Experimental Investigation on Air Breakdown under Lightning Impulses with Various Electrode Configurations

M. S. Kamarudin*, N. H. Radzi, S. A. Zulkifli and R. Abd-Rahman

Department of Electrical Power Engineering, Faculty of Electrical and Electronics Engineering, Universiti Tun Hussein Onn Malaysia
**saufi@uthm.edu.my*

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Abstract

This paper describes sparkover characteristics of air. Standard lightning impulse of 1.2/50 is used in this study, along with three different electrode configurations. It is found that U_{50} and E_{max} increase with air pressure, particularly in larger gap lengths, with tests being carried out up to 0.25 MPa (abs). It is also found that higher gap lengths provide higher U_{50} and E_{max} for a given electrode configuration. A non-uniform field configuration provides very high electric field upon breakdown, whereas a more uniform field configuration provides higher breakdown voltage level.

1 Introduction

Lightning protection is very important in an electrical network. A lightning discharge current can be as high as 200 kA with potential of millions of volts. According to [1], Malaysia is one of the countries with the most lightning strikes in the world, after Rwanda and Congo. The average thunder day level for Malaysia is within 180-260 days per annum [2]. With that in mind, it is very important to have sufficient levels of lightning protection for all electrical equipment, and this is made possible with a good insulator.

One of the simplest forms of insulator being used in high voltage applications is air. There are air circuit breakers, air-insulated switchgears, air-insulated transformers and other equipment. Although sulphur hexafluoride (SF_6) is regarded as the best gas insulator for high voltage applications, air is still being used due to easy maintenance property.

Since there are various designs of high voltage equipment, knowledge on the behaviour of air breakdown is essential in order to determine the best model for a specific application. One application may need a very high 50% breakdown voltage (U_{50}), while another application may have to have a high electric field withstand capability. Due to this reason, it is important to investigate both U_{50} and E_{max} characteristics in various electric field arrangements.

2 Experimental Setup

This section reports on some of the experimental setup used in the laboratory works.

2.1 Lightning Impulse Generation

A 400 kV Haefely impulse generator was used to generate the lightning impulse shape. A 50 ns risetime capacitive divider was used to measure the impulse voltage, and a digital storage oscilloscope was used to record the waveform.

2.2 Electrode Configurations

There are three main electrode configurations used in this study, namely plane-plane, rod-plane and hemisphere-plane. The plane electrode has a diameter of 90 mm, the hemisphere electrode has a diameter of 24 mm and the rod electrode has a tip diameter of 1 mm. In this particular study, hemisphere-plane electrode configuration is also known as R12-plane. An example of rod-plane electrode configuration is shown in Figure 1. These electrodes are made from brass, and their surfaces are mirror finished. In the tested electrodes, all high voltage electrodes are stationary; while the ground electrodes are vertically moveable, so that a desired gap length can be achieved.

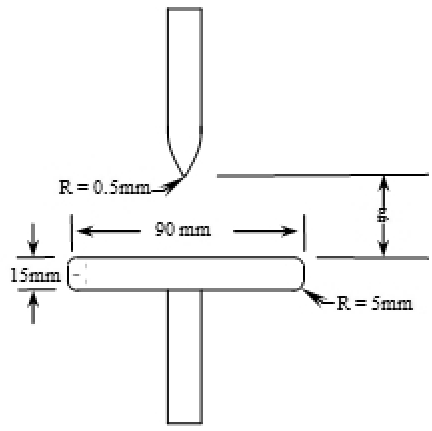

Figure 1: Rod-plane configuration

2.3 Pressure Vessel

A pressure vessel is needed in order to test air breakdown at various pressures. The electrodes and other related measurement devices, such as humidity and temperature sensors are placed inside the vessel. The vessel is built from stainless steel, with a polycarbonate window on its side. The vessel is cylindrical in shape and its thickness is 10 mm.

3 Measurement Techniques

This section reports on the techniques to obtain the U_{50} and E_{max} values for analyzing the behaviour of air breakdown under lightning impulses.

3.1 50% Breakdown Voltage (U_{50})

For this test, U_{50} for air breakdown are obtained as according to the Standard [3]. The up-and-down method is used to determine U_{50} by applying at least 20 impulse shots at a timed interval of 120 seconds.

3.2 Maximum Electric Field (E_{max})

A commercial finite element package, specifically COMSOL Multiphysics version 4.3a is used to carry out the modelling and electric field computations. The U_{50} values obtained from the experimental works are used to determine E_{max} just before the breakdown occurred. An example of model used for simulation is shown in Figure 2. Axis-symmetric features are used to simplify further the model without affecting the simulation results.

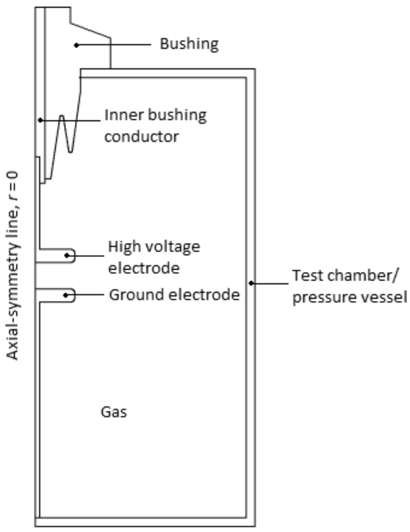

Figure 2: A 2D axis-symmetric model for simulation

4 Experimental Results

This section reports on the results obtained from laboratory tests on air breakdown.

4.1 Effects of Gap Length and Pressure

One particular electrode configuration, the rod-plane has been selected in order to investigate the effects of gap lengths on the breakdown behaviour of air. This is because the majority of the insulating systems are in non-uniform gap configurations. The gaps used in these tests are 5 cm, 6 cm, 7 cm and 8 cm. The results are shown in Figure 3, with Table 1 showing the values for positive lightning impulse.

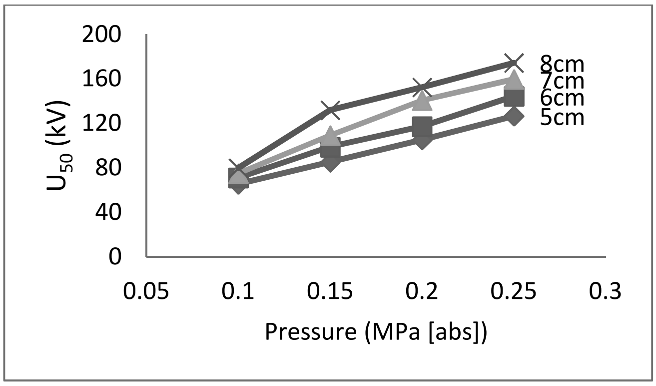

Figure 3: U_{50} for air breakdown in a rod-plane gap as a function of pressure (positive impulse)

	Gap length			
Pressure (Mpa [abs])	**5 cm**	**6 cm**	**7 cm**	**8 cm**
0.10	65.3	71.0	74.8	79.7
0.15	85.1	98.7	109.1	131.8
0.20	105.2	117.1	140.6	152.3
0.25	126.5	144.3	159.6	174.3

Table 1: U_{50} for air breakdown in rod-plane configuration (kV)

Figure 3 shows the U_{50} of air increases almost linearly with increasing pressure, particularly for the 5 cm gap length. By considering only U_{50} taken at 0.10 MPa and 0.25 MPa, the U_{50} increased by 1.94 times for the 5 cm gap, 2.03 times for the 6 cm gap, 2.13 times for the7 cm gap, and 2.19 times for an 8 cm gap. This shows that a bigger gap length in electrode configuration will introduce a slightly bigger increase in U_{50} with the increment of pressure. However, at 0.1 MPa, there is not much difference in the values of U_{50} for different gaps.

The increment trends with pressure for each gap length in U_{50} of air breakdown agree with investigations on air breakdown by Husain and Nema [4] and Govinda Raju and Hackam [5], where U_{50} increases almost linearly from 0.1 MPa (750 torr) to 0.25 MPa (1875 torr). This region is where the Paschen curve is linear, albeit according to Lux [6], Paschen's Law applies typically at *pd* products of less than 1000 torr-cm. Naidu and Kamaraju [7], however, has published a Paschen curve for SF_6 gas at *pd* products of up to 2000 torr-cm, which is a linear curve from 500 torr-cm onwards. Nevertheless, deviations from linearity of Paschen's Law can happen due to the geometry of the electrode, where high electric field is introduced in non-uniform electrode configuration, as being carried out in this study.

The value of each U_{50} in Table 1 is then used in the COMSOL Multiphysics software to evaluate the maximum electric field (E_{max}) in each test configuration. Table 2 shows E_{max} values for all the gap lengths in the rod-plane electrode configuration in correspondence with the respective U_{50}

values from Table 1. Figure 4 shows the E_{max} curves, in relation to gap lengths, based on each pressure.

	Gap length			
Pressure (Mpa [abs])	**5 cm**	**6 cm**	**7 cm**	**8 cm**
0.10	376	398	413	435
0.15	489	554	602	719
0.20	605	657	776	831
0.25	727	810	881	951

Table 2: E_{max} for air breakdown in the rod-plane configuration (kv/cm)

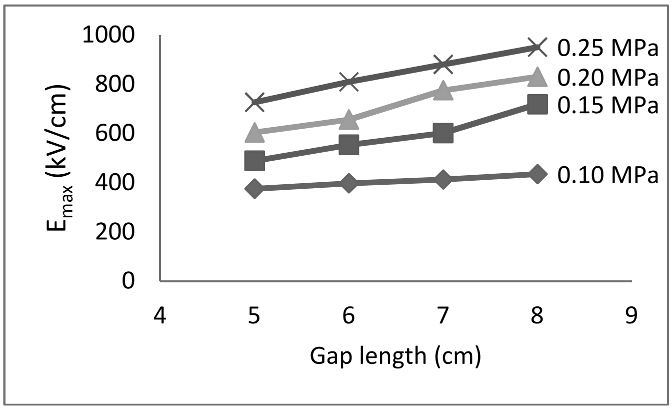

Figure 4: E_{max} for air breakdown in a rod-plane gap as a function of gap length (positive polarity)

Closer consideration of the E_{max} curves in Figure 4 offers a clear indication that, for low pressure (at 0.10 MPa), the E_{max} values are almost the same for every gap length. As the pressure is increased, the ability of air to withstand E_{max} (and high stress) is increased. This is particularly true for a higher gap length between the electrodes. Also, importantly, it can be deduced that by increasing a same amount of air pressure, a higher E_{max} withstand capability can be achieved in a longer gap length for this particular electrode configuration.

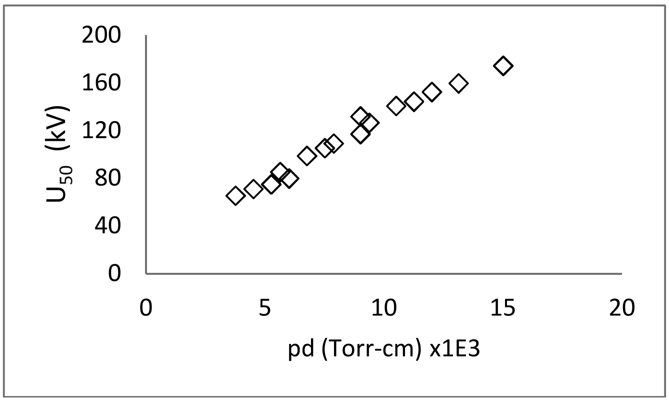

Figure 5: U_{50} curve for air under rod-plane electrode configuration in relation to product of pressure and gap length, *pd*

Figure 5 and Figure 6 show U_{50}-*pd* curve and the E_{max}-*pd* curve respectively, which can be seen as almost linear curves. The U_{50}-*pd* (and hence E_{max}-*pd*) curve agrees with Paschen characteristics as reported by Heylen [8] for the given pressures. Naidu and Kamaraju [7] also reported a linear Paschen curve for higher *pd* products. Although the magnitudes of the U_{50} in this investigation are significantly higher, as the tests were carried out using rod-plane electrode configuration, the U_{50}-*pd* curve is almost linear for the region specified, which conforms to [8].

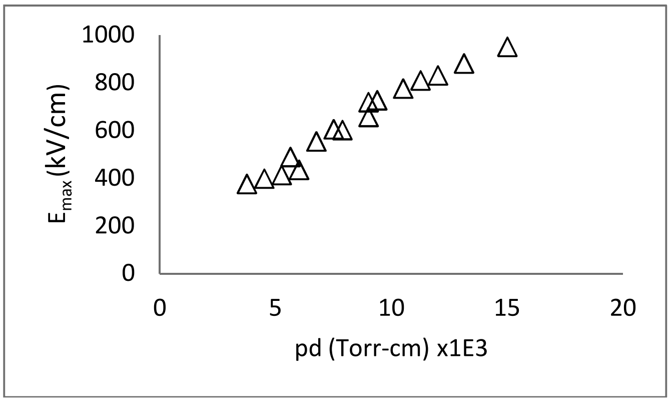

Figure 6: E_{max} curve for air under rod-plane electrode configuration in relation to product of pressure and gap length, *pd*

4.2 Effect of Electrode Configuration

These tests have been carried out to obtain U_{50} curves for different electrode profiles as shown in section 2.2. For the plane-plane electrode configuration, a 3 cm gap was used. For a R12-plane, a 4 cm gap was used, and for the rod-plane, a 5 cm gap was adopted. The results of U_{50} measurements are shown in Figure 7 and the values are given in Table 3.

Pressure (Mpa [abs])	Plane-plane; 3cm	R12-plane; 4cm	Rod-plane; 5cm
0.10	81.84	72.80	65.33
0.15	112.62	89.57	85.13
0.20	139.97	111.73	105.18
0.25	162.37	129.42	126.52

Table 3: U_{50} for different electrode configurations (kV)

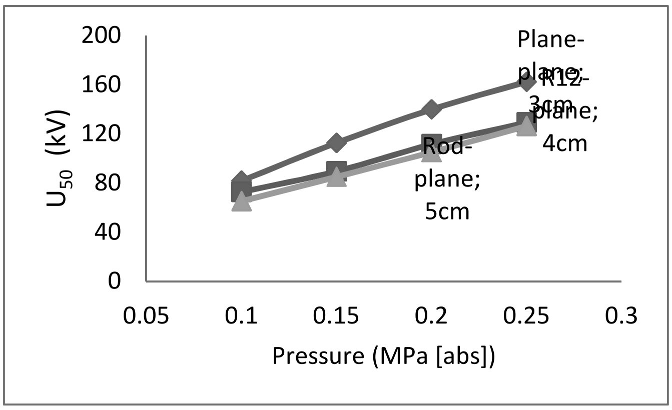

Figure 7: U_{50} for different electrode configurations

As depicted in Figure 7, although the rod-plane configuration has the biggest gap, the U_{50} values are the lowest for each given pressure, though only small differences exist when compared with that of the R12-plane configuration. For the plane-plane configuration, although it has the smallest gap length, the highest U_{50} of all the pressures is noted. For all electrode configurations, the U_{50} increases almost linearly with the pressure, in this case, from 0.10 MPa up to 0.25 MPa. Again, using COMSOL Multiphysics, E_{max} values corresponding with Table 3 are shown in Table 4.

Pressure (Mpa [abs])	Plane-plane; 3cm	R12-plane; 4cm	Rod-plane; 5cm
0.10	60	65	376
0.15	82	80	489
0.20	102	99	605
0.25	118	115	727

Table 4: E_{max} for different electrode configurations

According to Table 4, there is not much difference in E_{max} values between a 3 cm gap plane-plane electrode configuration and a 4 cm gap, R12-plane electrode configuration. Although in terms of geometry these electrode configurations are very different from each other, the U_{50} values, as shown in Figure 7, through the results of computational works on the electric field, reveal that the E_{max} values are very close to each other. This is true for all pressures carried out during the experimental works. It can be said that, in this particular study, the R12-plane electrode configuration with a gap length of 4 cm will result in the same magnitude of E_{max} for the air to breakdown as in the plane-plane electrode configuration with a gap length of 3cm.

Field utilization factor, η, can be calculated for each electrode configuration using Equation (1) to give an idea of the uniformity of the gap geometry, i.e. a higher value of η indicates a more uniform electric field

$$\eta = \frac{E_{mean}}{E_{max}} \quad (1)$$

and E_{mean} can be calculated using Equation (2)

$$E_{mean} = \frac{V}{d} \quad (2)$$

where V is the applied voltage and d is the gap length between electrodes. The field utilization factor, η, for each electrode configuration is shown in Table 5.

Electrode configuration	Field utilization factor, η
Rod-plane; 5 cm gap	0.035
R12-plane; 4 cm gap	0.281
Plane-plane; 3 cm gap	0.452

Table 5: Field utilization factors for each electrode configuration

The *pd* curves for U_{50} and E_{max} on all the electrode configurations are shown in Figure 8 and Figure 9. The *pd* curves in Figure 8 can be described as part of the Paschen characteristics for the given electrode system where the curves are linear at higher *pd* products, as reported by Heyley [8] and Naidu and Kamaraju [7]. Also, the above U_{50}-*pd* curves agree with an investigation carried out by Woo et al. [9] where it is concluded in general that the slope of breakdown voltage is decreased with the non-uniformity of the electric field. As have been discussed in the previous section, the slope of the Paschen's Law is not necessarily linear due to the geometry of the electrode system. As the electrode configuration varies, the Paschen's curve also varies accordingly, which is unique to the electrode system.

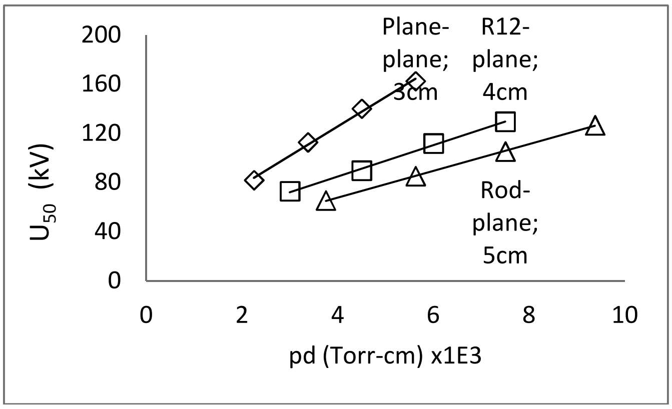

Figure 8: U_{50} curve in relation to the product of pressure and gap length, *pd*, for all electrode configurations

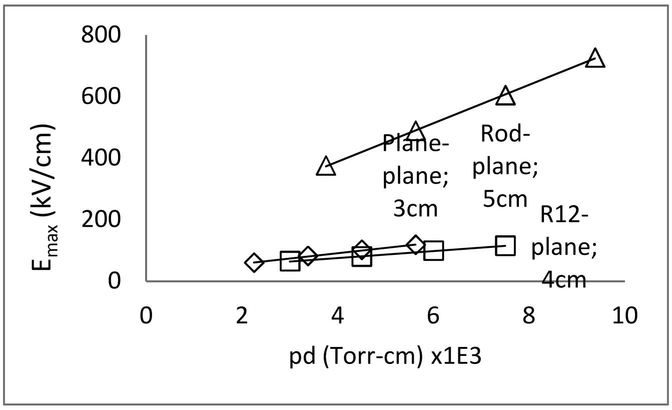

Figure 9: E_{max} curve in relation to the product of pressure and gap length, *pd*, for all electrode configurations

Conclusion

In this study, a model for finite element analysis has been developed. Fundamental tests on air breakdown have been carried out to investigate the U_{50} behaviour of air in various test conditions. Three different electrode configurations were used to represent three different electric fields. The results from the up-and-down method were taken to determine the electric field, based on models for each electrode configuration. This is used to give better understanding of the highest stress region inside the test chamber.

For the effects of gap length and pressure on air breakdown, it was found that the U_{50} of air increases with pressure. U_{50} also increases with gap length between electrodes, which in this particular case is rod-plane electrode, but the increment is much more significant under higher air pressures. Also, at higher gap lengths, bigger increase in U_{50} can be obtained with the increment of pressure. On the other hand, E_{max} is also affected with gap length and pressure. At low pressure, E_{max} values are almost the same for each gap length. Higher pressure will provide higher E_{max}, which implies higher ability of air to withstand higher stress. Hence, it was found that a higher E_{max} withstand capability can be achieved in a longer gap length by increasing the air pressure.

For the electrode configuration effects, it was found that rod-plane has the highest E_{max} with the lowest U_{50}, and with very low field utilization factor value, it implies very non-uniform field arrangement. Due to this fact, although this configuration has the highest gap length, the U_{50} values are the lowest for each given pressure. On the other hand, plane-plane configuration has the highest U_{50}. Also, it has the highest field utilization factor, which implies more uniform field arrangement effect, as compared to rode-plane and R12-plane. For all electrode configurations, the U_{50} increases almost linearly with the pressure. It was also found that, in this particular study, the R12-plane electrode configuration with a gap length of 4 cm will result in almost the same magnitude of E_{max} for the air breakdown as in the plane-plane electrode configuration with a gap length of 3 cm.

References

[1] R. Malakan, "Malaysia Negara Panahan Petir Tertinggi Di Dunia," 2009. [Online]. Available: http://kilatmalaysia.blogspot.com/2009/10/malaysia-negara-panahan-petir-tertinggi.html. [Accessed: 13-Aug-2014].

[2] PT. Aman Berkah Sejahtera, "Erico," 2004. [Online]. Available: http://www.petir.com/. [Accessed: 13-Aug-2014].

[3] European Committe for Electrotechnical Standardization, "BS EN 60060-1 : 2010 BSI Standards Publication High-voltage test techniques Part 1 : General definitions and test requirements," 2010.

[4] E. Husain and R. S. Nema, "Analysis of Paschen Curves for Air, N_2, and SF_6 using the Townsend Breakdown Equation," *IEEE Trans. Electr. Insul.*, vol. EI-17, no. August, pp. 4–7, 1982.

[5] G. R. Govinda Raju and R. Hackam, "Sparking Potentials of Dry air, Humid Air and Water Vapour between Concentric Sphere-Hemisphere Electrodes," *Proc. IEE*, vol. 120, no. August, pp. 927–933, 1973.

[6] J. Lux, "Pachen's Law," *High Voltage Experimenter's Handbook*, 2004. [Online]. Available: http://home.earthlink.net/~jimlux/hv/paschen.htm. [Accessed: 28-Jul-2013].

[7] M. S. Naidu and V. Kamaraju, "Paschen's Law," in *High Voltage Engineering*, 4th ed., Tata McGraw-Hill, 2009, pp. 45–48.

[8] A. E. D. Heylen, "Sparking formulae for very high-voltage Paschen characteristics of gases," *IEEE Electr. Insul. Mag.*, vol. 22, no. 3, pp. 25–35, May 2006.

[9] S.-Y. Woo, D.-H. Jeong, K.-B. Seo, and J.-H. Kim, "A Study on Dielectric Strength and Insulation Property of SF_6/N_2 Mixtures for GIS," *J. Int. Counc. Electr. Eng.*, vol. 2, no. 1, pp. 104–109, 2012.