A UNIFORM FIELD GAP PROTOTYPE

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الملخص

الثغرات الهوائية المنتظمة منها وغير المنتظمة المجال هي احدى التقنيات المستخدمة في القياس والوقاية في هندسة الجهد الفائق، حيث أن الثغرات الهوائية المنتظمة وغير المنتظمة عادة ما تستخدم في قياس الجهد الفائق داخل المعمل. شكل أقطاب الثغرة الهوائية المنتظمة يشكل أهمية في الابحاث، والتجارب، وكذلك في توصيف المواد العازلة.

نظريا شدة المجال يكون مكثفا في الفراغ المحصور بين الأقطاب المسطحة والمتوازية ذات الأبعاد اللانهائية. وعمليا لا يمكن أن تكون الأقطاب لانهائية، ولكن تصمم بدقة متناهية وذلك لكي نتحصل على مجال بين الأقطاب، مع ضمان الحصول على شدة مجال أضعف في باقي النقاط.

بايجاد حلول لمعادلة ماكسويل في المستوى Z الذي يؤدي إلى محيط خطوط الجهد المنتظم أو المتساوي لتصميم وتنفيذ الثغرة الهوائية. في هذا البحث تم تصميم وتنفيذ أقطاب لثغرة هوائية منتظمة المجال محليا، وتمت معايرتها ومقارنتها بالثغرات الهوائية العالمية بمعامل الجهد العالي بقسم الهندسة الكهربائية / جامعة طرابلس.

نتائج جهد تكسير الهواء المتحصل عليها في المعمل من نموذج الثغرة الهوائية المصممة والمنفذة لا تختلف كثيرا عن ثغرة بروس القياسية المستخدمة في معامل الجهد العالي.

ABSTRACT

Spark gaps, including uniform and non-uniform field gaps are one of the techniques used for measurement and protection in high voltage engineering, where the sphere gaps and uniform field gaps are commonly used for measurement of high voltages in laboratories.

The uniform field electrode configurations are of significance in basic research, testing, and characterization of insulating materials. Theoretically, the uniform field intensity is produced within the space limited between the two parallel plane electrodes of infinite dimensions. In practice since the electrode dimension cannot be infinite, carefully designed electrodes are necessary to produce uniform fields in the region of interest and to assure lower field intensities at all other points in the test gaps.

Solving Maxwell equation in z-plane yields to the contour of the equi-potential lines, used for a uniform field electrodes prototype for the design of the sphere.

In this paper a uniform field gap prototype was designed locally, and calibrated at the Electrical Engineering Department, University of Tripoli High Voltage Laboratory.

The data obtained for breakdown of air from the shows no significant difference between the designed prototype and standard Bruce uniform field gaps.

KEYWARDS: Spark Gaps; Uniform and Non-Uniform Fields; Field Electrodes; Maxwell Equations.

INTRODUCTION

In present, high voltages are used for a wide variety of applications covering the power systems, and research laboratories and in nuclear research laboratories, such as in particle accelerators using Van de Graff generators. For transmission of large bulks of power over long distances, high voltages are indispensable [1].

The demand for the generation and transmission of large amount of electric energy today, necessitates its transmission at extra-high voltages. In the developed countries like USA, power transmission voltages have reached up to 1500 kV systems. In middle east countries, 400 kV ac power systems have already come into operation, and in the next 10 years every state is expected to be linked by a national power grid operating at 400 kV or at 800 kV [1, 5].

In high voltage, engineering most of the problems concerned with electrical insulation of high direct, alternating, and impulse voltages are related to electrostatic and sometimes electrical conduction fields. It should be emphasized, however, that the permissible field strengths in the materials are interlinked with the electrostatic field distributions and thus the problems may become extremely difficult to solve [6].

High voltage testing is used as a quality test of new apparatus, or a maintenance test on older equipment, or as a method of evaluating developmental insulation systems. In other words, high voltage testing in any test done where the electric field gradient (stress) is sufficient to test and evaluate the properties of the insulation system in the performance of the device [5].

Measurement of high ac, dc, or impulse voltages involves unusual problems that may not be familiar to specialists in the common electrical measurement techniques. These problems are more complicated as the voltage magnitude increases.

Sphere gaps are commonly used in all laboratories for the measurement of the peak value of high ac, dc, or impulse voltages, for the advantage of simplicity, accuracy and are used for calibration and protection of high voltages equipments and test objects.

Calibration of high voltage measurement systems is accomplished by comparing the measurement with a preset sphere gap flashover voltage corrected to standard atmospheric and temperature conditions. The sphere gap is the universal calibration method because of its well known dc, ac, and impulse disruptive discharge voltages; due to low cost; ease to set-up, and the availability of accurate atmospheric and temperature correction factors for the test voltage used, including positive and negative dc and impulse voltages. Procedures documented in "IEEE Standard Techniques for High Voltage Testing", "IEEE Standard 4 for calibration using the sphere gap" [5].

SPHERE GAPS

Sphere gaps are one of the simplest and most common spark gaps in high voltage laboratories. Obviously, for many centuries, the sphere gap has been used as high voltage measuring device. Due to its reliability and simplicity, some present national and international standards [8].

Standard sphere gaps recommend for the measurement of the peak value of either dc, or ac at power frequency up to 500 HZ, or both kinds of impulse voltages. The standard sphere gaps insulated by atmospheric air can be used to measure the amplitude of a voltage above about 3 kV up to 2000 kV peak [14].

Spheres may be made of aluminum, brass, bronze or light alloys, for sphere of a particular diameter, the field in the gap becomes less uniform as the gap length increases from a sphere radius to a sphere diameter. B.S.358:1960 standard recommend that spacing should not exceed a sphere radius.

In general, the spheres mounted with the axis of the sphere gap vertical and the lower sphere is earthed. When measurement of a symmetrically applied voltage has to be made, spheres are arranged horizontally and both spheres are insulated. The breakdown voltage characteristics will then be slightly different [2, 6].

It is often believed that some disadvantages of the sphere gaps for peak voltage measurement could be avoided by using properly designed plate electrodes providing a uniform field distribution within a specified volume of air [6].

There are applications which require a uniform electrical field between two electrodes such as breakdown voltage testing and large volume laser discharge cavities. The ideal infinite flat plates are somewhat difficult to realize in a lab of reasonable dimensions. Finite sized plates produce a uniform field at the middle of the plate, but the high field at the edges creates a local discharge problems. Rogowski presented a profile design for uniform field electrodes for breakdown voltages up to 600 kV.

Rogowski developed a technique that starts by determining a realizable field, then constructing an electrode shaped so that the surface of the electrode lies on an equipotential surface. He started with an analytical solution of the field due to a finite plane plate parallel to an infinite plane [2, 15].

The breakdown voltage of a uniform field gap can be calculated based upon fundamental physical processes and their dependency upon the field strength. The breakdown voltage (V) can be expressed by:

$$V = AS + B\sqrt{S} \tag{1}$$

A & B are constant, S is the gap spacing in cm, and V is the peak breakdown voltage. Based on that, the limitation of the sphere gap spacing to the sphere diameter led to the development of uniform field gap. Typical uniform field electrodes shown in Figure (1).

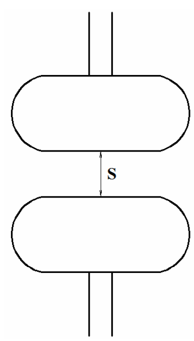


Figure 1: Uniform field Electrodes

Bruce has shown that the breakdown voltage of a gap of length (S) cm in air at 25 °C and 760 mmHg is within (±0.2%) value given by the relation:

$$V = 24.22S + 6.08\sqrt{S} \tag{2}$$

The advantage of a uniform field gap that there is no polarity effect and no influence of nearby earthed objects could be expected if the dimensions are properly designed. All these advantages, however, are compensated by the need for very accurate mechanical finish of the electrodes, the extremely careful parallel alignment, and last but not least the problem arising by unavoidable dust, which cannot be solved for usual air conditions within a laboratory. As the highly stressed electrode areas become much larger than for sphere gaps, erratic disruptive discharges will tend to occur. Therefore, a uniform field gap insulated with atmospheric air is not applicable for voltage measurements [6].

PROTOTYPE DESIGN OF UNIFORM FIELD GAP

The realization of homogeneous fields within a finite volume of insulating is very difficult. Using parallel metal plates of limited dimensions creates the problem of a proper stress control at the edges of the plates. The field problem becomes thus three-dimensional, though a rotational symmetry exists if the parallel plates are circular discs.

Depending upon the material to be tested, the breakdown strength may be very sensitive to local high fields within the whole electrode arrangement. Therefore, the highest stress should only be present in the homogeneous field region, where the plates are in parallel [6]. A certain profile of electrodes is necessary outside the plane region to limit the dimensions, but the field strength at the curved edges should never exceed the value: $E = \frac{V}{S}$. (3)

If (V) is the applied voltage and (S) the distance between the parallel plates. The electrodes for uniform fields for axially symmetrical systems whose profile follows the analytical function first introduced by Maxwell:

$$z = \frac{a}{\pi}\left(w + 1 + e^{w}\right) \tag{4}$$

z and w represent the complex coordinates in the (z- and w- planes).

Substitution of the coordinates for the complex values $(z = x + iy)$ and $(w = u + iv)$ in equation (4):

$$x + iy = \frac{a}{\pi}\left(u + iv + 1 + e^{(u+iv)}\right) \tag{5}$$

$$x + iy = \frac{a}{\pi}\left(u + iv + 1 + e^{u} \times e^{iv}\right) \tag{6}$$

Where $e^{iv} = \cos v + i \sin v$

The real part equal $x = \frac{a}{\pi}\left(u + 1 + e^{u} \times \cos v\right)$ (7)

The imaginary part equal $y = \frac{a}{\pi}\left(v + e^{u} \times \sin v\right)$ (8)

Assuming two infinite, parallel plates in the (w-plane).

Quantitatively the field strength within the (z-plane) may be computed in several ways, as follows:

The absolute values computed by: $\left|E_Z\right| = \sqrt{E_X^2 + E_y^2}$ (9)

or, the absolute value of (E_Z) may be computed by:

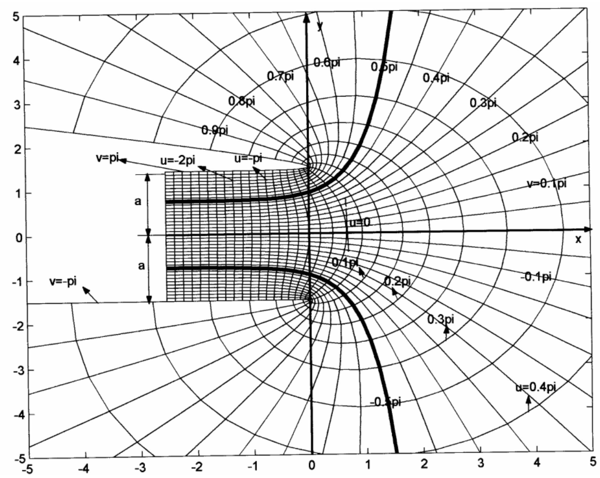
$$\left|E_z\right| = \frac{1}{\sqrt{\left(\frac{\partial x}{\partial v}\right)^2 + \left(\frac{\partial y}{\partial v}\right)^2}} \;. \tag{10}$$

The easiest method applies to separate analytical function, eqn. (11). Combining eqns. (7), (8) and (10), easily the field strength may find as:

$$\left|E_Z\right| = \frac{\pi}{a\sqrt{1+e^{2u}+2e^{u}\cos v}} = f(u;v) \tag{11}$$

To quantify this expression with any applied voltage it is necessary to perform a calibration with the field intensity within the original (w-plane). If the line ($v=\pi$) is at potential ($\phi = V$) and the line ($v=-\pi$) at potential ($\phi=-V$), the magnitude of the field strength in the (w-plane) is $\left(\left|E_w\right| = 2V/2\pi = V/\pi\right)$. Hence, the absolute magnitude in the (z-plane) becomes: $\left|E_Z\right| = \dfrac{V}{a\sqrt{1+e^{2u}+2e^{u}\cos v}}$ (12)

Solving equations (13) and (14) using Math lab program. The transformation of a square grid from a (w-plane) in the displayed (z-plane) by equation (14) $\left(V = \pm\pi/2\right)$ shown in Figure (2).



$\left(v = \pm\pi/2\right)$, a= 1.5

Figure 2: Transformation of a square grid from (w-plane) in the displayed (z-plane)

The coordinates of which are given by ($v=\pm\pi$=constant), it can be recognized from equation (14) that these plates are transformed into (z-plane) to the left half-plane only. All other lines (v= constant) with $\left(-\pi < v < +\pi\right)$can be assumed to be other equipotential lines, and all lines (u= constant) with $\left(-\infty \le u \le +\infty\right)$can be assumed to be field lines in the (w-plane), representing a uniform field distribution.

These lines in the z-plane as shown in Figure (2), providing the electrical field distribution of parallel plates terminating at (x=0). The concentration of the equipotential lines, (v= constant), within the (z-plane) may well be recognized at, or in the vicinity of, the edges of the plates.

The parallel plates, $(v = \pm\pi)$, are thus inadequate to fulfill the demand for field distribution whose intensity is limited to the field strength within the homogeneous part of the arrangement, i.e. for $(u \leq -\pi)$. It is obvious that the field strength along equipotential lines for which $(-\pi < v < +\pi)$ provide better conditions.

For $(u \leq 3\_5)$, $|E_Z|$ is practically constant and =V/a, but for (u=0) and ($v = \pm\pi$), i.e. at the edges of the plates, $|E_Z|$ increases to infinite values. There are, however, many equpotential lines in the (z-plane) for which $|E_Z|$ is always limited to values $\leq V/a$. The general condition for this behavior is given by ($\cos v \geq 0$) or v within $\pm(\pi/2)$. As the strongest curvature of an equpotential line will provide the smallest possible electrode arrangement.

The profile has been chosen at ($\cos v = 0$) or ($v = \pm\pi/2$), the so-called 90^0 Rogowski profile in Figure (2). Along this line, the field strength has its maximum values between the plates in the "homogeneous field region" $u \leq -(3-5)$ and decreases gradually within the curvature with increasing values (u). As for all field lines starting at the curved part, the field strength decreases to a minimum value for ($v = 0$), breakdown should not occur between the curved regions of the electrodes. The actual distance of two metal electrodes shaped in this way would be (S=a), and equations (14) and (18) indicate the necessity of dimensioning the electrodes in accordance to the maximum gap length (S=a), necessary for the breakdown tests. For smaller gap lengths and the same profile, the field strength at the curved profile will decrease relative to the homogeneous field region.

UNIFORM FIELD GAP DESIGN:

A half contour of one of the electrodes used by Bruce [2] shown in Figure (3). The flat portion (AB) is of a diameter not less than the maximum gap length to be used, the portion (BC) of the curve is based on the axes (0B) and (0C), such that

$$XY = 0C \sin\left(\frac{BX}{B0} * \frac{\pi}{2}\right).$$

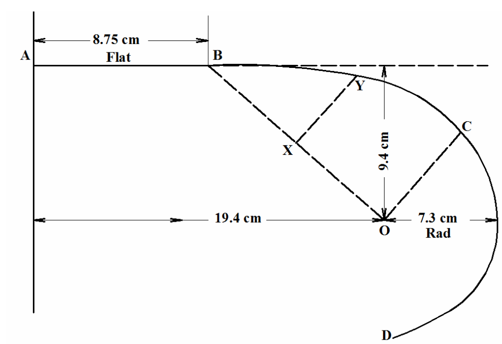


Figure 3: Half-contour of uniform field electrode used by Bruce [26]

(CD) forms the arc of circle with centre at (0). In order to maintain the uniformity of the field at different gap lengths, different pairs of electrodes were used. The diameters of the flat surfaces were (2.25, 4.4 and 7.8 in.) for the measurement of voltage up to (140, 280, 420 kV) respectively. The corresponding overall diameters of the electrodes were (4.5, 9, and 15 in.). Theses electrodes are used for voltages from (9 to 315 kV peak).

The profile of the contour of the uniform field electrode used in this project is designed using the same procedure used by Bruce.

Following the same procedure, the profile of the contour of the uniform field electrodes prototype designed in this project, a half contour of the uniform field prototype designed, shown in Figure (4). The uniform field gap is subjected to high voltage in the high voltage laboratory with a vertical shaped gap.

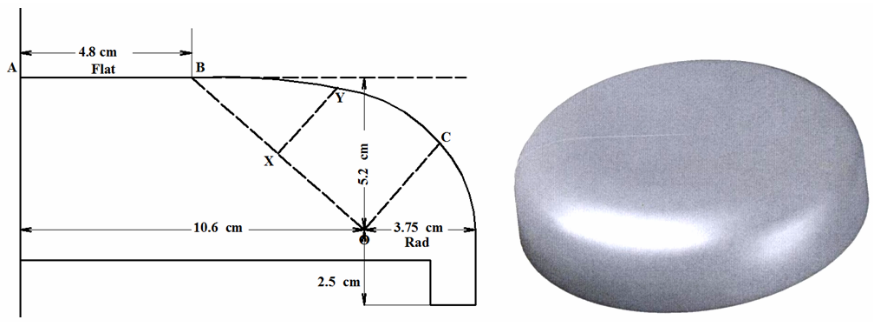


Figure 4: Half-contour of uniform field electrode prototype designed (in cm), and AutoCAD isometric of the uniform field gap

TESTING RESULTS OF THE PROTOTYPE DESIGNED

Keeping the gap spacing (S) constant and increasing the voltage slowly until breakdown between gaps occurs, then increase the gap spacing by lowering the earthed electrode to the specified distance and repeating the same procedure. Table (1) shows the measured breakdown voltage and break down field.

Table 1: Breakdown peak voltage of the uniform field gap

Gap spacing (S) (cm)	Breakdown voltage (V) (kV)	Breakdown electric field (E) (kV/cm)
0.20	08.20	41.00
0.30	11.30	37.67
0.40	14.20	35.50
0.50	17.10	34.20
0.60	19.87	33.12
0.70	22.60	32.29
0.80	25.30	31.63
0.90	28.10	31.22
1.00	30.20	30.20
1.50	44.30	29.53

T = 27.5 ^{0}C , P= 760 mmHg

CALCULATION OF A AND B CONSTANTS:

The breakdown voltage of a uniform field gap is given by:

$$V = AS + B\sqrt{S} \quad kV_P........ \qquad (S \ in \ cm) \qquad .(13)$$

Using the data obtained in Table (2) the mean value of A and B constants (at 27.5 ^0C and 760 mmHg) are A=26.53 kV/cm & B=4.99 kV/$cm^{1/2}$

The breakdown expression will be:

$$V = 26.53S + 4.99\sqrt{S} \quad kV_p..........(13) \quad \text{at} \quad P = 760 \text{ mmHg} \ , \ t = 27.5\,^0C$$

$$Error\% = \frac{Measured \ \ DB \ \ Voltag - Calculated \ \ DB \ \ Voltag}{Measured \ \ DB \ \ Voltag} \times 100$$

Table 2: Comparison between the calculated and measured breakdown voltage

Gap spacing (cm)	Breakdown Voltage Measured (kV)	Breakdown voltage calculated (kV) V=26.53S+4.99√S	%Error
0.2	08.20	07.54	8.050
0.3	11.30	10.69	5.390
0.4	14.20	13.77	3.030
0.5	17.10	16.79	1.810
0.6	19.87	19.78	0.450
0.7	22.60	22.75	-0.660
0.8	25.30	25.69	-1.540
0.9	28.10	28.61	-1.818
1.0	30.20	31.52	-4.371
1.5	44.30	45.91	-3.626

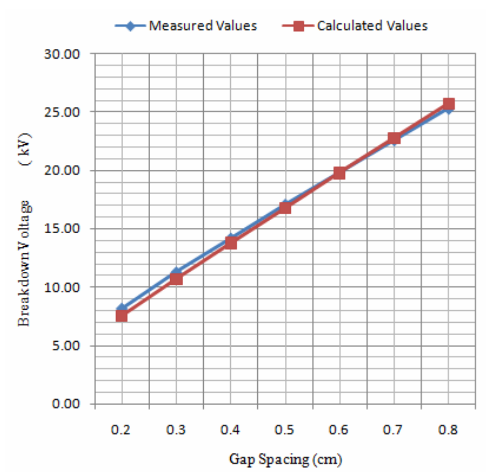


Figure 5: Measured and calculated breakdown voltage.

It is clear from Table (2) that the empirical formula can be used to calculate the sparking voltage for a given gap spacing (S) between (0.4 cm) and (1.5 cm) at the specified temperature and pressure. Introducing the air density correction factor (ρ), at t=27.5 ^0C and P=760mmHg, to standard temperature and pressure (STP) t=20 ^0C and p=76ommHg $\quad \therefore \rho = \frac{760}{760} \times \frac{273+20}{273+27.5} = 0.975$

Then the prototype breakdown voltage formula at (STP) will be in the form of :

$$V = 27.21S + 5.12\sqrt{S} \quad kV_p.......... \tag{14}$$

Table 3: the comparison between Bruce gap and prototype at (S.T.P)

Gap spacing (S) (cm)	Breakdown voltage V=27.21S+5.12√S (kV)	Breakdown voltage Bruce gaps (kV)	%Error
0.20	07.73	07.56	2.19
0.30	10.96	10.60	3.28
0.40	14.12	13.54	4.11
0.50	17.22	16.41	4.70
0.60	20.28	19.24	5.13
0.70	23.33	22.04	5.53
0.80	26.34	24.81	5.81
0.90	29.34	27.57	6.03
1.00	32.32	30.30	6.25
1.50	47.09	45.00	4.43

t= 20 ^0C , P= 760 mmHg , $\rho = 1$

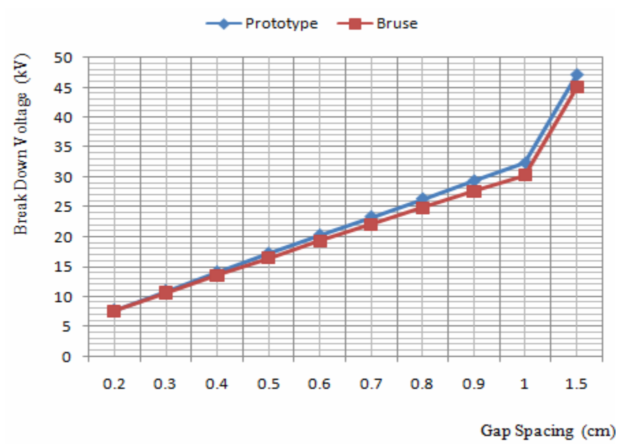


Figure 6: Comparison between Bruse and the prototype Sphere

Figure 7: Experimental work in H.V. Laboratory

Table 4: The experimental of break down voltage results between the prototype and different standard spheres

Gap spacing	break down voltage			
	Two Prototype	Prototype to Sphere	Prototype to Plane	Prototype to Rod
cm	kV			
0.2	08.20	07.59	07.33	-
0.3	11.30	7.98	10.99	-
0.4	14.20	13.04	14.66	-
0.5	17.10	16.30	18.33	-
0.6	19.87	18.86	20.04	-
0.7	22.60	21.42	21.76	-
0.8	25.30	23.98	23.47	-
0.9	28.10	26.54	25.19	-
1.0	30.20	29.10	26.90	12.50
1.2	-	34.42	-	-
1.5	44.30	-	39.00	14.00
2.0	-	-	-	17.50
2.5	-	-	-	20.00
3.0	-	-	-	21.70
3.5	-	-	-	23.00
4.0	-	-	-	25.00
4.5	-	-	-	28.00
5.0	-	-	-	30.00

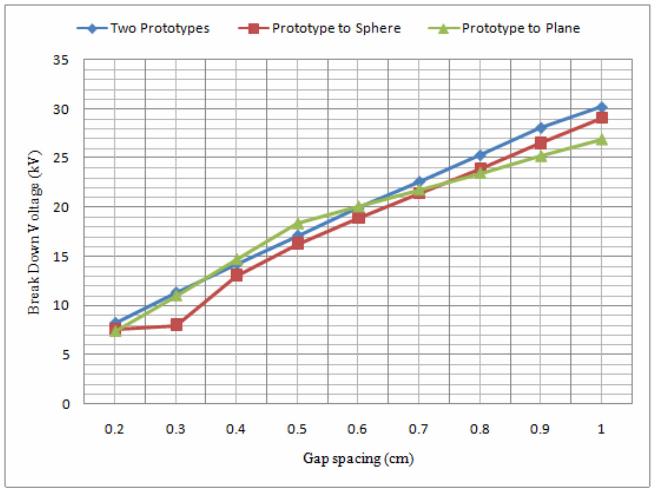


Figure 8: B.D. Voltage between the Prototype sphere and different electrodes

CONCLUSION

- The data obtained for breakdown of air in Table (3) shows no significant difference between the designed prototype and standard Bruce uniform field gaps.
- The breakdown voltage measured is less than that the standard gaps because irregularity of the designed which will lead to lower the breakdown voltage.
- The (A & B) constants calculated are very close to the standard values and the empirical formula can be used to calculate the sparking voltage for a specified spacing (S) up to (1cm).
- The sphere to rod breakdown voltage is lower than that of a uniform field gaps or sphere to plane air gaps for the same spacing due to rod sharpness.
- In spite of the superior performance and accuracy, the uniform field spark gap is not usually used for measurement for large gap spacing purposes, as very accurate finish of the electrode surfaces and careful alignment are difficult to obtain in practice.
- Theoretically the field between two equal spheres is very nearly uniform for values of (spacing/radius) ratios less than 10%, and practically the results obtained seem to be respecting the above condition for space gaps (0.2cm) to (0.6cm).
- The limitation in gap distance provides a homogeneous field distribution so that no pre-discharge or corona appears before breakdown.
- The prototype material used is not pure Aluminum and spacing between two electrodes is not too accurate, these factors have affected the breakdown voltage measurements, as well as the effect of the atmospheric conditions (humidity and dust) in air and the finishing of the tested electrodes

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