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SIMULATION ON THE CONDITIONS AFFECTING PARTIAL DISCHARGE INITIATION IN MICROBUBBLE IMMERSED IN DIELECTRIC LIQUID

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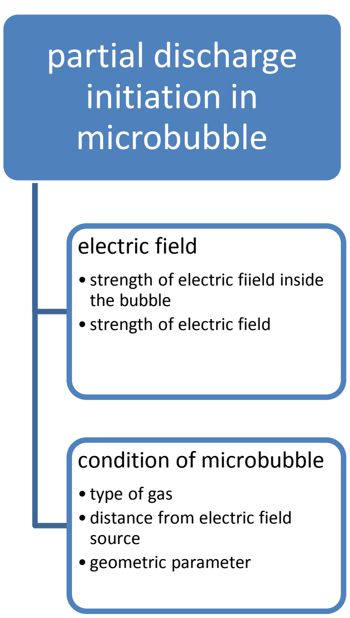
Graphical abstract



Abstract

Microbubble floating in liquid dielectric and subjected to an electric field may initiate partial discharge (PD). This paper studies the parameters that affect the initiation through a computer simulation. This study inspects how the type of gas inside the microbubble, the size of the microbubble, distance from an electric field, E_o, source and, the magnitude of source's voltage affect the start of PD. For a prolate spheroid shape, there is an important parameter called 'c'. This ratio is between the radius of the microbubble polar ('a') and the radius of the equator ('b'). At constant E_o and c, different gases will initiate PD at different distances from source due to differences in a localised electric field inside the microbubble (E_{max}). E_{max} is one of the important factors for PD initiation. It is interesting to report that if the 'a' and 'b' values are chosen so that 'c' will be constant, changes in E_{max} are insignificant. On the other hand, changes in 'c' will result in significant changes in E_{max}. Finally, changes in source's voltage certainly affect the E_{max}.

Keywords: Partial discharge, simulation, dielectric liquid, transformer, microbubble

Abstrak

Buih mikro di dalam dielektrik cecair mungkin akan menghasilkan discaj separa (DS) apabila dikenakan medan elektrik. Kertas ini membincangkan parameter yang mempengaruhi DS melalui simulasi computer. Perbincangan dibuat bagi melihat bagaimana jenis gas di dalam buih, saiz buih, jarak dari punca medan elektrik, E_o, magnitud sumber voltan mempengaruhi permulaan DS. Bagi bentuk 'prolate spheroid, terdapat satu parameter penting yang dipanggil 'c'. Parameter ini merupakan nisbah antara radius antara kutub dan radius antara ekuator sferoid berkenaan. Pada E_o dan c yang malar, jenis gas mempengaruhi permulaan DS pada jarak yang berbeza akibat perbezaan dalam medan elektrik setempat E_{max}. E_{max} merupakan salah satu faktor penting dalam permulaan DS. Adalah penting untuk diutarakan bahawa jika nilai-nilai 'a' dan 'b' dipilih supaya 'c' adalah malar, perubahan dalam E_{max} adalah kecil. Manakala perubahan 'c' akan mengakibatkan perubahan besar dalam E_{max}. Akhirnya didapati perubahan dalam voltan sumber menyebabkan perubahan nyata dalam E_{max}.

Kata kunci: Discaj separa, simulasi, dielektrik cecair, alat ubah, buih mikro

1.0 INTRODUCTION

Partial discharge (PD) in dielectric liquid has been an active research due to its importance in determining the condition of insulation. In addition, PD also contributes to the degradation of insulation quality [1]. This phenomenon takes place due to several factors. For example, PD can be initiated due to microbubble, small floating material or impurity in the dielectric liquid. This paper will focus on PD due to microbubble. In fact, the presence of microbubble is essential in explaining the existence of PD in liquid [2], [3], [4]. The presence of bubble is the cornerstone of streamer theory that explains PD. Streamer theory has become more dominant in recent years [5]. Under this theory, the PD is actually the breakdown of the elongated gas bubble due to cumulative collision-ionisation processes.

By definition, PD refers to a phenomenon where insulation is partially bridged electrically [6],[7]. This is in-line with the above explanation about the breakdown in a gaseous bubble. Regarding the collision-ionisation process in the bubble, two factors come into play: the presence of free electrons and adequately high electric field inside a gaseous microbubble, $\boldsymbol{E}$ [8], [9], [10], [11]. If $\boldsymbol{E}$ is larger than the breakdown of the gas residing in the bubble, $\boldsymbol{E_b}$, PD could be initiated. The value of $\boldsymbol{E}$, on the other hand, is affected by several conditions. Some of the conditions are going to be studied in this research.

In this study, only $\boldsymbol{E}$ would be considered as an enabling factor for PD. It is assumed that the numbers of electrons are adequate. The resultant $\boldsymbol{E}$ will be studied under several conditions. They are the type of gases inside the microbubble, microbubble geometric parameters, the strength of electric field source and its distance from the source itself. From the value of $\boldsymbol{E}$, it is assumed that PD would start.

Simulation on the PD initiation will usually involve two charged electrodes with a specified gap and microbubble is placed in between [11], [12]. However, for this paper, a different approach is taken. A model was developed to mimic the actual dimension in a power transformer. It means that only one charged electrode exists: the core.

The voltage of the core will be varied, while the other electrode is the grounded transformer tank. Microbubble will be placed within the space, which is filled with dielectric liquid with specified parametric values. The distance of the microbubble relative to the surface of electric field source will also be varied.

The size and geometry shape of the microbubble also are going to be varied. The geometrical parameters that will be varied are the polar-equator radius ratios as well as the shape of the bubble. Gasses that chosen to fill the microbubble are air, ethane and methane [13].

Results from the simulation should then be analysed in term of its parameters influence in enabling the initiation of PD. Understanding can give an insight into the probability of PD to initiate inside oil-filled power transformer.

2.0 METHODOLOGY

Microbubble is the heart of the simulation presented in this paper. It will be subjected to a different magnitude of electrical filed, filled with different gas, located at a different distance from the electric field source and its geometric parameters are varied.

Throughout this paper, the terms microbubble and bubble are used interchangeably. Both mean the same: the minute when the bubble existed in the dielectric liquid within the power transformer.

It is important to acknowledge that distance from the pole of the microbubble to the surface of electric field source must be constant regardless of the size of the bubble. A small mathematical relationship has been developed in this paper to cater to the problem.

2.1 Microbubble in Dielectric Liquid

There are several views on the formation of gaseous microbubbles in the liquid dielectric. Among others are pre-existence, joule heating, electro-chemical effect (such as PD itself), electron collision, formation at a lower temperature of the moist region and different of pressure (e.g. due to vibration) [3], [4], [14], [15], [16]. In [17] it was noted that microbubble may be naturally occurred due to the presence of dissolved gasses subjected to the electric field. Among gasses that are commonly found include hydrogen, oxygen, nitrogen, methane, ethane, carbon dioxide and carbon monoxide [18], [19].

Each gas has different physical parametric values including relative permittivity, ε_r, and electric conductivity, σ. It is a fact that ε_r and σ values are affected by pressure and temperature. Hence, for the purpose of this paper, pressure and temperature are made constant throughout the time taken during any period of observation.

However, it can be shown that the resultant $\boldsymbol{E}$ in microbubble is only related to ε_r. Therefore, for each gas accurate, ε_r will be fed into the simulation. On the other hand, the value of σ for each of the different gases can be assumed to be in the range of 1 fS/m as specified in [20]. For air, σ = 0 S/m and ε_r = 1 as provided by simulation software itself.

2.2 Microbubble in Dielectric Liquid Subjected to Electric Field

Microbubble that is subjected to the external electric field, $\boldsymbol{E_o}$, will experience Coulomb force that eventually deforms its original shape and affects its original position. The geometric shape of a microbubble in the presence of $\boldsymbol{E_o}$ has been reported to be prolate spheroid [2], [17], [21]. The microbubble (shaded shape) with prolate spheroid shape is shown in Figure 1. The microbubble position is shown relative to the quarter - circular conductor at the left bottom of the figure.

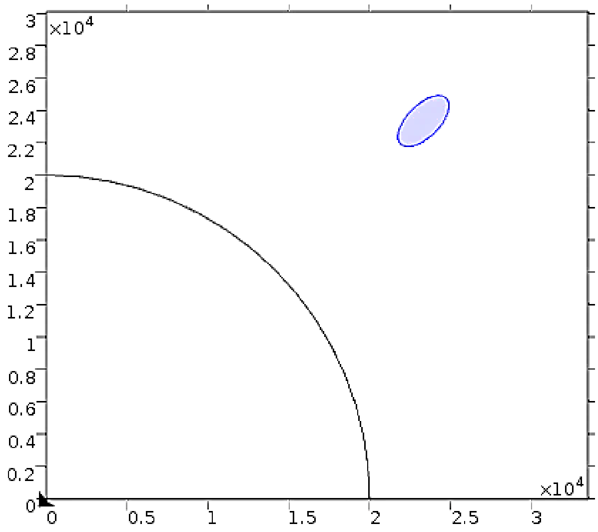


Figure 1 Prolate spheroid microbubble orientation relative to the surface of the conductor

One aspect of studies in this paper is to observe the susceptibility of PD to start for different gases. Different gas with distinct ε_r will result in different ***E***. For bubble, ***E*** can be described using [22]:

$$\boldsymbol{E} = \boldsymbol{E_o}\left(\frac{3\varepsilon_r}{2\varepsilon_r+1}\right) \quad (1)$$

Another matter to be investigated is the effect of the size of microbubble on ***E***. It is unknown whether there is minimum or maximum bubble size for PD to take place. However, most of the articles or papers are referring to the void as microbubble [13], [23]. In fact, in [13] the size of the microbubble is stated as between 2 – 10 µm.

However, there was an experiment done using larger sizes of bubbles. Babayeva *et al*. reported a study where the size of the bubbles are 40 – 100 µm [22]. For their own study, they are simulating PD for the bubble of 100 – 500 µm in size.

In another study, bubbles sizes were divided into large (around 100 µl), medium (around 30 µl) and small (around 5 µl) [24]. Assuming that the natural shape of a small bubble in oil (before subjected to the electrical field) is spherical [25], the diameter of the bubbles would be 0.00576 m (5.76 mm, large), 0.00386 m (3.86 mm, medium) and 0.00212 m (2.12 mm, small). PD was initiated in all sizes of bubbles at a different voltage, or also known as partial discharge inception voltage, PDIV. Table 1 is the tabulation of the relation between the size of bubbles and PDIV.

Table 1 Relation between the size of bubbles and PDIV [24]

Bubble size	Size of bubble (ml)	PDIV (kV)
Large	around 100	around 40
Medium	around 30	around 56
Small	around 5	around 64

Researchers in [12] reported an experimental set-up was not very much different from [24]. However, they did not report the size of the bubbles produced in the experiment [12]. Nonetheless, in their subsequent simulation designed to study the microbubble's electric field distribution in oil, the size of the bubbles were mentioned as a = 3 mm and b = 6 mm. In the article, alphabets 'a' and 'b' refer to the diameters of a stretched ellipsoid, with 'b' is parallel with the electric field. In the study, it was found that for bigger a/b ratio, ***E*** inside the bubble was higher.

The motion of microbubble due to thermal conduction or any other reasons is not considered. Instead, the bubble is presumed to be stationary. The shape of the bubble is therefore assumed to be maintained [12].

The lifetime of the bubble is assumed to be long enough as if the conditions are correct, it will lead to PD commencement.

2.3 Model Description

Most of the properties for materials applied in this simulation have been predetermined by the software. For example, properties for air are already preloaded in the software. Hence, it is not necessary to be shown in Table 2. However, several other properties need to be defined manually. Table 2 shows the tabulation of the parameters for material properties used in modelling/simulation.

Table 2 User-defined materials properties in the simulation software

Materials	Property (unit)	Value
Transformer oil	Electrical conductivity, σ (S/m)	1.52 pS/m [26], [27]
Transformer oil	Relative permittivity (dielectric constant) , µ (unitless)	2.2 [28], [29]
Ethane (gas)	Electrical conductivity, σ (S/m)	1 fS/ m [20]
Ethane (gas)	Relative permittivity (dielectric constant) , µ (unitless)	1.001 38 [30]
Methane (gas)	Electrical conductivity, σ (S/m)	1 fS/m [20]
Methane (gas)	Relative permittivity (dielectric constant) , µ (unitless)	1.000 80 [30]
Tank (metallic)	Side length, mm	532
Current source (Copper conductor)	Radius (quarter), mm	20
Microbubble	Radius (polar, equatorial), µm	Varies

Apart from material properties, other parameters also need to be inserted by the user. Table 3 presents the list of parameters set prior to the simulation. For Times property, the range of simulation will be from 0 – 0.02 s: one cycle of a 50 Hz sinusoidal electrical power supply. While the interval of the Times will be 0.001 s.

Table 3 User-defined components' properties in modelling software

Components	Settings (unit, if any)	Value
Study – Step	Times (s)	0, 0.001, 0.02
Mesh	Physics-controlled, extra-fine	Not applicable
Results – Surface	Time (s)	0.005
Results – 1D plot group	Time (s)	0.005
Electric current	Out-of-plane thickness (m)	1
Electric current	Reference impedance (Ω)	50
Electric current – current conservation	Absolute pressure (atm)	1
Electric current – current conservation	Temperature (K)	300

For the purpose of the simulation, only one quadrant of the 2D surface is considered for the transformer tank and the conductor. For microbubble, the full 2D 360° surface is going to be used.

Within the simulation software environment, the edge of geometrical shape is called a boundary. Hence, the surface of the conductor and sides of the square are all known as boundaries. The same applies to the interface between microbubble and fluid in which it is submerged. Each boundary has a number. Any boundary can be assigned to a specific character such as electric potential, just like the surface of a conductor.

Another important concept is domain. The domain is the area enclosed by geometrical shape. For example, the area represented by a bubble is a domain. As with boundary, any domain will be assigned a number. All domains need to be assigned to appropriate materials.

Table 4 is the list of boundaries and domains and their assignment.

Table 4 Assignment of boundaries and domains

Components	Boundary/ domain	Value, if any
Electric currents – Electric potential	Conductor surface/ boundary	Varies V V*sin(2*pi*50*t)
Electric currents – Electric insulation	Left and lower square boundaries	Nil
Electric currents – Ground	Right and upper square boundaries	Nil
Electric currents – Current conservation	All domains	Pressure – 1 atm
Electric currents – Initial values	All domains	0 V

The simulation software also has the ability to gauge result in a specific space. For this simulation, the measurement of the electric field along a line section that included the microbubble is recorded.

Figure 2 below shows the construction of the line graph. By using this facility, a 2D graph of the electric field along the line can be produced.

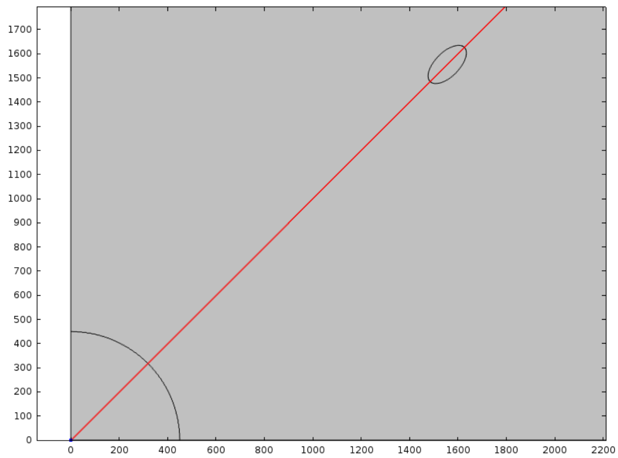


Figure 2 A line graph of measurement

The shape of microbubble under electric field has been reported as prolate spheroid where polar radius, a, is larger than the equatorial radius, b. If a < b, the resulting shape is called oblate spheroid. In [12], another parameter, c, is defined as a spheroid shape characteristic parameter. The parameter is defined as the following [12].

$$c = \frac{a}{b} \tag{2}$$

Where radius a is along the x-axis and radius b is along the y-axis. Upon inspection, the y-axis is found to be parallel to the electric field, $\boldsymbol{E_o}$.

It is important to make sure that all microbubbles with different radius will be subjected to the same contour of $\boldsymbol{E_o}$. Hence, the distance between the conductor surface and the conductor-facing pole tip, L, must be the same. This is regardless of the bubble size. To achieve that, a simple arithmetical relationship between L and b has been developed. The key is to change the mid coordinate of the bubble. Following is the relationship.

$$x = \frac{T}{\sqrt{2}} \tag{3}$$

Where, x is the coordinate for the middle of microbubble (x = y), T is the total length of the radius of the conductor, r, L and b. Since r and L are fixed, change in b will result in the new calculation of x. Figure 3 demonstrates the statement in graphical representation.

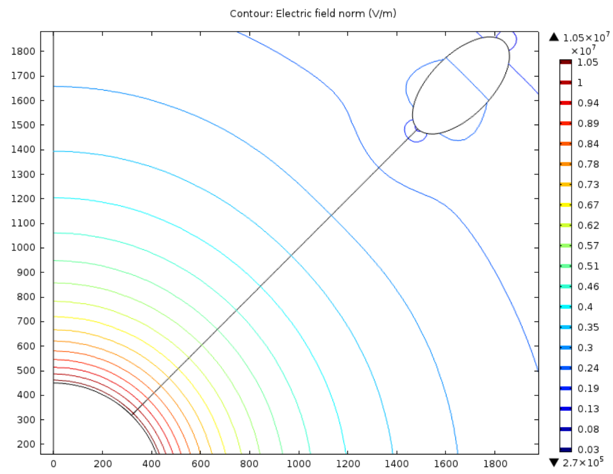


Figure 3 Contour of E_o with a fixed dimension of the bubble. Also shown is the fictitious line measuring distance from the conductor surface and the tip of the pole of a bubble

3.0 RESULTS AND DISCUSSION

For each simulation, the E_{max} inside the microbubble will be noted down. This is following the convention set in [12] except for simulation that involved different gases, the rest used air-filled microbubble.

Table 5 shows the result for two out of four parameters of interest: type of gas and distance of microbubble. It can safely be concluded that the further a microbubble from the surface of the conductor, the lower E_{max} inside it. This observation holds true for all three types of gases. Parameter c is 0.5 (a = 10 mm, b = 20 mm) with potential applied on the conductor is 275 kV.

Value of E_{max} inside the microbubble for each gas is different. For example, at 9 mm, E_{max} for methane and air is 3.4595 kV/mm and 3.4699 kV/mm. The electric field strength of methane is 3.45 x 1kV/mm while for air it is 3 kV/mm. Hence at 9 mm, PD could be initiated for both microbubbles occupied with methane or air. Beyond this point, PD is not going to be initiated in a methane-filled microbubble. For air-filled microbubble, on the other hand, initiation of PD is possible up until the distance of 13 mm.

Table 5 Measurement of E_{max} for different gaseous microbubble with fixed geometric dimension at different distances

Distance (mm)	E_{max} (kV/mm)		
	Ethane	Methane	Air
5	4.0080	4.0083	4.0089
6	3.8695	3.8598	3.8603
7	3.7140	3.7145	3.7149
8	3.5865	3.5868	3.5873
9	3.4592	3.4595	3.4699
10	3.3433	3.3435	3.3441
11	3.2330	3.2333	3.2337
12	3.1361	3.1365	3.1368
13	3.0411	3.0414	3.0418
14	2.9534	2.9537	2.9540
15	2.8686	2.8689	2.8692

The reduction of E_{max} inside a microbubble is evidently seen in Figure 4 below. The reduction can largely be explained due to the distance of microbubble to the edge of the conductor. For air it is 99.17%, methane is 99.12% and ethane is 99.09%.

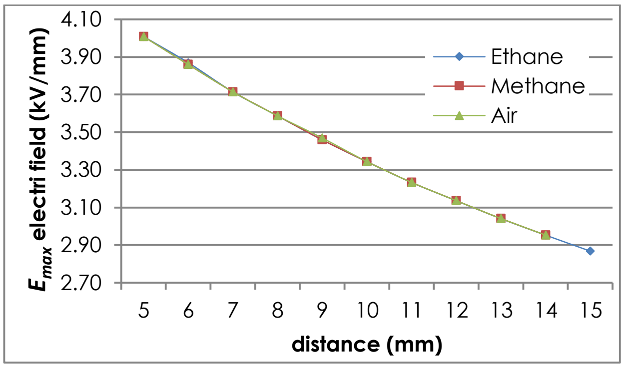


Figure 4 Value of E_{max} for different gases at different distances

Parameter c can be made from a different pair of a and b. Table 6 shows how c = 0.5 can be made from different pairs of a and b. It can be deduced that values of a and b for the same c do not influence E_{max} very much. For example, difference of E_{max} for a/b = 1/2 and a/b = 25/50 is only 1.36%. In fact for a/b = 1/2 and a/b = 20000/1000, the difference of E_{max} is only 3.3%. Statistically, the standard deviation of E_{max} is found to be only 0.03.

Table 6 Constant c = 0.5 for different a and b pairs (arc distance = 14 mm, electric source 275 kV)

a /b (µm)	E_{max} (kV/ mm)
1/2	2.95
2/4	2.95
4/8	2.95
5/10	2.95
10/20	2.95
15/30	2.96
20/40	2.99
25/50	2.99
50/100	3.00
100/200	3.00
200/400	3.00
500/1000	3.00
750/1500	3.00
1500/3000	3.00
3000/6000	3.02
10000/20000	3.05

Table 7 shows resultant E_{max} for different c. From the table, it can be seen that as c is increased, so is E_{max}. This is in-line with the results shown in [12]. For microbubble with c = 0.125, the maximum E_{max} is not enough to initiate PD. Following results in Table 6, any combination of dimensions of microbubble that yield c = 0.125, no PD is expected to be started.

Table 7 Value of $\boldsymbol{E_{max}}$ for variants of c for spheroid-shape microbubble, (arc distance = 14 mm, source 275 kV)

Radius a (μm)/ radius b (μm)	c	E_{max} (kV/mm)
1/ 8	0.125	2.68
2/ 8	0.25	2.90
3/ 8	0.375	2.95
4/ 8	0.2	2.95
5/ 8	0.625	3.10
6/ 8	0.75	3.18
7/ 8	0.875	3.27

Using data in Table 7 above, the relationship of parameter c and $\boldsymbol{E_{max}}$ can be shown in Figure 5 below. The R^2 is 88.95% indicating that changes in $\boldsymbol{E_{max}}$ can be largely explained by changes in c.

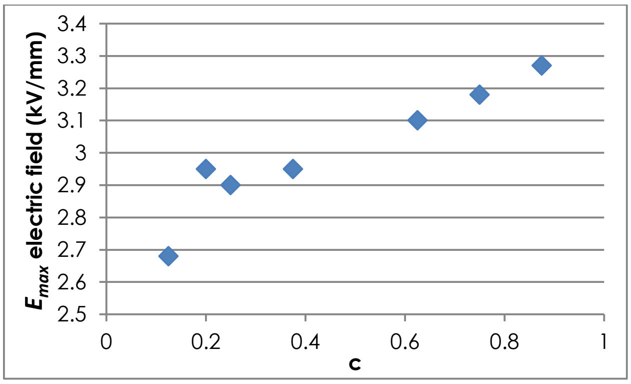


Figure 5 Relationship between parameter c and $\boldsymbol{E_{max}}$

By changing the source voltage, the external electrical, ***E***, strength engulfing the microbubble is also changing. Thus, $\boldsymbol{E_{max}}$ is also affected. Table 8 shows the result of such simulation. Change in the source's voltage magnitude caused $\boldsymbol{E_{max}}$ to change linearly.

Table 8 Value of $\boldsymbol{E_{max}}$ for spheroid-shape microbubble, c= 10/20, subjected to a different magnitude of voltages, (arc distance = 10 mm)

Source voltage (kV)	E_{max} (kV/ mm)
11	0.13
22	0.27
33	0.40
66	0.80
132	1.61
275	3.34
500	6.08

The fact of linear relationship can be emphasised further when the data are plotted as in Figure 6. The linearity is so strong that the R^2 is 100%. The source voltages of 11, 22, 33, 66, 132, 275 and 500 kV are based on the common utilities' distribution and transmission voltage levels found in Malaysia. However, 22 and 66 kV are believed to be currently phased out from usage.

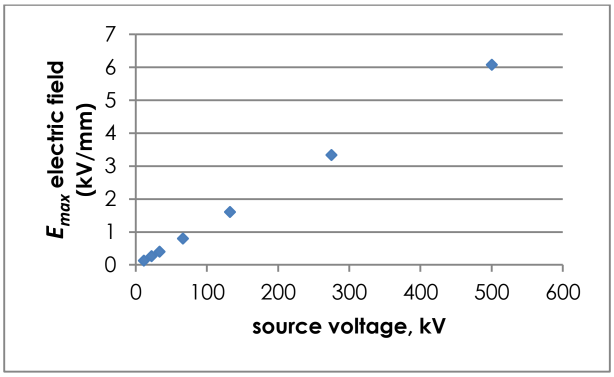


Figure 6 Relationship between the source voltage and $\boldsymbol{E_{max}}$

4.0 CONCLUSION

By assuming there are enough free electrons existed in the microbubble, several conditions that may contribute to PD initiation can be studied.

It is found that the $\boldsymbol{E_{max}}$ is strongly affected by the type of gasses. This is due to the fact that $\boldsymbol{E_{max}}$ is influenced by ε_r for each gas.

From the study, it was found that at the same source' voltage magnitude, $\boldsymbol{E_{max}}$ reduced significantly by the enlargement of distance.

On the other hand, increased in $\boldsymbol{E_{max}}$ is observed for increased in c and in source's voltage magnitude.

However, no significant changes can be observed in $\boldsymbol{E_{max}}$ changes of size of microbubble for constant c.

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