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PARTIAL DISCHARGE AS A FUNCTION OF PRESSURE UNDER VARYING LEVELS OF APPLIED VOLTAGE AMPLITUDE, VOID CONDUCTIVITY AND MATERIAL CONDUCTIVITY

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ABSTRACT

Partial discharges are inevitable in Electrical insulators. These discharges are closely tied to the ageing and degradation of Electrical insulators that will lead to an eventual breakdown which can quite possibly result in more significant damage to the entire Electrical grid. It is therefore imperative that a good understanding of how and why these discharges occur is established and what can be done to mitigate the effects of these discharges. A model was developed on MATLAB to simulate these discharges in a void present in the insulator. Parameters like applied voltage, inception voltage, extinction voltage, void conductivity, material conductivity and Gas Pressure were incorporated into the model under AC/DC conditions. These parameters affect how many discharges occur. Also, under AC conditions the phase of the discharges is affected as well. An increase in the applied voltage leads to more discharges, while an increase in parameters like Gas Pressure, material conductivity, inception voltage, extinction voltage results in decrease in the number of discharges. A decrease in void conductivity leads to a decrease in the number of discharges. The finished model was able to adequately recreate partial discharge data under both AC and DC conditions. Gas Pressure changes the distribution of the discharges and as this pressure builds up, there is a decrease in the number of discharges until this pressure builds up to a stage where conditions are no longer feasible for a discharge to occur.

KEYWORDS: Partial Discharges, void conductivity, material conductivity, Electrical Insulators.

1. INTRODUCTION

Electrical insulators make up an integral part of the Electrical grid; however, like other components that make up this grid, they are subject to degradation over time. The degradation of Electrical insulators starts off at a microscopic level but it has the potential to set off a chain of cascading failures that start off with the breakdown of the insulator and possibly end with the catastrophic shutdown of the entire Electrical grid.[1]

Electrical insulators, no matter how much care went into making them will lack uniformity throughout the material or will contain gas bubbles (void) due to some impurity, these 2 conditions are ideal for Partial discharges to occur when the insulator is subjected to a Voltage higher than the inception Voltage of the void.[2,3]

The effects of partial discharge are not limited to Electrical insulators; it extends to motors, generators as well as other Electrical distribution equipment.[4]

Partial discharges can occur in all the states of matter; Solid, Gaseous and Liquid media in the presence of an applied voltage. Partial discharges occur as isolated electrical discharges in a void or some form of free volume when the Electrical field within the void exceeds a certain threshold value. The threshold value for the void is dependent on the type of gas present in the void.[5,6]

Partial discharges are transient and do not fully bridge the gap between 2 conducting surfaces. Partial discharges can also occur on the surface of insulators.[7]

Partial discharges significantly speed up the deterioration of these insulators. Physical and chemical aging in the form of rise in temperature and the conversion of parts of the insulator to gas after each discharge also contribute to the degradation of the insulator.[8,9] Electrical aging in the form of electrical trees, water trees and sputtering also contribute to the degradation of the insulator.[10,11] Regular reoccurrence of Partial discharges leads to the eventual breakdown of the insulation material. Because of the severe consequences resulting from Partial discharges, an in-depth look into why and how they happen is warranted.[12]

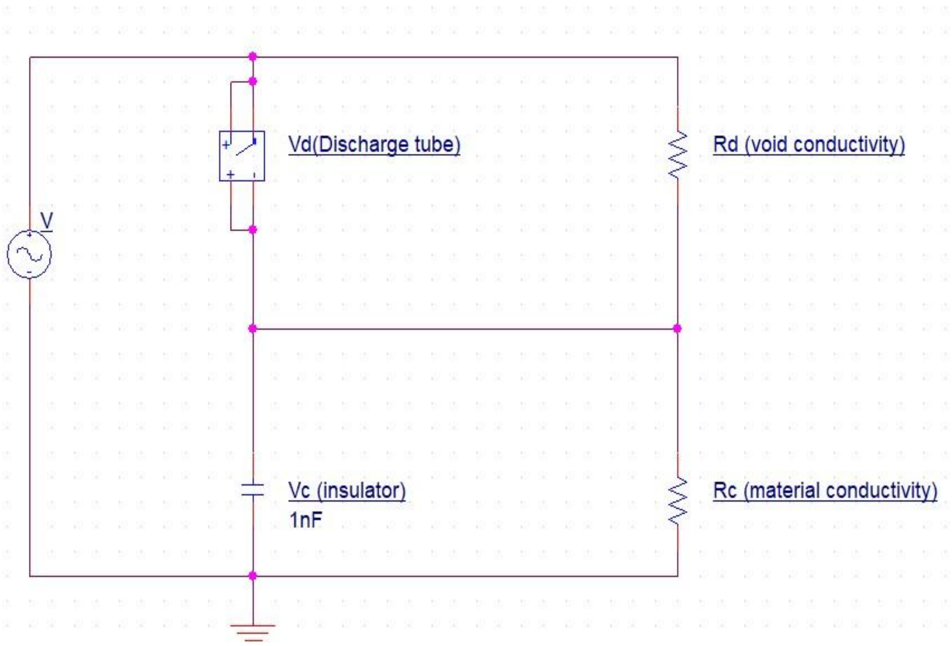
Partial discharge monitoring is a vital tool to have as an Engineer. Maintenance and replacements of parts can be centred on a partial discharge model and as a result significantly minimize or completely eliminate faults stemming from partial discharge.

This paper will examine the effect of pressure and other parameters like applied voltage, inception voltage, extinction voltage, void conductivity and material conductivity on the formation of Partial discharges occurring in a void present in an insulator.

2. LITERATURE REVIEW

Related literature under this topic includes; partial discharge measurement, simulation and modelling. Seghir et al.,[13] studied the amalgamated influence of cavities and space charge on the electric field, temperature distribution and potential distribution within solid insulation. Illias, et al.[14] developed a partial discharge model for a spherical cavity within a uniform dielectric material using the finite element analysis software. The partial discharge characteristics were a function of both frequency and amplitude of the applied voltage and the effect of applied voltage; AC sinusoidal, AC damped and impulse voltages, on partial discharge activity in a void in a solid dielectric insulation material were observed. The partial discharge behaviour was observed through phase resolved partial discharge patterns for the different applied voltages. Forssen.[15] studied how cavity diameter and height are a major influence on the frequency dependence of partial discharges using the variable frequency phase resolved partial discharge analysis technique. Illias, Chen and Lewin.[16] developed a partial discharge model that investigates the effect of cavity size on the frequency with which the discharges take place per cycle. Paoletti and Golubev.[4] explains the theory behind the evolution of partial discharge implementation and measurement. It also discusses how partial discharge monitoring is an effective on-line predictive maintenance test for electrical equipment. Also, it touches on insulation modelling and partial discharge modelling in electrical machines which also applies to electrical equipment as well. It also compares established partial discharge test methods with new and developing partial discharge monitoring. Morshuis, Jeroense and Beyer.[17] discussed the identification and interpretation techniques for partial discharge in DC equipment. The paper gives insight into the complications involved with partial discharge analysis in DC equipment. The assessment technique used was based on characteristic PD patterns for various fault types. Some faults were readily recognizable based on their Charge versus change in time plots while for more complicated faults required the use of the ADAMS classification method. Emersic et al.[18] designed an experiment to determine the damage rates due to partial discharge with pressure as low as 116mbar, a temperature range between -55^0 C to 70^0 C and voltages up to 6 kV. Reduced pressure increased the rate of damage while at low temperatures, there was minimal degradation recorded.

3. METHODOLOGY



The figure above represents the model developed for this project. The void is an insulator that will exhibit conductor-like properties when the conditions are ripe for a discharge. Basically, the discharge tube is an open-circuit, until a discharge takes place and it becomes a short-circuit. The void is represented by a discharge tube; the voltage across the discharge tube is represented as $V_{d.}$ This discharge tube is an electronically controlled switch. The capacitor represents the insulation medium; the voltage across the capacitor is represented as V_c. The resistors R_d and R_c represent the void conductivity and material conductivity respectively.

When an AC voltage is applied, the voltage across the discharge tube, V_d gradually increases as the phase of the AC signal changes. The discharge tube will remain an open circuit until V_d becomes greater than the inception voltage at which stage the discharge tube temporarily becomes a conductor, this builds up the charge in the capacitor which brings the voltage across the discharge tube back down to the extinction voltage, at which stage the discharge tube becomes open circuit again. When the discharge takes place, there will be a step change in the voltage of the capacitor and the voltage remains the same until the next discharge. The voltage across the discharge tube would build up again until it reaches the inception voltage and another discharge takes place. The whole discharge process keeps repeating as we move through the complete cycle (i.e. from 0-360^0 degrees of phase). The discharges tend to take place on the leading and lagging edges of the sine wave and they do not appear at the peak. R_d adds electrical conductivity to the model, it models a leakage current because even insulators do conduct. R_d provides extra charge to the capacitor, which means the step increases will not be constant. R_c represents the conductivity of the material surrounding the void. The current through R_c is the conduction current through the material. While R_d charges the capacitor, R_c discharges it and at the same time charges the material around the void. Therefore, for each time increment, a charging current, i_{c1} and a discharging current, i_{rc} are present in the model. After each discharge, pressure builds up in the void. The inception voltage is made a function of this increasing pressure.

The entirety of this project was done using MATLAB. The basic Partial discharge model consisting of 2 electrodes with a gas region (void), which is represented by a discharge tube and an insulator was the starting point for this project. The project later grew in complexity with the addition of void conductivity. The next step was to introduce material conductivity after which both the void conductivity and material conductivity were used in conjunction. The final step is incorporating Gas pressure into this model.

The Basic Model

The first step taken was to initialize the variables which are the peak, inception and extinction voltages and then make matrix arrays for applied Voltage, Voltage across the Capacitor and Voltage across the Discharge Tube and make sure they have the same dimension as the time array. The simulation was set to run from 0-5 seconds with 1 millisecond increments. The increments were achieved using the For-loop which allows to efficiently write a loop that executes a specific number of times or in this case until the program reaches the end of 5 second. Within the loop, we are able to calculate the voltage supplied and the Voltage across the void. The next step is to use the If-loop to calculate the value of the voltage across the capacitor. The If-loop is a conditional operator that tells our program to perform a certain task when certain conditions are met, in this case if the Voltage across the discharge tube is greater than the inception Voltage, a discharge occurs and we add the Voltage across the capacitor at the previous step to the difference of the inception Voltage and extinction

Voltage to give us the value across the capacitor at the current step and then increment the n-counter. The step mentioned above is repeated for the negative half cycle as well, if the Voltage across the discharge tube is less than the negative inception Voltage a discharge occurs and we subtract the Voltage across the capacitor at the previous step to the difference of the inception Voltage and extinction Voltage to give us the value across the capacitor at the current step and then increment the n-counter. At the end of the loop, the next value of the Voltage across the capacitor is replaced by the current Voltage across the capacitor and the loop repeats until we reach the final step increment in time. The function of this final stage resembles that of a shift Register whereby the input of a subsequent loop is the output of the loop that precedes it. The final stage of the program is plotting the applied Voltage, Voltage across the discharge tube and Voltage across the Capacitor against time. This process was executed at different amplitudes of the AC voltage. The num2str function is used to convert the numeric array (n) in this case the number of discharges to a character array that represent the number of these discharges. Below is an excerpt of the code taken from MATLAB.

```
Vp= 240; %input('The peak applied voltage = ');
Vinc=80; %input('The inception voltage = ');
Vext=40; %input('The extinction voltage = ');
T=[0:0.001:5];
Vc=zeros(1,length(T))
V=zeros(1,length(T));
Vd=zeros(1,length(T));
n=0;
for i=1:1:length(T)-1
    V(i)= Vp*sind(50*2*pi*T(i));
    Vd(i)=V(i)-Vc(i);
if Vd(i)>=Vinc
        Vc(i)=Vc(i)+(Vinc-Vext);
        n=n+1;
    else if Vd(i)<=-Vinc
            Vc(i)=Vc(i)-(Vinc-Vext);
            n=n+1;
        end
end
 Vc(i+1)=Vc(i);
end
plot(T,V,'r',T,Vd,'b',T,Vc,'g')
```

Figure 3-1: Basic Partial discharge model.

Next we set the values for the capacitance and the 2 Resistances (void conductivity and material conductivity). The 2 Resistor values are varied.

Gas Pressure Model

The next step after successfully introducing void conductivity in conjunction with material conductivity to the basic model is to add Gas Pressure. The first step taken was to initialize the variables which are the peak, inception and extinction voltages and make matrix arrays for applied Voltage, Voltage across the Capacitor and Voltage across the Discharge Tube and make sure they have the same dimension as the Time. Next we set the values for the capacitance and the 2 Resistances (void conductivity and material conductivity). The values of the 2 Resistors are varied. Next set the values for the Volume, Temperature, number of mole and Boltzmann constant because the inception voltage is made a function of pressure using the ideal gas law. The simulation was set to run from 0-5 seconds with 1 millisecond increments. The increments were achieved using the For-loop which allows to efficiently write a loop that executes a specific number of times or in this case until the program reaches the end of 5 second. Within the loop, we are able to calculate the voltage supplied, the Voltage across the void, the current through the 2 resistors, Pressure, change in pressure, pressure lost due to diffusion and inception Voltage. The next step is to use the If-loop to calculate the value of the voltage across the capacitor. The If-loop is a conditional operator that tells our program to perform a certain task when certain conditions are met, in this case if the Voltage across the discharge tube is greater than the inception Voltage, a discharge occurs. The discharge results in an increase is pressure, the change in pressure and the new value for pressure are calculated in the if loop and we add the Voltage across the capacitor at the previous step to the difference of the inception Voltage and extinction Voltage to give us the value across the capacitor at the current step and then increment the n-counter. The step mentioned above is repeated for the negative half cycle as well, if the Voltage across the discharge tube is less than the negative inception Voltage a discharge occurs. The discharge results in an increase is pressure, the change in pressure and the new value for pressure are calculated in the if loop and we subtract the Voltage across the capacitor at the previous step to the difference of the inception Voltage and extinction Voltage to give us the value across the capacitor at the current step and then increment the n-counter. At the end of the loop, the next value of the Voltage across the capacitor is replaced by the current Voltage across the capacitor plus the change in the Voltage across the capacitor due to the current flowing from the resistor minus the change in the Voltage across the capacitor due to the current flowing from the capacitor to the resistor and the loop repeats until we reach the final step increment in time. The function of this final stage resembles that of a shift Register whereby the input of a subsequent loop is the output of the loop that precedes it. The final stage of the program is plotting the applied Voltage, Voltage across the discharge tube and Voltage across the Capacitor against time. The process is repeated under both AC/DC conditions, different levels for the 2 Resistances. The num2str function is used to convert the numeric array (n) in this case the number of discharges to a character array that represent the number of these discharges. A scatter plot was used to display the cycle count and the phase of the discharges.

4. RESULTS AND DISCUSSION

Effect of varying applied voltage

The result below is for 3 levels of peak voltages; 120V, 240V and 480V with the inception Voltage at 80V and the extinction Voltage at 40V using AC Voltage with frequency set 50 Hz.

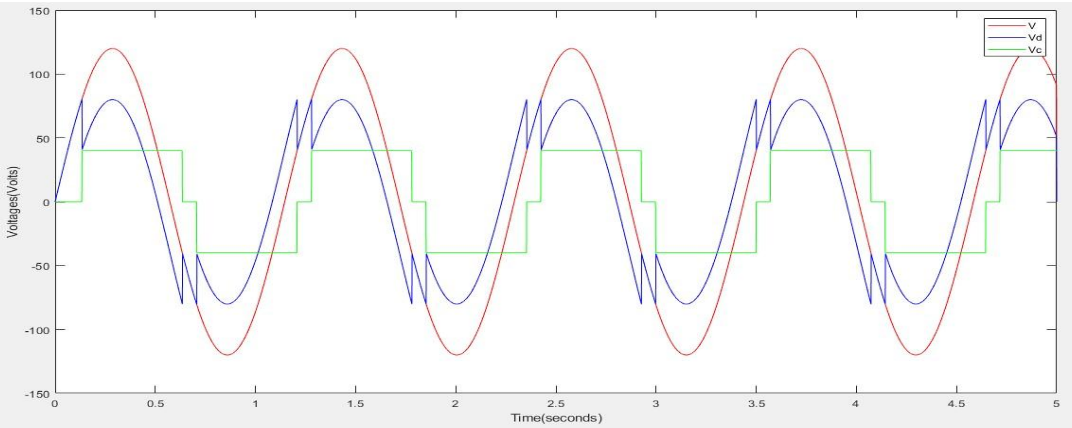


Figure 4-1: Partial discharge data with applied voltage at 120V.

Table 4-1 Number of discharges for different levels of peak voltage.

Peak Voltage(Volts)	Number of discharges
120	18
240	69
480	171

The results above show an increase in the number of discharges with an increase in the amplitude of the applied Voltage.

Effect of varying void conductivity

The results below were achieved with a capacitance of 1nF, a peak voltage of 240V with frequency set 50 Hz, an inception Voltage of 80V, an extinction Voltage of 40V and 5 different levels of Resistance; 1e6Ω, 1e7Ω, 1e8Ω, 1e9Ω, 1e10Ω, 1e11Ω and 1e12Ω using AC Voltage.

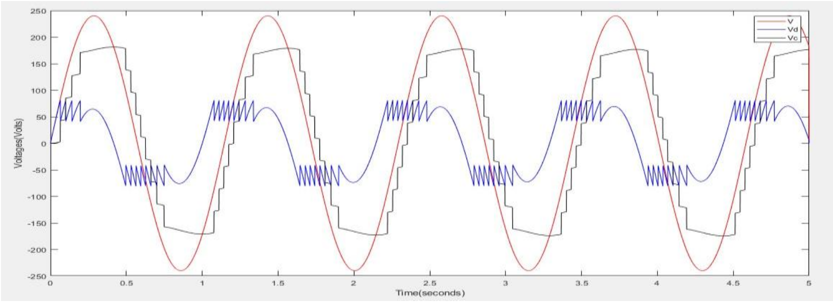


Figure 4-2: Partial discharge data for an applied voltage of 240 V and void resistance of 1e9Ω.

Table 4-2 Number of discharges for different levels of void conductivity.

Resistance (ohms)	Number of discharges
1e6	0
1e7	0
1e8	33
1e9	68
1e10	68
1e11	76
1e12	72
1e13	68

There are no discharges when the conductivity is high, however as the conductivity is decreased, there is an increase in the number of discharges. The number of discharges peaks with the resistance at 1e11Ω with 76 discharges. As we increase the resistance further, the number of discharges goes back down to 68 and stays there.

Effect of varying material conductivity

The results below were achieved with a capacitance of 1nF, a peak voltage of 240V with frequency set 50 Hz, an inception Voltage of 80V, an extinction Voltage of 40V and 5 different levels of Resistance; 1e15Ω, 1e14Ω, 1e13Ω, 1e9Ω and 1e8Ω using AC Voltage.

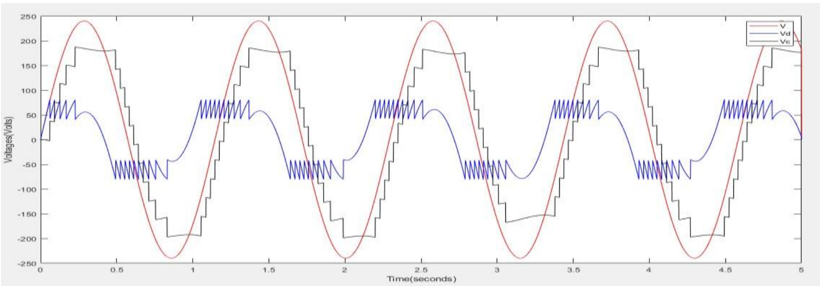


Figure 4-3: Partial discharge data for an applied voltage of 240 V and material conductivity of 1e9Ω.

Table 4-3: Number of discharges for different levels of material conductivity.

Resistance (ohms)	Number of discharges
1e15	68
1e14	69
1e9	83
1e8	118

With the Resistance set to a value of 1e15Ω or higher, the number of discharges is 68. However, an increase in the magnitude of the conductivity results in an increase in the number of discharges in contrast with the Void conductivity model.

Effect of varying both void and material conductivity

The results below were achieved over 5 cycles with a capacitance of 1nF, a peak voltage of 240V with frequency set 50 Hz, an inception Voltage of 80V, an extinction Voltage of 40V and 8 different permutations of the Resistances representing void and material conductivity; 1e12Ω and 1e12Ω, 1e12Ω and 1e8Ω, 1e12Ω and 1e6Ω, 1e10Ω and 1e12Ω, 1e8Ω and 1e12Ω, 1e7Ω, and 1e12Ω using AC Voltage.

Table 4-4: Number of discharges for different levels of void conductivity+material conductivity.

Void Conductivity (Ohms)	Material Conductivity (ohms)	Number of discharges
1e12	1e12	89
1e12	1e8	89
1e12	1e6	231
1e10	1e12	79
1e8	1e12	79
1e7	1e12	80

Getting the combination for the Void conductivity and Material conductivity right so that conditions are suitable for a discharge to take place was the tricky part of dealing with this model. In some cases, there were no discharges while in others, there was a rather significant number of discharges. As shown in the 2 previous models, a decrease in void conductivity increases the number of discharges, while an increase in the material conductivity increases the number of discharges. However, this effect is not as pronounced as it was in the other 2 models because to some extent, the 2 conductivities counteract the effect of each other.

Gas Pressure Model

The results below were achieved with a capacitance of 1nF, using both AC/DC voltages, a peak voltage of 240V with frequency set at 50Hz, the void Conductivity and material conductivity were 1e12Ω and 1e9Ω respectively, the Volume was 0.6L, the number of moles was 1 mol, the ideal gas constant was 0.082057 L-atm/mol-K and the Temperature in Kelvin, increased with increasing pressure. The results start off with a small number of cycles, and then progressively increase to show the effect of increasing pressure. Different Values for the 2 Resistances were used when dealing with the DC Voltages.

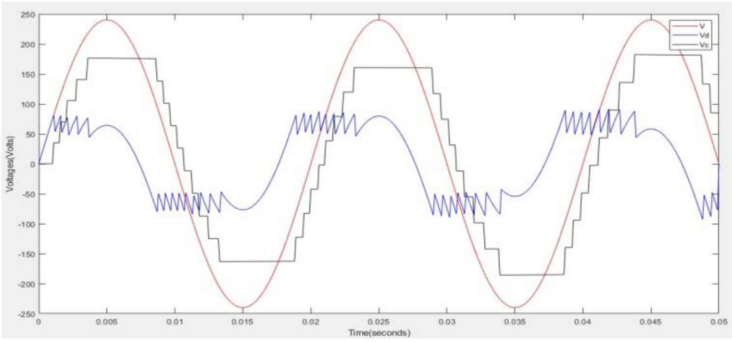


Figure 4-4: Partial discharge data for Gas pressure model after 3 cycles for an AC voltage.

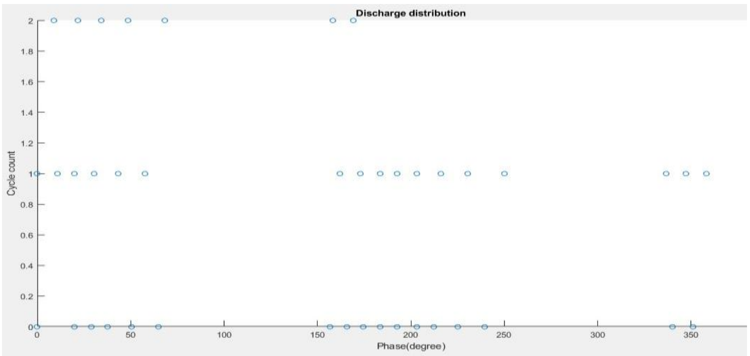


Figure 4-5: Phase resolved partial discharge data for Gas pressure model after 3 cycles for an AC voltage.

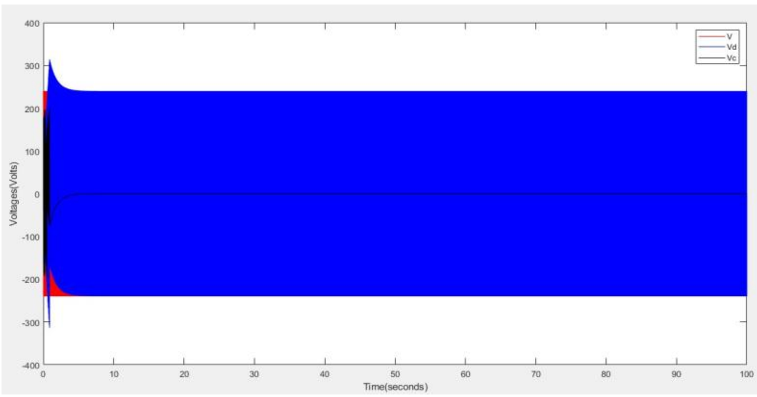


Figure 4-6: Partial discharge data for Gas pressure model after 1000 cycles for an AC voltage.

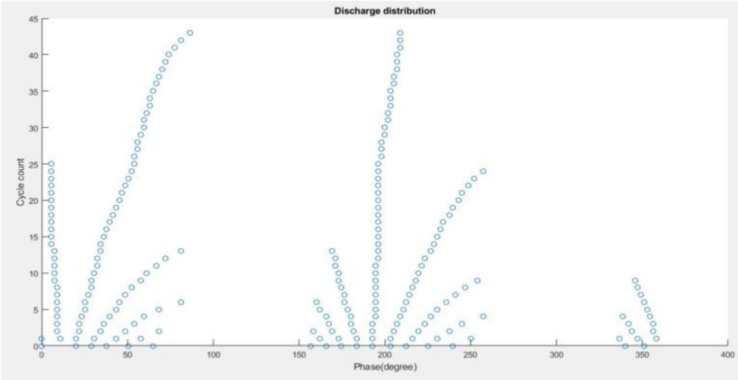


Figure 4-7: Phase resolved partial discharge data for Gas pressure model after 1000 cycles for an AC voltage.

Table 4-5: Number of discharges for the gas pressure model for increasing number of cycle for AC voltage.

Number of cycles	Number of discharges
3	41
5	72
25	184
40	215
44	223
50	223
1000	223

A significant number of discharges were distributed in the earlier cycles. As the cycle count increases, the number discharges keep falling, in stark contrast to the first few cycles. The discharges eventually stop completely when the cycle count is high enough.

For the simulation using a DC Voltage, the following resistor pairing were used; 1e12Ω and 1e6Ω, 1e12Ω and 1e7Ω, 1e12Ω and 1e8Ω. The simulation ran for 0.1 seconds. The results are shown below.

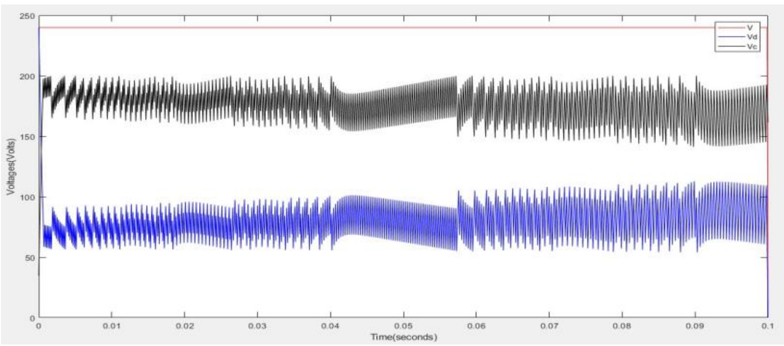


Figure 4-8: Partial discharge data for gas pressure model for a void resistance of 1e12Ω and material conductivity of 1e6Ω.

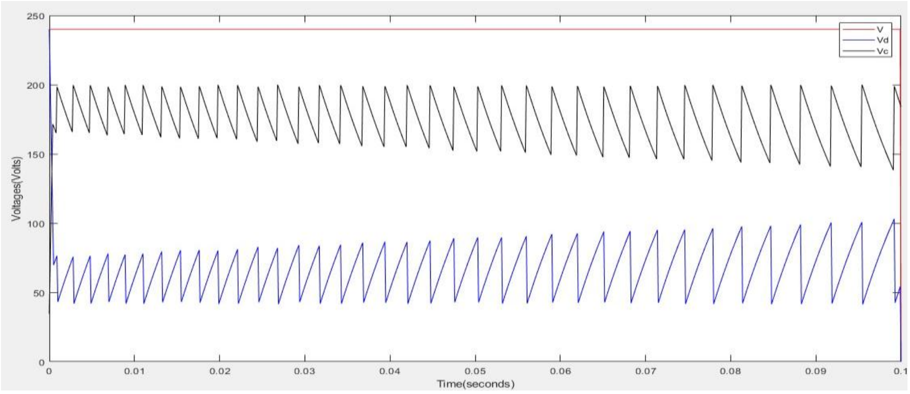


Figure 4-9: Partial discharge data for gas pressure model for a void resistance of 1e12Ω and material conductivity of 1e7Ω.

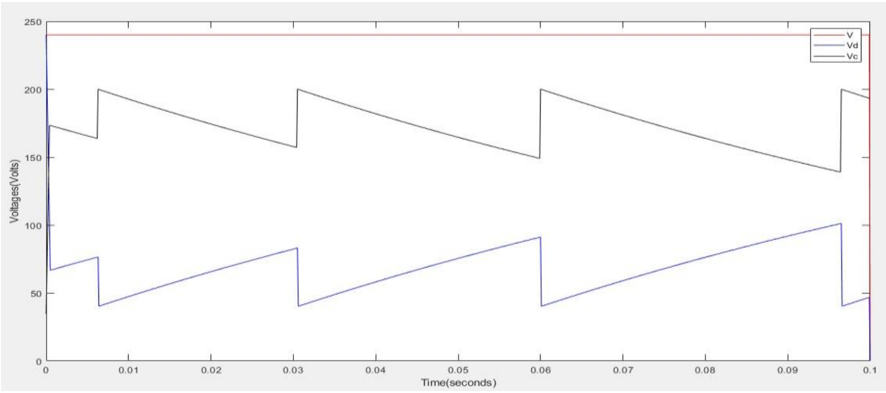


Figure 4-10: Partial discharge data for gas pressure model for a void resistance of 1e12Ω and material conductivity of 1e8Ω.

An increase in material conductivity leads to a decrease in the number of discharges. There is also a progressive increase in the amplitude of the discharges.

Table 4-6: Number of discharges for the gas pressure model for increasing number of cycle for DC voltage.

Void conductivity (ohms)	Material conductivity (ohms)	Number of discharges
1e12	1e6	346
1e12	1e7	43
1e12	1e8	10

5. CONCLUSION AND FUTURE RECOMMENDATION

CONCLUSION

An increase in the applied voltage comes with an increase in the frequency with which partial discharges occur. An increase in Electric field accompanies the increase in applied voltage, as a result there is more energy available to start an electron avalanche and keep it going for longer which in turn leads to more discharges. Every time there is a discharge, there is a step increase in the voltage across the capacitor. The step waveform is flat because there is no electrical conductivity incorporated yet.

Increasing the value for void conductivity decreases the number of discharges until a value of void conductivity is reached whereby conditions are no longer suitable for discharges to take place. When the void conductivity is high enough, it leads to a short-circuit, this implies that the applied voltage is approximately equal to the voltage across the capacitor. The increase in conductivity means that the voltage across the capacitor is being altered by the charging current that is flowing into it which is bypassing the discharge tube all together. The capacitor is charging up partially through R_d as well as every time there is a discharge. The faster the capacitor charges up, the lower the number of discharges. Every time there is a discharge, there is a step increase in the voltage across the capacitor. Some of the step waveforms have a degree of inclination to them due to the effect of the void conductivity; this is due to the extra charging the capacitor is being subjected to from R_d.

Increasing the value for material conductivity leads to an increase in the number of discharges. While R_d act leads to charging, R_c discharges. Every time there is a discharge, there is a step increase in the voltage across the capacitor. Some of the step waveforms have a degree of declination due to the effect of the material conductivity; this is due to the extra discharging the capacitor is being subjected to from R_c.

When void conductivity and material conductivity are accounted for, then both charging and discharging of the capacitor take place and as a result depending on which effect is stronger, there would be some inclination or declination in the steps of the step waveform or they might have equal effect so that the steps are flat.

An increase in pressure makes it harder to form discharges. After each discharge, part of the insulator is converted into gas, gas takes up more volume than solids for the same number of atoms and as a result, there is pressure build up in the void. This increase in pressure leads to an increase in the inception voltage and because the magnitude of the electric field necessary to start off the electron avalanche remains the same, it progressively becomes more difficult to form discharges.

FUTURE RECOMMENDATION

Introduction of additional variables that will increase the accuracy of this predictive model should be considered. This work should be extended to include motors, generators as well as other Electrical distribution equipment and not just Insulators.

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