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Modeling of Partial Discharge Mechanisms in Solid Dielectric Material

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Abstract— Partial discharge (PD) represents a physical phenomenon, in which discharges are involved in electrically weak regions of solid insulation materials (mostly within gaseous or liquid inclusions). They cause damage to the insulation and often start from the enclosed voids and/or at interface defects. The period in which the insulation is still in good operating condition is of great practical interest. The effect of PD also results in failure of the dielectric much before the expected life-time. This project was conducted by simulations based on an extended PD equivalent circuit in order to understand the characteristics of PD in solid dielectric materials. In this project, PD mechanism in solid dielectric material was modeled using Simulink in MATLAB®. This project focused on the results of the partial discharges in solid dielectric with a single cavity as defect. AC source with 50Hz frequency voltage was applied. It is observed that the discharge current is proportional with the input voltage. The discharge current amplitude for input 10 kV is half the input of 20 kV and a third of 30 kV input. All discharge currents and discharge voltages occur in nano-seconds.

Index Terms—**Partial Discharge, Extended PD Equivalent Circuit, Modeling of Partial Discharge, Solid Dielectric.**

I. INTRODUCTION

Partial discharge (PD) is defined as localized electrical discharge within only a part of the insulation between two separated conductors. In the real applications, PD is caused by the existence of voids in the insulation. Even if the local electrical field in the void exceeds a threshold and a discharge occurs, it is limited within the void due to the strong surrounding insulation, enough to avoid a complete breakdown. PD in voids is considered harmful, especially in high-voltage systems from the engineering viewpoint as they cause energy loss and gradually degrade the insulation [1].

PD may occur in solid, liquid and gaseous insulation media and are generally initiated by an excessive localized electric field. The PD induced current in an external circuit depends on the nature of the discharge and the geometry of the system [2]. In many cases, where there are electrically weak areas in solid dielectric materials (most often gaseous or liquid inclusions), PD can be measured when enough voltage is applied. PD phenomenon causes degradation in insulated materials. The investigation of insulated material behaviour under electrical stress and the data obtained from PD measurements, provide the possibility to predict dielectric breakdown. There are three main types of PD: (i) micro discharges in small voids, which always exist both at the surface of electrodes and in the volume of insulators; (ii) breakdowns along the boundaries between two insulators (typically along the solid insulator–gas interface); and (iii) PD in the channels of branched structures (streamers) propagating in the volume of a dielectric medium. The second and third PD types can be considered as incomplete breakdown, since the insulating properties of a dielectric are not violated. The most complete information is provided by the so-called "phase resolved data," which have been determined for PD of all types in numerous experimental investigations [3]. Some PD simulation results which related with this work have been reported during this decade [4-9].

Fig. 1 shows an ideal PD pulse. The pulse is characterized by rise time (T_r), decay time (T_d), and pulse width (T_w). Pulse rise time (T_r), is the time required to rise from 10% to 90% levels of the peak pulse value; pulse decay time (T_d), is the time required to decay from 90% to 10% levels of the peak pulse value; whereas pulse width (T_w), is the time interval between 50% levels on both sides of the peak pulse value.

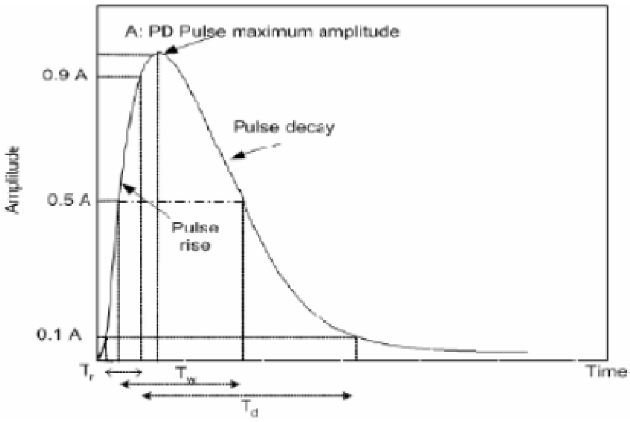


Fig. 1. Parametric characterization of PD pulse [10].

PD behaviour in inclusions (cavities, defects, etc.) in dielectrics can be represented by simple equivalent circuit developed by Gemant & Philippoff in 1932 [10], known as capacitance model. A dielectric with an internal void is shown schematically in Fig. 2, where:

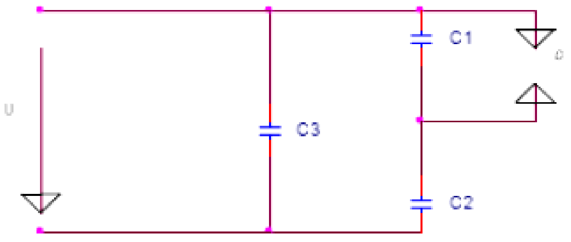


Fig. 2. Equivalent circuit of partial discharge

U : applied voltage at power frequency,
C_1 : capacitor representing the cavity,
C_2 : capacitor representing insulating material around cavity,
C_3 : capacitance of the remaining insulating material,
S : spark gap representing discharge of C_1.
C_1 and C_2 are generally not measurable.

However, the capacitance model can lead to quite incorrect conclusions, because it does not take into account the influence of all the relevant void parameters. In considering the additional electric field generated by the preceding discharge, an improved equivalent circuit has to be used. Circuit models that represent PD behavior have been developed long ago. A lot of improved circuit models have been established by researchers to get better understanding on PD. Old circuit models did not consider the role of space charges, but it can be solved by improvements to the equivalent circuit.

This project aims to simulate a circuit model of PD mechanisms in solid dielectric material utilizing MATLAB® software version 7.0.0.19920 (R14). The characteristics of PD in solid dielectric material were studied from the simulation results. This simulation involved the extended equivalent circuit based on Gemant & Philippoff's capacitance model.

II. MODELING OF PARTIAL DISCHARGE IN VOIDS

Modelling is used in this research in highlighting some of the techniques that have been used, modified, and proposed in an effort to come out with a meaningful contribution to PD analysis and interpretation. For some discharge phenomena, physical models have been developed by researchers such as Brunt, 1991 and Neimeyer, 1995. However, until now little work has been accomplished to formulate a generalized and theoretical framework to describe the PD stochastic phenomenon. By far, computer simulation programs and models for PD are scarce commodities in research. Hence, integrated models such as the one pursued in this research have not been fully realized by previous researchers, due to the complexity of the PD process. Heitz (1999) has suggested that until then there is often a severe mismatch between very sophisticated measuring facilities on one hand and strong difficulty in interpretation of the measured PD data on the other hand. Progress has recently been made by Hoof and Patsch (1998) who developed a model which is valid for different defect types. However the model was later criticized by Wu (2004), who suggested that conventional methods such as these, assumes a purely deterministic discharge behaviour and cannot be used for situations where the inherent stochastic properties of the PD generation are relevant.

Wu (2004) specifically referred to the conventional method of phase – resolve PD pattern (i.e. -q-n pattern, q: phase angle, and n: PD number) as an ineffective approach to disclose the PD mechanism. Reference was also made to the Monte Carlo simulation of the phase-resolved PD pattern. This conventional method of simulation, assumed that the total field in a cavity after PD, is reduced in proportion to the PD magnitude, and that the critical field for PD occurrence and the residual field after the discharge, mainly determine the subsequent PD magnitude. These kinds of models are thought to be inefficient in describing the large difference among PD magnitudes in cavities, in insulating materials, and the implications of changes in PD pattern with degradation.

The PD process can be considered as defined by a sequence of electrical discharges under the influence of an externally applied field $E_0(t)$. The discharges (PD events) lead to a charge deployment in the vicinity of the PD defect which initiate a so called internal field $E_i(t)$. Each PD event changes the internal field suddenly. Between the successive PD events, the internal field changes due to charge dissipation mechanism like surface conduction in voids, or charge carrier drift in gas discharges. The dynamics of the process can be described briefly in the following.

During a discharge at time t the total electric field $E_{tot}(t)$,

$$E_{tot} = E_o(t) + E_i(t) \tag{1}$$

Drops to a residual filed E_{res} :

$$E_{tot} \rightarrow E'(t) = \pm E_{res} \tag{2}$$

III. PHYSICAL MODEL

Based on experimental investigations of PD resulting from various insulation defects, a model has been developed that involves only three physically meaningful parameters. A PD occurs if the electric strength within a certain region of the insulation of an electric device is locally exceeded, but the surrounding insulation is strong enough to avoid a total breakdown. Hence the local discharge inception field is a relevant parameter. Resulting from the charge separation during a PD, local space or surface charges q , prevents the PD by producing an electric field, ΔE opposite to the ignition field, E_i. This prevents resignation until a change of the external voltage and/or a decay of the local charge again lead to an electric field, E_l, which exceeds the local inception field, E_i.

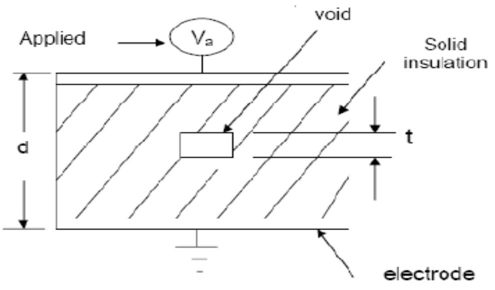


Fig. 3. Physical Modeling of a Void in Polymeric Cables [11].

As long as the defect is not changed by the influence of the PD, the numerical value of the inception field E_i where the local breakdown occurs neither will be changed. After a corresponding change of the externally applied voltage *u* another PD will occur. The fundamental correlations are shown in Fig. 3. The local field E_l before discharge n+l is given by equation (3).

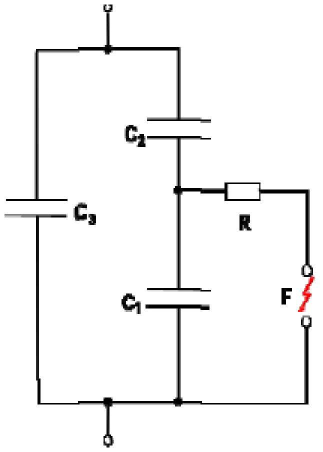


Fig. 4. Conventional PD circuit [10].

Consequently, along with the inception field, the numerical values of the field resets ΔE_q due to charge carriers being moved in the PD and a characteristic decay time τ for their dissipation and/or recombination are two other important parameters. The parameter ΔE_q, is determined by residual charges from preceding discharges. As with all physical quantities, there is a certain scatter in the numerical values of the parameters, which has to be included in the simulations.

$$E_l(t_{n+1}) = \hat{E}\sin(\omega t_{n+1}) + [\Delta E_q + \Delta E^{\pm}]exp\left(-\frac{t_{n+1}-t_n}{\tau_q^{\pm}}\right) \quad (3)$$

It is obvious that geometrically non symmetric discharge paths behave different for both polarities of the applied voltage. Hence, there will be different numerical values of the three parameters for different polarities. The important point in the model is the decoupling of the magnitude of the local electric field from the externally applied voltage. Therefore the phase angle of the applied voltage cannot be taken as a meaningful parameter as can be seen in Fig. 6 [10].

IV. SIMULATION

The PD circuit that has been used in this project came from a conventional circuit proposed by Gemant & Philippoff in 1932. The circuit is also known as 3 Capacitance Model as shown in Fig. 4. The model was then reconstructed in order to consider the additional electric field generated by preceding discharges, as can be seen in Fig. 5.

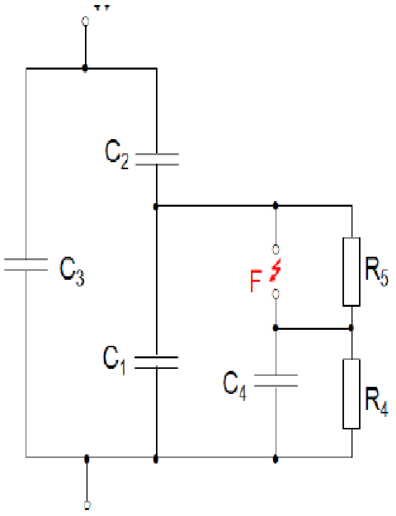


Fig. 5. Extended PD equivalent circuit [10]

Where:

F	: spark gap,
C_1	: capacitance of defect (void, impulse),
C_2	: capacitance of the healthy series with the defect,
C_3	: parallel capacitance in specimen, and
C_4	: capacitance of local charges accumulation.

$$Q = \frac{C_1C_2}{C_1+C_2} \times \frac{C_4}{C_1+C_4} \times (U_1 - U_4) \quad (4)$$

$$U_F = U_1 - U_4 \quad (5)$$

The capacitor C_4 is charged from the capacitor C_1 during the PD process until the two voltages are equal. A consecutive discharge occurs only if the voltage in equation (5) reaches the ignition voltage $U_{F'}$ of the spark gap. This may happen by a change of U_1 by the external voltage or by a change of U_4 (via a discharging process over R_4) or by both. The value of components in the circuit for the simulation is described in Table 1. This circuit was implemented with Simulink application in MATLAB® software. The spark gap in the Fig. 5 has been changed with the breaker in simulation circuit as shown in Fig. 7. This breaker is set with certain time value to represent PD occurring time.

The circuit developed in Simulink application in MATLAB® for the experiment is shown in Fig. 8. Scope 1 is used to observe discharge current, Scope 2 is to observe voltage discharge waveform and Scope 3 is to observe input voltage. In the simulation the solver solves initial value problems for ordinary differential equations (ODEs). Different solver can solve with different accuracy. We chose ode23tb with low accuracy to solve the stiff problem. The algorithms used in the ODE solvers vary according to the order of accuracy [11] and type of systems (stiff or non-stiff) they are designed to solve.

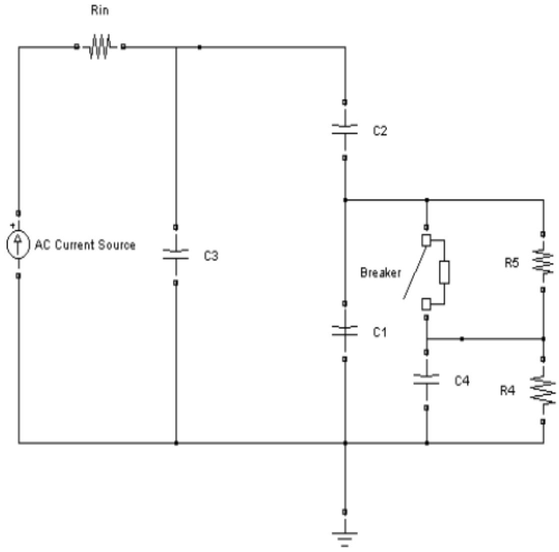


Fig. 6 Simulation Of PD Circuit With AC Source in Simulink.

Table 1. Value Of Circuit Component In AC Source For Simulation

AC Vin(kV) 50Hz		10
		15
		20
		30
Rin		5kΩ
C_1		10pF
C_2		20pF
C_3		15pF
C_4		1pF
R_4		10kΩ
R_5		5kΩ
Breaker Timing (second)	Open	1/60
	Close	1/55

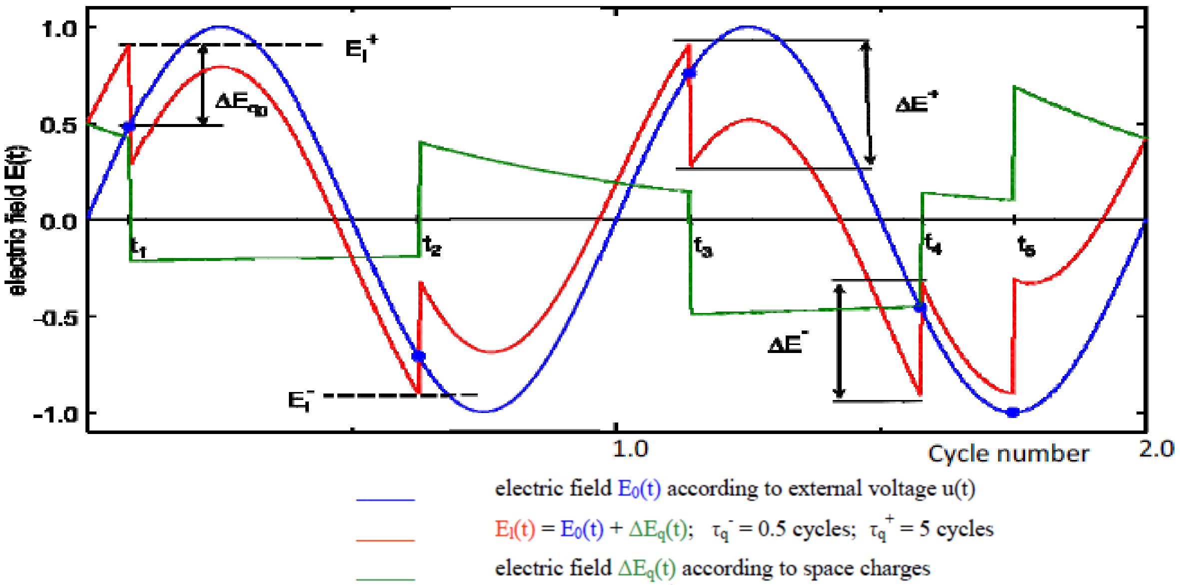


Fig. 7. Physical Model for the Simulation [10].

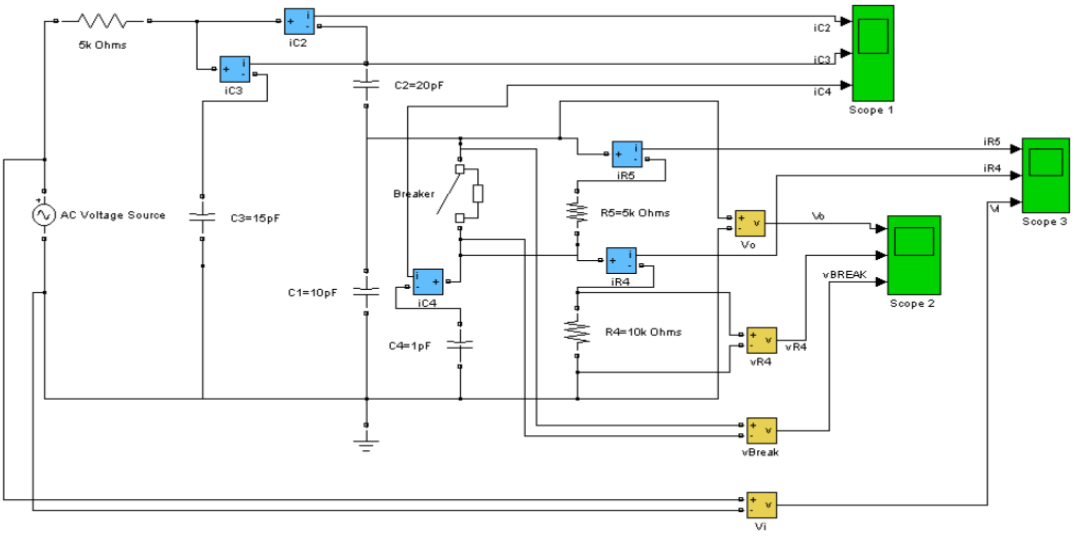


Fig. 8. Simulated Circuit Established in Simulink

V. RESULTS AND DISCUSSION

The simulation was run for 0.06 second. The applied voltage frequency was set to 50 Hz. The results of the simulation are shown in Figs. 9 to 12 for each applied voltage (10, 15, 20, and 30 kV respectively) which were observed from Scope 1 to 3, respectively (arranged in vertical order from top to bottom). From the results, discharges vary at every input voltage. For an increasing AC source, the amplitude of waveform in sampling resistance increased, as well as the single discharges waveform in a void. We observed that the discharge current is proportional with the input voltage, as can be seen in Table 2. The discharge current amplitude for input 10 kV is half of 20 kV input and a third of 30 kV input. All discharge currents and discharge voltages occurred in nano-seconds. The discharge occurred once because of the non repetitive switching mode of the breaker. To make the switching more frequent, it is necessary to replace the breaker with a circuit appropriate for repetitive switching.

Table 2. Current Discharges in 1 Decimal Places Corresponding With Applied Input Voltage

Applied Input Voltage (kV)	Current Discharge (A)
10	7.2
15	10.8
20	14.4
30	21.6

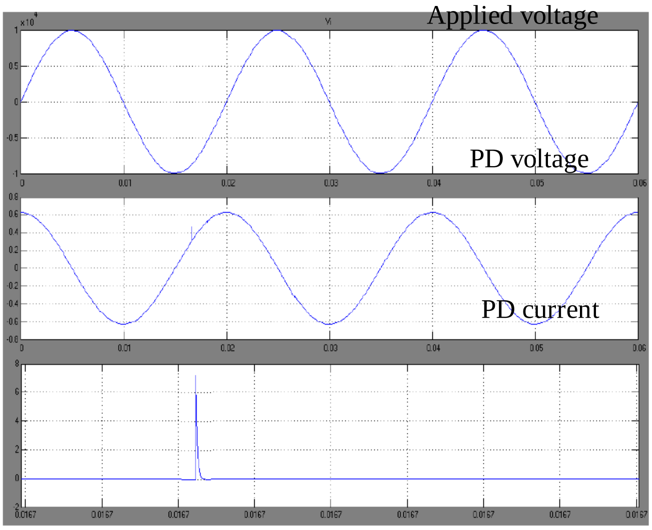
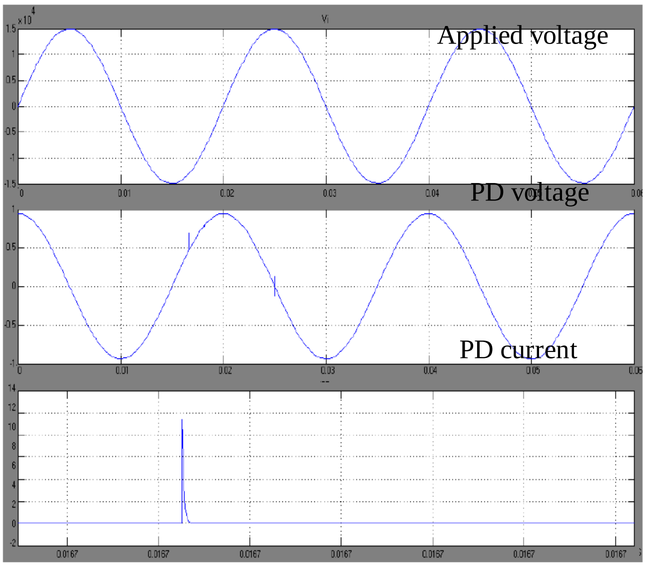


Fig. 9. Result of Simulation of Applied Voltage 10kv.



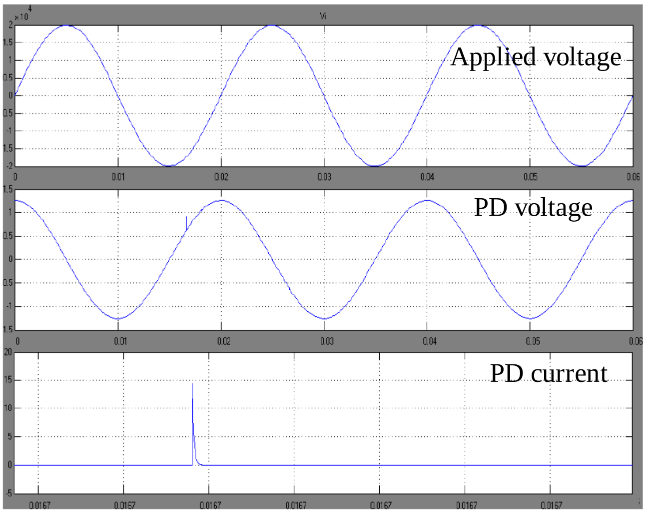


Fig. 11. Result of simulation of applied voltage 20kV.

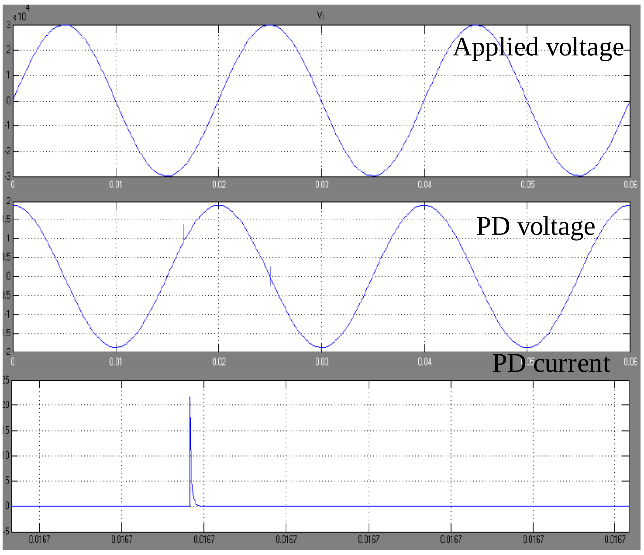


Fig. 12. Result of simulation of applied voltage 30kV.

Fig. 10. Result of Simulation of Applied Voltage 15kv.

VI.

CONCLUSION

The simulation conducted showed that the extended PD equivalent circuit was able to represent the behaviour of PD in solid dielectrics. This circuit is more accurate because it considered the influence of local charge accumulations generated by preceding discharges.

There is a slight difference of voltage waveform and current discharges in the void from the original model. This is due to the timing mode of the breaker. Breakers cannot simulate the perfect timing for PD to occur. The breaker simulates the PD only once. The value of discharge current is dependent on the input voltage. If the input voltage is increased then the discharge current will increase.

The authors recommend mathematical modelling of the circuit operation as more manipulative efforts can be applied in further research work. The mathematical model can be base on the proposed from the extended PD equivalent circuit and simulated using MATLAB M-file application.

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