Signal Processing and Renewable Energy
March 2017, (pp.47-54)
ISSN: 2008-9864

The Effect of Practical Voltages on Maximum Amplitude of Partial Discharge with Considering Different Number of Cavities

Mandana HojatTabatabaei[1] , Seyed Mohammad Hassan Hosseini[2*]
[1,2] Electrical Engineering Department, Islamic Azad University, South Tehran Branch,Tehran, Iran

Abstract
In the high voltage (HV) electrical power systems, different materials are used as the role of insulation to protect the incipient failure inside the HV power equipments. One of the common phenomenas in insulations is Partial Discharge (PD). Because of the high voltage stress, the weak section inside the insulator causes the partial discharge (PD), which is known as a local electrical breakdown. The maximum amplitude of PD could accelerate the destruction process of insulation material. Also, during practical applications in the power systems, voltages with different levels are used or created suddenly. Therefore, it is necessary to analyze the effect of voltage characteristics on the PD. In this paper, the effect of DC, AC and impulse voltage on the maximum amplitude of PD are studied within the MATLAB Simulink platform. Finally, to show the effect of each voltage level on the PD, results are compared with each other in the single and multi cavity situations. The test materials for this research are epoxy resin and oil-impregnated paper. Also, this paper provides a comparison between two different insulation materials.

Keywords: Partial Discharge (PD), Practical Voltages, Impulse Voltage, Impulse Voltage Generator Circuit, MATLAB Simulink Platform, multi cavity condition

1. INTRODUCTION

Recently, some investigations are presented regarding the partial discharge studies. As an example, an extensive off-line and on-line test are applied to the stator winding insulation in motors and generators rated 6 kV or more (Edin, 2001). The results show that the PD current may only occur for a short time prior to failure with some types of mechanisms. Therefore, to avoid in-service failures, it is necessary to have a continuous monitoring scheme. As another instance, author (Smith, 2005) evaluate the effect of the cavity size and the cavity location on the PD frequency dependence. In the paper, variable frequency phase-resolved partial discharge analysis (VF-PRPDA) is presented, in which the frequency is varied between (10 mHz- 100 Hz) intervals. The results show how the frequency dependence of PD is influenced by the cavity place and the diameter. In the (Nyanteh, Graber, Edrington, Srivastava and Cartes, 2011), a new technique is proposed to decide the gas pressure in a vacuum interrupter based on the PD analysis. In fact, in such studies the PD analysis are a means of pressure detection. In this method, the pressure below and above 260 Pa on the basis of

*Corresponding Author's Email: Smhh110@azad.ac.ir

the rise time and the peak intensity of the partial discharge light pulses are detected. The results show that the proposed approach, where a relatively longer rise time with a smaller magnitude was attributed to a Townsend-like discharge at the pressures below 260 Pa, is accurate. Also, a sharper rise with a larger magnitude is a streamer-like discharge above 260 Pa. Some literatures have proposed several methods in order to find the PD features of particles under the AC condition. In fact, the PD characteristics of the free spherical conducting particle in the quasi-uniform electric field are analyzed in (Lai, Phung and Blackburn, 2009), regarding the better explanation of the PD measurement. In this paper the different voltage types are considered through case studies. In addition, the effect of oil aging is evaluated in this method. The results indicate that the PD pattern is different in various particle motion stages and the number of particles has a significant influence on the PD frequency and a mere influence on the PD pattern. In (Suzukil, Aihara and Okamoto, 2004) two sub-networks for PD recognition are constructed. Then, in order to reduce the possibility of misclassification, a new fusion decision-making system for the PD recognition is proposed on the basis of fusing the results from sub-networks. The classification results indicate that the proposed scheme decreases the uncertainty and effectively improves the credibility of diagnosis. The authors in (Salam, Mazen, Anis, Hussein El-Morshedy,

Ahdab ,Radwan and Roshdy ,2000) suggest a time-frequency analysis and fuzzy clustering over RF pulse waveforms generated by partial discharge which obtains and saves, and isolates the partial discharge signals from different partial discharge sources and interferences. From this scheme, it is possible to accurately position multiple partial discharge sources. In (Naidu, Kamaraju,1995) the partial discharge issue is studied in the gas insulated systems (GISs) at high voltage AC and DC types. The comparison of these voltage types is presented through a case study section in this paper. Two PD patterns are used for HVAC and HVDC analysis, namely, the phase resolved partial discharge patterns (PRPD) and the time resolved partial discharge patterns (TRPD). The study of PD is done in (IEC Standard 60270, 1996) for small-air-gap in cast-resin insulation system. Indeed, this article focuses on the Paschen curve theory. Using this theory, the PD behavior is evaluated in different high voltage types. The references (Umemura, Nakamura, Hikita, Maeda, Higashiyama, 2013) focus on the intrinsic features of the typical flaws in GIS, such as the amplitude of the time-domain signal and the frequency spectrum characteristics. Four types of specific partial discharge sources are designed and fabricated, including floating metal, protrusions, particle on the spacer, and void in solid insulation. Several different structure sizes of each fault ensure the consistency of the results and discover the factors that affect the frequency spectrum characteristics. The study results present the crucial characteristics of the partial discharge. It can be applied to the design of the coupler and amplifier circuits. In addition, the sensitivity and anti-interference capability of the UHF scheme are promoted effectively, and it is worthwhile to calibrate the intensity of PD in GIS. Also, in (Li, Hu, Zhao, Yao, Luo, Li, 2011) the partial discharge pulse, the sequence patterns and the cavity development time in transformer oil under AC conditions are investigated in order to analyze the effect of PD pulse on the insulation. The latter were indicatives of a short-lived cavity expansion-collapse time period, whereas the former referred to a relatively large streamer within the liquid phase that initiated the cavity.

The electrical insulation is one of the most important parts in high-voltage components and its quality determines the reliability of the whole equipment (Edin, 2001).

This important part of the system must protect equipment against electrical stresses caused by applying voltages, mechanical stresses, temperature variations, etc. A variety of solid, gaseous, liquid and the combination of these materials are used as an insulation material in the power systems. To observe the equipment in operation, the insulation must be able to maintain the same quality during the time that the system is operated. But, it gradually could be degraded because of some reasons, such as the environmental conditions, the chemical, the electrical, and the mechanical stresses caused by electrical failures.

According to the IEC 60270 standard (IEC Standard 60270,1996), the Partial Discharge (PD) is a low-level electrical breakdown phenomenon confined to the localized region of an insulation material between two conductors at different voltage levels (Lai, Phung and Blackburn, 2009).

The partial discharge (PD) may be in a gas filled void inside a solid insulating material that may be developed during the manufacturing process or in impurity voids present in the material, in a gas bubble in a liquid insulator or around an electrode in the gas. When PD occurs in the gas, it is usually known as corona (Smith, 2005).

In a solid insulation, the cavities built through the manufacturing process can be in the form of any geometrical shape such as rectangular, spherical, elliptical, cylindrical, etc. These cavities are usually filled with gas which is of lower breakdown strength than the surrounding solid. Even if the local electrical field in the cavity exceeds a threshold and a discharge occurs, it is limited within the cavity, because the surrounding insulation is strong enough to avoid a complete breakdown (Nyanteh, Graber, Edrington, Srivastava and Cartes, 2011). However, once the PD starts inside the high voltage power equipment it continues for a long time, if it is not taken care of , finally insulation properties of such materials degrade in quality. The time of destruction of the insulation material deals with the maximum amplitude of PD. Therefore, the high amplitude of PD causes to accelerate the destruction process of the insulation material. So, in this work, we want to analyze the maximum amplitude of PD to show the effect of different types of voltage with different levels on the PD. Also, the effect of cavity number on the maximum amplitude of PD is evaluated.

There are some techniques for modeling PD and studying the parameters which affect that such as temperature, shape and size of the void, frequency, shape and the level of voltage, etc (Nyanteh, Graber, Edrington, Srivastava and Cartes, 2011). In this work the well-known 3 capacitor model that is located in physics on the based group is used and the effect of the waveform, magnitude and frequency of the applying voltage is studied.

As to the structure of the paper: Section 2 indicates the fundamental of a simulation model of PD. Section 3 explains the characteristics of practical voltages (i.e. DC, AC and impulse voltage) and the impulse generator circuit. In the section 4, by using the simulation model, DC, AC and the impulse voltage with different levels applied to test the objects (i.e. the Epoxy resin, and the oil-impregnated paper) and the results are compared to each other.

2 . FUNDAMENTAL OF PARTIAL DISCHARGE SIMULATION MODEL

To conduct the simulation, assume a solid insulator of thickness *d* contains a small cylindrical shaped cavity of thickness *h*, and area *A*, as shown in Fig. 1. The most frequently used model of the electrical insulation with a void is shown in Fig. 2(Suzukil, Aihara and Okamoto, 2004). The capacitance C_c corresponds to the cavity which has a short-circuit at the moment of discharge, C_b represents the capacity of the dielectric that is in series with C_c and the remainder of electrical insulation is represented by the capacitance C_a.

The value of this capacitance can be calculated with use of

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{1}$$

where

ε_0 : permittivity of free space

ε_r : relative permittivity

A : area between electrodes

d : separation of electrodes

It is assumed that the gas in cavity has ε_r approximately 1, so:

$$C_c = \frac{\varepsilon_0 A}{h} \tag{2}$$

and

$$C_b = \frac{\varepsilon_0 \varepsilon_r A}{d-h} \tag{3}$$

where the ε_r is relative permittivity of the solid insulator.The voltage across the cavity is

$$V_c = \frac{C_b}{C_b + C_c} V_o \tag{4}$$

where V is the voltage across the whole insulation (i.e. testing object).

By substituting equations (2) and (3) into (4) the voltage and electrical fields across cavity will be equal:

$$V_c = \frac{1}{1 + \frac{1}{\varepsilon_r}\left(\frac{d}{h} - 1\right)} V_o \tag{5}$$

$$E_c = \frac{d}{h\left(1 + \frac{1}{\varepsilon_r}\left(\frac{d}{h} - 1\right)\right)} E_o \tag{6}$$

As regards in most states h<<d and ε_r is greater than 1, it can be seen that the electrical field in cavity is greater than the surrounding insulation. Regarding the ratio d/h>>1, with a good approximation, equation can be described as:

$$E_c = \varepsilon_r E_o \tag{7}$$

According to this model, the usual description of PD process is as follows: Assuming that an alternative waveform like sinusoidal voltage is applied to the insulation, in the beginning due to not existing the net electrical charge on the surface of void, voltage across the C_c increases until the voltage V_c reaches the critical voltage, $V_{critical}$, at this time breakdown takes place and is followed by V_c decrease and some free charge accumulates on the surface of the void. Quantity and distribution of this charge are depended on the shape, size and surface conductivity of the void, etc. This charge is remained across the void if it is presumed that the insulator surrounding the void is perfect insulator otherwise some of those penetrate to the insulator. This free charge creates an electrostatic field in the opposite direction of the main field, E_0, that is shown with E_q in fig , hence for the next PD, more voltage should be applied across the void to help the field in the void reach the critical quantity which leads to the breakdown. After *n* PD the free charge accumulated in the void is equal to the sum of the charges accumulated due to each PD. This act will continue until the rate of rise applied voltage becomes small, near the peak voltage, in this time do there won't be any PD. After peak voltage is passed, the voltage will decrease to some extent, now the field created due to the free charge accumulation overcomes the main field and PD takes place, but this time in the opposite direction and new free charge accumulates in contrary to primary charge that will cause the total charge of void to reduce. In negative period, the total charge will be negative. In the other words, the surface of the void will have opposite charge relative positive period. So the PD will take place in the same direction with derivatives of applied voltage, that is to say when voltage is incrementing the polarity of PDs is positive and vice versa.

Fig. 3, illustrates how the electric field and current pulse across a cavity changes with applied voltage (Edin, 2001).

3.CHARACTERISTICS OF PRACTICAL VOLTAGES

The most power systems use AC voltages for transmission and distribution the power. But nowadays with developing the power electronics devices, the HVDC systems are considered widely and in the some regions are used. Also, the use of these equipment for converting AC/DC and DC/AC voltages in DC systems causes to observe the high level impulse voltages. In addition to being switched by power electronic devices, as mentioned, the lightning is one of the sources of the generation impulse voltage. This form of voltage has some special characteristics such as the high amplitude ratio to nominate system voltage and wide frequency band.

Because of these reasons, it is necessary to study the effect of these voltages at PD in insulator of HV power equipment.

The impulse waveform is nearly doubled exponential in shape. It can be represented by the difference of two equal magnitudes exponentially decaying waveforms. The Impulse voltage that is shown in Fig. 4, in (Salam, Mazen, Anis, Hussein El-Morshedy, Ahdab ,Radwan and Roshdy, 2000), can be generated by an impulse voltage test generator based on Marx multi-stage circuit.

The basic circuit of Marx generator is shown in Fig. 5.

According to IEC, the time that take for the surge to reach the 90% of its peak (front time) is essentially determined by the resistance of the front resistor R_1 located in the impulse voltage test generator and the capacitance C_2, and the time taken for this surge to decay from its peak to its half way value (tail Time) is determined by the discharge capacitance C_1 and the resistance of the tail resistor R_2 being Parallel with the capacitor of C_2. If testing object is considered such as shown in Fig. 5, the new value of C_2will be equal to $C_{2+}C_{to}$. According to IEC, there are the following time parameters and tolerances for the standard:

Front time $T_1 = 1.2$ μs + 30 %

Time to half-value $T_2 = 50$ μs + 20 %

There is a standard ratio of C_1/C_2 for that particular Marx generator circuit, as represented in Table. 1.Calculation for one stage Marx generator in (Salam, Mazen, Anis, Hussein El-Morshedy, Ahdab ,Radwan and Roshdy, 2000) :

Table 1.*Limiting value of C_1/C_2 for different standard waves .*

	Value measure	T_1/T_2 (μs)			
Fig. 5		1.2/5	1.2/50	1.2/200	250/2500
	Max(C_1/C_2)	-	40	185.19	6.37

From standard waveform of Marx generator,

$$T_1 = 3\times R_1 \times \frac{C_1 \times C_2}{C_1 + C_2} \approx 3\times R_1 \times C_2 \qquad (8)$$

and

$$T_2 = 0.7\times (R_2 + R_1)\times (C_1 + C_2) \approx 0.7\times R_2 \times C_1 \qquad (9)$$

With having the value of C_2, value of R_1 and R_2will be achieved by (8) and (9).

It is important to note that if we use the Marx multistage circuit for generating the higher amplitude impulse waveform, Fig. 6, in this state the nominal output voltage is the number of stages (i.e. *n*) multiplied by the charging voltage and the discharge capacitance, C_1 , will be C/n.

Usually, charging resistance R_s is chosen to limit the charging current to about 50 to 100 mA while the generator capacitance C is chosen so that the product CR_s is about to 10s to 1 minute. The discharge time constant CR_1/n (for n stages) will be too small (microseconds), compared to the charging time constant CR_s which will be few second (Naidu, Kamaraju ,1995).

4.CASE STUDIES

To assess the impact of different voltages on PD, the epoxy resin and oil-impregnated paper with a small cylindrical void inside the solid insulation materials, are considered as the testing object. Table. 2 shows the simulation parameters needed to conduct the study. In this study, firstly epoxy resin is considered as a test object, and then the oil-impregnated paper is supposed to be tested. Finally, a comparison between the results is presented.

Also, the PD simulating circuit is shown in Fig. 7. According to the equations (2) and (3), by using the parameters that are given in Table.1, one can calculate the values of testing object capacitors. Table. 3 illustrates the specifications of components and their values used for the PD simulation.

Table 2. ***The simulating parameters used in the study.***

	Parameter	Symbol	Value	Dimension
1	Gas spacing between electrodes	d	0.005	m
2	Relative permittivity of oil-impregnated paper	ε_r	5	--------
3	Relative permittivity of epoxy resin	ε_r	3.5	--------
4	Permittivity of free space	ε_0	8.852×10^{-12}	F/m
5	Constant characteristics of gas	B	8.6	$Pa^{0.5}.m^{0.5}$
6	Pressure	P	10^5	N/m^2

Specification of different components and their values used for simulation

Table 3. ***The obtained values for different components.***

No.	Components	Value/ Rating
1	HV transformer	0.23/70 kV, 100 kVA
2	HV measuring capacitor	200/1500 pF
3	HV coupling capacitor	1000µF
4	Detector circuit resistance	50 Ω
5	Detector circuit inductance	0.63 mH
6	Detector circuit capacitance	0.47 µF

A.Epoxy resin test object

To analyze the effect of different voltages on the PD amplitude, DC, AC, and the impulse voltage are applied to the circuit of modeling insulation material (i.e. Epoxy resin as a solid insulation material).

By applying different DC voltage levels to the circuit given in Fig. 7, the maximum PD amplitude is obtained and shown in Fig. 8.

Also, the different AC voltage levels are applied to simulation model and results are represented in Fig. 9.

In addition, Fig. 10 illustrates the maximum amplitude variation of PD due to increasing frequency of AC voltage in the specific amplitude voltage.

By comparing the maximum amplitude of PD in different frequencies of AC voltage shown in Fig. 10, we can obtain, when the frequency of voltage increases, the maximum amplitude of PD decreases because of decreasing the time of discharge in high frequency.

This time, the impulse voltage is applied to simulation modeling. The circuit used to generate the impulse voltage is shown in Fig. 6. The value of components used for generating impulse voltage is given in Table. 4. By simulating this circuit, the impulse voltage with the specific characteristics (i.e. Given in Table.1.) is obtained.

Table 4. ***The values of component to simulate the impulse generator circuit.***

	T_1/T_2 (µs)	R_1 (Ω)	R_2 (Ω)	C_1 (µF)	C_2 (µF)	R_s (kΩ)
Impulse generator circuit	1.2/50	32	142	0.5	.0125	18

By applying different impulse voltage levels, the maximum PD amplitude is obtained and the results are shown in Fig. 11.

By comparing the obtained results from simulation in equal voltages, one can find out that the maximum amplitude of the PD in impulse type voltage is more than AC and DC voltages. So in equipment with high probability of impulse voltage occurrence, we need to use the more quality of insulation materials to decrease the occurrence of PD.

In the last part, the effect of cavity number on the maximum amplitude of PD is presented in Table. 5. As shown in Table. 5, the maximum amplitude of PD in different number of cavities are compared to each other.

Table 5. ***The comparison of maximum amplitude of PD in different number of cavities with typical voltage levels in epoxy resin test object.***

Number of Cavities	**1**	**2**	**3**	**4**
12000 V DC voltage	0.0073 A	0.0071 A	0.0064 A	0.0053 A
16000 V DC voltage	0.0091 A	0.0089 A	0.0085 A	0.0082 A
12000 V AC voltage	0.01 A	0.009 A	0.008 A	0.008 A
16000 V AC voltage	0.025 A	0.024 A	0.024 A	0.022 A

By comparing the results, it can be noted that increase of the number of cavities can decrease the maximum amplitude of PD in the epoxy resin test object. That is, the applying voltage is divided between cavities. So, each cavity has fewer mount of voltage than before. Consequently, the maximum amplitude of PD decreases.

B. Oil-impregnated paper test object

To study the effect of voltages on the PD maximum magnitude, another test object is used to examine the previous section results. In this part, the oil-impregnated paper is used as a test object. As previously stated, the difference between epoxy resin and oil-impregnated paper is related to their relative permittivity.

Initially, the AC voltages are considered to apply on the simulating circuit, including oil-impregnated paper as an insulation material. The simulation result is shown in Fig. 12. The vertical axis shows the amount of maximum amplitude of the PD in the case of different voltage values. From the above we can infer that the maximum amplitude of PD in the case of AC voltages is quite the same as the results under the condition of epoxy resin testing object.

Also, the effect of frequency on the maximum amplitude of PD is shown in Fig.13. It is obvious that the maximum amplitude of PD is negligible when there is a high frequency application.

In another case, the DC voltages are applied to the testing system in which oil-impregnated paper is placed as a testing object. In this case the maximum amplitude of the PD rises as shown in Fig. 1.

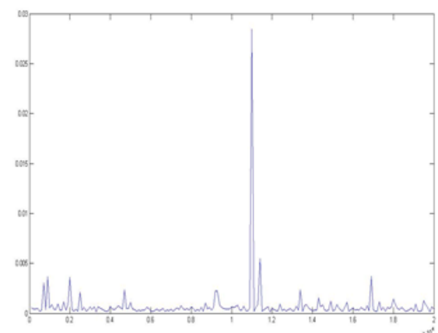

Fig. 1. The maximum amplitude of PD in the case of DC voltages in oil-impregnated paper testing object

In comparison to the previous testing object, namely epoxy resin, on can find out that the epoxy resin runs a risk of happening the high maximum amplitude of the PD. As shown, in the second testing object, the maximum amplitude of the PD is below 0.5 A. However, the maximum amplitude of the PD in epoxy resin is above 0.5 A in the most voltage values. So, it can be concluded that the quality of oil-impregnated paper is better than epoxy resin against PD.

As the last result, for an example, a simulation result is shown in Fig. 15. In this figure, the voltage value of DC source is set to10 kV.

5. CONCLUSION

This paper aims to analyze the effect of practical voltages on Partial Discharge (PD). To conduct the simulation, the 3 capacitor model is used and the epoxy resin is considered as a solid insulation material. By comparing the maximum amplitude of PD in different frequencies with definite voltages, decreasing of maximum amplitude of PD is obtained due to low time of discharge in high frequency. Also, by comparing the results in the different types of voltages, we find out that the maximum amplitude of PD in impulse voltage is more than other voltages in a specific applied voltage. So, in equipment with high probability of occurrence of PD, it is necessary to use more quality insulation materials to protect the insulation materials. Also, the increase of the number of cavities can decrease the maximum amplitude of PD. Moreover, the quality of oil-impregnated paper is better than epoxy resin regarding the PD phenomenon.

REFERENCES

[1] Abdel-Salam, Mazen, Anis, Hussein, El-Morshedy, Ahdab, Radwan, & Roshdy. (2000). High-Voltage Engineering: Theory and Practice. 2nd. ed. United States of America: Marcel Dekker, pp 550-565

[2] Edin, H. (2001) . Partial Discharges Studied with Variable Frequency of the Applied Voltage (Doctoral dissertstion).

[3] Lai, K.X. Phung B.T, Blackburn, T.R (2009). Investigation of partial discharge in single void and multi-voids using data mining technique, Power Engineering Conference 2009, AUPEC.

[4] Li, J. Hu, Q. Zhao,X. Yao,X. Luo,Y.

[5] Li,Y. (2011). Partial-Discharge Characteristics of Free Spherical Conducting Particles Under AC Condition in Transformer Oils.

[6] Naidu, M.S. & Kamaraju, V. (1995). High Voltage Engineering. 2nd. ed. New Delhi: Tata McGraw-Hill, , pp 148-151.

[7] Nyanteh, Y. Graber, L. Edrington, C. Srivastava, S. & Cartes, D. (2011). Overview of Simulation Models for Partial Discharge and Electrical Treeing to Determine Feasibility for Estimation of Remaining Life of Machine Insulation Systems" Electrical Insulation Conference (EIC). pp. 327-332, 5 - 8 June.

[8] Dr. Smith, C. (2005). Partial Discharge & Insualtion Failure. IPEC Ltd..

[9] Suzukil, H. Aihara, K. Okamoto, & T. Complex. (2004) behaviour of a simple partial-discharge model, " EPO Europhys. Lett , 28-34.

[10] IEC Standard 60270. (1996). High Volt age Testing: Partial Discharge Measurement.

[11] Umemura, T. Nakamura, S. Hikita, M. Maeda, T Higashiyama, M. (2013). Partial Discharges of Small-air-gap in Cast-resin Insulation System. Dielectrics and Electrical Insulation.