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Classification and study on factors affecting partial discharge in cable insulation

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To investigate the Partial Discharge (PD) inside the solid insulation a MATLAB based Simulink model has been developed in this work. The fuzzy classification technique has been used for the classification of apparent charge due to PD activity. The model is used to study the effect of applied voltage, different void sizes and different insulation materials on Partial Discharge. It is found that with the increase in applied voltage and void size there is significant increase in the apparent charge. Also apparent charge changes with the different insulating materials. It establishes the fact that Partial Discharge activity in insulation highly depends upon certain factors like applied voltage, size of the void and dielectric constant of insulation material.

Keywords: Partial Discharge, apparent charge, void, fuzzy logic system.

1. Introduction

Cables in a power system network are one of the most important component as well as the part most vulnerable to failure. More than half of the cable failure is due to electrical reason. The quality of insulation plays an important role in the operation of cables and high voltage (HV) power equipments. Different types of materials like solid, liquid and gaseous materials are used for insulation purpose in high voltage power equipment. However, the insulation property of power equipments gradually degrades due to electrical, chemical and mechanical stresses caused by temperature, chemical reactions, partial discharges (PDs) etc. Of this PD is a factor which degrades the insulation quality more. The presence of voids inside the insulation weakens the insulation region and is responsible for occurrence of PDs in insulation region of high voltage power equipment. It is observed that with the increase in applied voltage the PD activity also increases [1],[8].Once the PD is initialised in the insulation region of high voltage power equipment, it continues for a long time if it is not taken care of and finally insulation properties of such materials degrade. Because of the above reason PD detection and measurement is necessary [2].

According to IEC (International Electrotechnical Commission) Standard 60270, partial discharge is a localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor [3]. A gas filled cavity within a solid dielectric insulation material may be created during manufacturing, installation or operation of a high voltage system. The physical properties of voids have great effect on the characteristics of PD. A number of PD parameters can be measured by test; however, it is difficult to investigate the physical processes in voids when PD occurs. The computer simulation of PD is a well-known tool to explain the behaviour of PD in insulation system, to understand it and explore new information of that system.

In this paper, the insulation of a cable is considered as a circuit with capacitance between two conductors. With the help of Matlab/Simulink tool the circuit model is implemented. The behaviour of PD characteristics depends on apparent charge measured in the circuit model. Apparent charge of PD pulse is defined in IEC 60270 as “that charge which, if injected within a very short time between the terminals of the test object in a

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specified test circuit, would give the same reading on the measuring instrument as the PD current pulse itself [9]. The apparent charge varies with variation in applied voltage, dielectric constant and void size. Based on the values obtained by simulation, a fuzzy classification is proposed in this paper, in which applied voltage, dielectric constant and size of the void are considered as the inputs and output is the value of apparent charge.

2. Factors affecting Partial Discharge (PD)

PD activity in a cable depends upon applied voltage, dielectric constant of material and size of the void. These are considered as the factors affecting Partial Discharge in cable insulation.

2.1. Applied voltage

When applied voltage is increased, the electric field is enhanced and the electron generation rate is increased. As a result more PDs will occur. High voltage ranging from 8 kV to 50 kV is applied to the solid insulation model to observe PD activity due to the presence of void, which is done using Matlab/Simulink.

2.2 Different sample materials

Depending upon different materials used in the insulation model the apparent charge varies. Parameters in Table.1 are simulated using MATLAB/SIMULINK to observe the variation of Partial Discharge with different materials used in the sample model. Each material is having different dielectric constants.

Table 1: Parameters used in the simulation

Material	Dielectric constant ϵ_r
Air	1
Polypropylene resin	2
Cross-Linked Polyethylene (XLPE)	2.4
Fluroethylene (ECTFE)	2.5
Paper	3
Polyvinyl Chloride (PVC)	3.4
Epoxy Resin	3.6
Porcelain	5.2
Mica	6
Vulcanised Rubber	7
Alumina porcelain	10

2.3 Different void size

In the insulation of power equipment, voids are one of the main factors which cause PD and its variation in size has great effect on the characteristics of PD [5]. The lifetime of an insulation very much depended on the size of the void. Smaller size of void takes longer time to harm the insulation. Using Matlab simulation the behaviour of PD in insulation system with different void size is studied.

3. Equivalent circuit under PD

For the simulation of model, a sample made of epoxy resin of size (30mmx30mmx5mm) is considered and 50 Hz AC voltage ranging from 8kV to 50kV is applied across this sample. The permittivity, ϵ_r value of the epoxy in sample model is 3.6. To study the behaviour of PD, a void filled with air of height 4mm and radius 2mm is considered in the sample model. Fig.1 represents the sample model of insulation with void represented using capacitors.

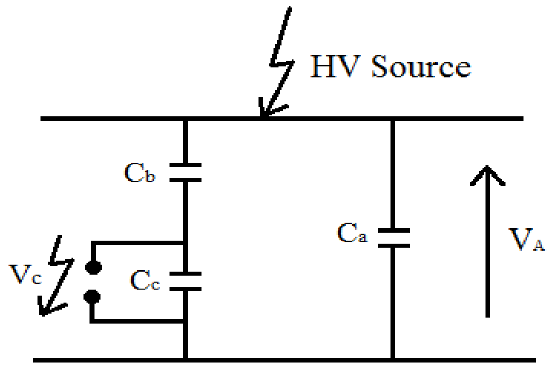


Fig.1 Sample model with void.

In the sample model C_c corresponds to the cylindrical void present inside the solid insulation. C_b corresponds to the capacitance of the remaining part of the insulation in series with void. C_a corresponds to the lumped capacitance of the rest of the solid insulation [3].

The capacitance value of the sample model with void in Fig.1 is calculated using following equations,

$$C_a = \frac{\in_0 \in_r (a-2b)b}{c} \quad (1)$$

$$C_b = \frac{\in_0 \in_r r^2 \Pi}{c-h} \quad (2)$$

$$C_c = \frac{\in_0 r^2 \Pi}{h} \quad (3)$$

Where a – length of the cube sample (mm), b – breadth of the cube sample (mm), c – thickness of the cube sample (mm), r – radius of the cylindrical void (mm), h – height of the cylindrical void (mm).

In Fig.1 the voltage across the cylindrical void C_c and the apparent charge *q* of a discharge is given by equation (4) and (5).

$$V_c = \frac{V_a C_b}{(C_a + C_b)} \quad (4)$$

$$q = C_b \Delta V_c \quad (5)$$

Where, ΔV_c is the voltage drop across the void.

Different type of insulation materials will have different values of relative permittivity or also known as dielectric constant of the insulation, denoted by ϵ_r. The relationship between dielectric constant ϵ_r and capacitance is given by equation (6),

$$C = \frac{\in_0 \in_r A}{d} \quad (6)$$

Where, ϵ_0- Dielectric constant of free space

ϵ_r- Dielectric constant of insulation material
A- Area of the electrical conductor (mm^2)
d- Thickness of the insulator layer (mm)

4. Simulation

To evaluate the occurrence of PD in the insulation sample the MATLAB Simulation circuit shown in Fig.2 is used. In the circuit C_k represents the coupling capacitor. It should have low inductance. When the coupling capacitor and the measuring system are connected separately a higher level of Partial Discharge is measured where measuring system and test object are connected in series. High voltage supply should have low degree of background noise to pass the discharge magnitude which is to be measured for a particular voltage. The input impedance of the measuring system consists of R and C. It is used for the reduction of background noise from the power supply. Measuring instrument performs the function of PD detection by measuring the charge associated with the PD pulse. Display unit and PC software is used for the characteristic study and analysis of Partial Discharge. Table.2 shows the various components and their values/rating considered for simulation.

Table 2: Value/Rating of components taken for Partial Discharge simulation.

Sl.No	Components	Value/Rating
1	HV Transformer	0.23/5 V, 50kVA
2	Coupling Capacitor, Ck	1000 µF
3	Capacitor, C_a	4.83pF
4	Capacitor, C_b	0.389 pF
5	Capacitor, C_c	0.027 pF
6	PD detector resistor	0.01 Ω

For simulation of the equivalent circuit model, a switch is connected across the capacitor C_c in Fig.2. In order to demonstrate the occurrence of PD this switch is made ON and OFF. When the switch is open no PD occurs while when it is closed a short circuit occurs, which means that an electrical breakdown occurs, as a result PD happens and discharge current flows. The switches are made ON and OFF for some instants of both the half cycles. The ON time of switch representing occurrence of PD varying from 0, 0.0002,0.0006,0.001, 0.0014 and 0.0018 and corresponding OFF time of switch varying between 0.0004, 0.0008, 0.0012 and 0.0016 indicating absence of PD. Fig.3 shows the simulation result of the simulation circuit model. The first graph i.e. voltage Vs time shows the voltage across the void capacitor and second graph shows the PD current obtained at each instants of switching on both half cycles.

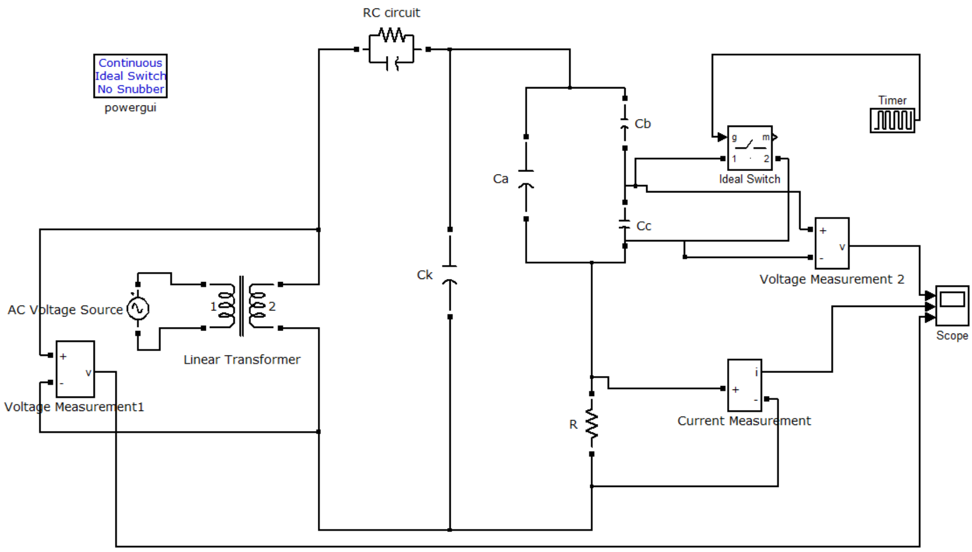
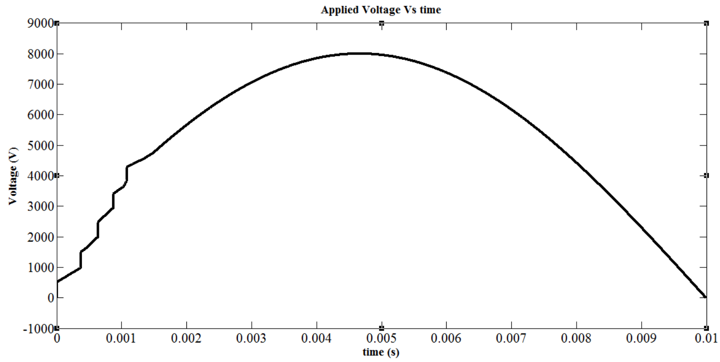
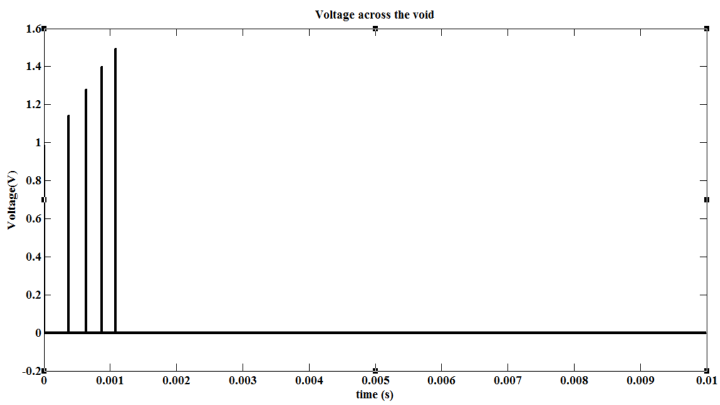


Fig.2: Simulation circuit model using MATLAB SIMULINK



(a)



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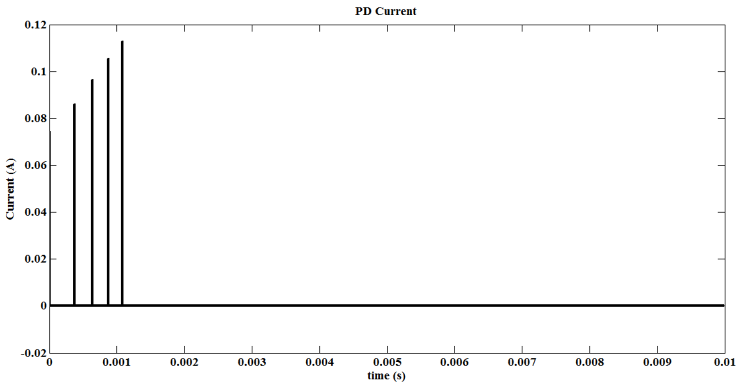

(c)

Fig 3: Simulation result of the electrical equivalent circuit model.
(a) Applied Voltage, (b) Voltage across the void, (c) PD current

In Fig 3, (a) shows the applied voltage, (b) shows the voltage across void and (c) shows the PD current. It can be concluded that whenever breakdown occurs in the void, which can be represented by the ON state of the switch connected across the capacitor C_c, PD occurs and a PD pulse is obtained.

5. Classification of PD behaviour using Fuzzy System

Fuzzy systems are found to be a powerful strategy for classification purpose, since they are capable of learning and tuning the membership functions (MF) in an explicit form [6]. The Fuzzy system was used as a suitable tool for mapping the input PD factors and the output apparent charge based on the 'If-Then' rule generated in FIS Editor GUI tool in Matlab. In this classification, PD factors are considered as the input to the Fuzzy system and the value of apparent chrage is considered as the output. Based on simulation, the input and output data for fuzzy rules are shown in Tables 3-5.

Table 3: Variation of PD with applied voltage for given dielectric constant (2.5) and void size (0.5mm)

Switch ON (sec)	Applied Voltage (kV) (Instantaneous value)	PD Pulse Amplitude (A)	Apparent charge(q) (Coulomb)
0.001	8	0.097	3.641e-16
	10	0.1217	4.555e-16
	15	0.1826	6.8308e-16
	20	0.2434	9.10e-16
	25	0.3042	1.1382e-15
	30	0.365	1.365e-15
	35	0.4256	1.5927e-15
	40	0.4863	1.8193e-15
	45	0.5468	2.0462-15
	50	0.6074	2.2729e-15

Table 4: Variation of PD amplitude for different dielectric constant for a given applied voltage (25kV) and size of the void (0.5mm)

Dielectric constant (Єr)	Capacitance value, C_b (pF)	PD Pulse Amplitude (A)	Apparent charge (q) (Coulomb)
2	0.2225	0.0533	1.175e-16
2.4	0.267	0.0646	1.7079e-16
2.5	0.2781	0.0674	1.855e-16
3	0.3337	0.0812	2.6822e-16
3.4	0.37829	0.092	3.447e-16
3.6	0.389	0.0946	3.641e-16
5.2	0.57856	0.1386	7.9378e-16
6	0.6675	0.1582	1.0454e-15
7	0.7788	0.1818	2.00268e-15
10	1.1126	0.2478	2.723e-15

Table 5: Variation of PD amplitude for different size of void for a given applied volatge (25(kV) and dielectric constant (2.5).

Radius of void (mm)	Void Capacitance (F)	PD Pulse Amplitude (A)	Apparent charge (q) (Coulomb)
0.5	2.503e-14	6.588e-3	1.6327e-18
1	1.0013e-13	0.0259	2.5693e-17
1.5	2.253e-13	0.0568	1.2667e-16
2	4.005e-13	0.0974	3.86e-16
2.2	4.846e-13	0.1159	5.5583e-16
2.5	6.258e-13	0.1456	9.0184e-16
2.8	7.85e-13	0.1783	1.377e-15
3	9.012e-13	0.1991	1.7769e-15
3.5	1.226e-12	0.256	3.1054e-15
4	1.602e-12	0.3144	4.9838e-15

All the three PD factors, applied voltage, dielectric constant and void size are having trianguler membership funtion in the range of low (L), medium (M) and high (H) . Then the output apparent charge corresponding to each input also having trianguler membership funtion in the range of low (L), medium (M) and high (H) . Table.6 shows the ranges of input and output membership function. The value of apparent charge mainly depends upon the PD factors like applied volatge, dielectric constant and size of the void present in the model. Based on the simulation result, the value of the apparent charge is classified in the range of low (L), medium (M) and high (H). If apparent charge is in low range then posibility of occurring PD is very less compared to medium and high ranges.

Table 6: Ranges of inputs and output membership fuction

		Low	Medium	High
Inputs	Applied Voltage (kV)	0-20	18-35	32-50
	Dielectric constant of the material	1-3	2.8-6	5.8-10
	Size of the void (mm)	0.5-2	1.8-3	2.8-4
Output	Apparent charge (C)	1.0e-18 – 5.5e-16	3.8e-16 – 9.1e-16	7.9e-16 – 5e-15

The knowledge base used for fuzzy are i) if more than one input variables are in low,medium or high then the output variable apparent charge also be in low,medium or high respectivily. ii) if all the input variables are different range then the output variable apparent charge is in medium. Based on the knowledge , fuzzy rules are framed and furnished in Table 7.

Table 7: Fuzzy rules

Rule No.	Inputs			Output
	Applied Voltage	Dielectric constant	Void size	Apparent charge
1	L	L	L	L
2	L	L	M	L
3	L	L	H	L
4	L	M	L	L
5	L	M	M	M
6	L	M	H	M
7	L	H	L	L
8	L	H	M	M
9	L	H	H	H
10	M	L	L	L
11	M	L	M	M
12	M	L	H	M
13	M	M	L	M
14	M	M	M	M
15	M	M	H	M
16	M	H	L	M
17	M	H	M	M
18	M	H	H	H
19	H	L	L	L
20	H	L	M	M
21	H	L	H	H
22	H	M	L	M
23	H	M	M	M
24	H	M	H	H
25	H	H	L	H
26	H	H	M	H
27	H	H	H	H

6. Results and Discussions

Apparent charge of a PD pulse is the most fundamental quantity of all PD measurements. It is usually expressed in picocoulombs. The apparent charge is not equal to the amount of charge locally involved at the site of discharge and it cannot be measured directly. So during actual measurements a calibration procedure is required where apparent charge q of well-known magnitude is injected. Tables 3-5 shows the apparent charge calculated using equation 5. In Table.3 it is observed that the value of the PD amplitude (current) increased as the applied voltage increased. This means that PD activity has a direct effect on the applied voltage. In Table.4 it is observed that the apparent charge increased with material having high value of dielectric constant are used in simulation. The radius of void used for the simulation is 2mm with material of different dielectric constants. Simulation shows that when dielectric constant value increases the apparent charge also increases. To study the PD activity due to presence of cylindrical void inside the solid insulation, size of the void is also considered. In Table.5 it is observed that with the increase of the radius of the cylindrical void apparent charge also increased. Here the radius of the cylindrical void is varied from 0.5 mm to 4 mm and correspondingly apparent charge varied from 1.6327×10^{-18}C to 4.9838×10^{-15}C respectively.

Based on the fuzzy rules, a fuzzy inference system is built, which automatically tunes the system parameters and membership functions for each rule to suit the system output given in the training set. As referred Tables 3-5, the value of apparent charge varies with increased value of applied voltage, dielectric constant and size of void in the model. The range of apparent charge can be decided by the fuzzy rules explained in Table 7. For case study , considered applied volatge is in medium range 30kV, dielectric constant is in low range 3 and the size of vois is in low range 0.5mm then the apparent charge is 2.2e-17 in low range . From this fuzzy rules based classification, PD activity can be predicted , based on the range of apparent charge . The chances of PD and thus insulation failure are more when apparent charge is at high range.

7. Conclusion

PD is considered as one of the greatest threats to cable insulation in the electrical power industry.This paper investigated the effect of parameters like applied voltage, dielectric constant of insulating materials and size of void (air) present in solid dielectric sample on partial discharge. A MATLAB SIMULINK based model has been developed which leads to better understanding of PD activity in solid dielectric with void. The model was used to simulate PD in solid dielectric under sinusoidal voltage. The value of the peak PD voltage depends on the values of applied voltage across the solid dielectric. The PD magnitude increases with the increased input applied voltage. Dielectric constants of different types of insulation materials are considered in order to see the significant difference to the peak PD voltage when different insulating materials are used. A significant change in PD magnitude could be observed when different void sizes are used. Also, this paper introduces fuzzy logic which classifies the apparent charge into different ranges by using various input PD factors. A fuzzy based rule is developed to link apparent charge to input parameters applied volatge, dielectric constant and void size. The model can be extended to two or more voids for further investigation in the future.

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