shown Equation 4 above. It is therefore a variable of interest that determines the PD inception voltage. The relative permittivity parameter therefore becomes an essential link on the effect of impulse ageing on PD inception voltage.

It is postulated that impulse voltage effect on insulation causes PD inception voltage to change in response to changes in the stress enhancement factor. It is important to note that Equation 4 holds under initial conditions only. Subsequent discharge mechanisms become greatly influenced by the evolutionary tendencies of the phenomena. The following section discusses PD magnitude in the context of how it could be influenced by impulse ageing of the insulation.

5 PD MAGNITUDE AND HOW IT CAN BE INFLUENCED BY IMPULSE AGEING

The field reduction in the void from an initial value $E \geq E_{str}$ to the residual E_{res} is associated with a charge transport as expressed in Equation 5 [11]:

$$q \propto \varepsilon\varepsilon_o r^2 (E - E_{res}) \qquad (5)$$

Where:

ε	is the relative permittivity (F/m)
ε_o	is the permittivity of free space (F/m)
E	is the applied field (V/m)
E_{res}	is the residual voltage (V/m)

The charge is deposited on the void walls. This charge can be regarded as an electric dipole configuration because the resultant charge inside the wall is zero [9]. PD magnitude induced at the measuring electrode (apparent charge) is given by Equation 6 which is commonly referred to as Pedersen's model [14]:

$$q = K\varepsilon\varepsilon_o (E_i - E_l)\Omega\nabla\lambda_0 \qquad (6)$$

Where:

K	is the geometry factor of the enclosed void (dimensionless)
Ω	is the void volume (m^2)
E_i	is the applied electric field for the inception of the PD of the streamer type (V/m)
E_l	is the limiting applied field for ionization (V/m)
ε	is the permittivity of the insulating material (dimensionless)
ε_0	is the known dielectric constant (F/m)

For plane-to-plane electrode spacing of *d* (m), $\nabla\lambda_0$ is the inverse of the gap spacing.

The enhanced electric field within a spherical void enclosed in a solid insulation is given by equation 7 [12]:

$$E_b = 3\varepsilon E/(2\varepsilon + 1) \qquad (7)$$

Where E is the electric field applied to the insulation and ε is the permittivity of the surrounding solid insulation. Substituting E_b for E_i in Equation 6 gives an expression for the apparent charge as given in Equation 8 [3]:

$$q = K\varepsilon\varepsilon_0 \left[\left(3\varepsilon \frac{E}{2\varepsilon + 1} \right) - E_l \right] \Omega\nabla\lambda_0 \qquad (8)$$

As in PD inception, the permittivity (ε) is a key parameter in the analytical expression of PD apparent charge. Changes in this parameter as may be caused by impulse ageing of the insulation hypothetically results in changes in PD magnitude. Figure 2 shows a linear relationship between the dielectric constant and stress enhancement factor.

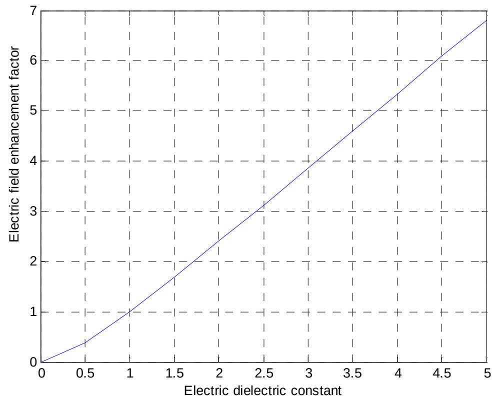

Figure 2: The relationship between the electric field enhancement factor and relative dielectric constant for the PD apparent charge

6 PD PHASE RESOLVED PATTERN AND HOW IT CAN BE INFLUENCED BY IMPULSE AGEING

The distribution of PD pulses on the power frequency sinusoidal wave is commonly referred to as PD phase resolved patterns (PDPRP) and is a widely used tool in characterisation of partial discharges [11]. The relationship between PDPRP and impulse ageing of insulation can generate useful knowledge in PD diagnosis technology.

With reference to PD mechanism as illustrated in Figure 1, if E_{inc} is changed due to cavity surface changes in response to impulse ageing, the number and rate of occurrence of pulses in each quadrant changes, consequently the PDPRP changes.

The actual details of how the cavity surface boundary conditions respond to impulse ageing and how this in turn influences the PDPRP cannot be postulated at this point. More insights into this will be experimentally explored in future work.

7 CONCLUSION

Impulse stress affects the electrical and physical properties of polymer insulation and, this in turn has implications on PD behaviour. This paper has demonstrated that the relative permittivity of insulation provides a link between impulse stress and PD apparent charge and inception voltage.

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