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CALIBRATION OF THE SPHERE GAP VOLTMETER

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The breakdown strength of air between spherical terminals has been found to be rather constant, and the sphere gap has been suggested as a standard instrument to be used in the measurement of high voltage. Results obtained with different apparatus by different experiments, however, have not been in perfect accord, and the ultimate dielectric strength of air indicated by calculating the maximum intensity from these tests, has shown some calibrations of the gaps to disagree with results obtained by other methods.

If spheres of sufficient size are used, and if the separation and breakdown voltage are such that there is no corona at the surface of the spheres, it is fair to assume that the complete breakdown of the air gap will occur at the voltage at which the stress due to the intensity at the surface of the spheres corresponds to the ultimate strength of the air. It also seems as though the rupture of a given sphere gap should be independent of frequency of time of voltage application, and that it should depend only upon the maximum value of the voltage impressed, provided that there is no ionization before breakdown which in effect alters the shape of the terminals and changes the dielectric gap.

The purpose of this paper is to present the calibration curves for the three sizes of sphere gaps which have been suggested as standards.*

To be of value in measuring voltage, the sphere gap must be furnished with a calibration curve showing the relation between the breakdown voltage and length of gap. The results of any

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*See paper by Farnsworth and Fortescue, p. 733 of this volume.

calibration can be no better than the method used in the test, and unless such calibration is accurate the sphere gap voltmeter is not a desirable standard.

Different methods used to calibrate spark gaps at high voltage show great variations in the relation between voltage and separation of spheres. Some also show a great variation with frequency. It can be shown that such differences are due to conditions of test rather than to any real variation of the sphere gaps themselves.

The most usual method of measuring the high-tension voltage is to measure the primary potential and multiply by the ratio of the transformer. Voltages obtained by this method are generally very much in error, due to the distributed capacity in the high-tension winding of the transformer, harmonic distortions of the applied voltage wave, and the capacity of the terminal bushings and the apparatus to which the high-voltage winding is connected. The effective, or r.m.s., low-tension voltage is usually indicated so that there is no measure of the maximum unless a pure sine wave of voltage is applied, there are no appreciable distortions due to the harmonic components of the exciting currents, and the capacity regulation can be corrected.

The use of a second high-voltage transformer to step down the voltage for measurement with a voltmeter, is an improvement over the straight ratio method, but requires corrections in most cases, and another expensive transformer.

Another method of measuring the high voltage which has been used by the authors is to connect an electrostatic voltmeter of low electrostatic capacity in parallel with one or several sections (at the ground side) of a condenser type terminal. This method corrects the reactive errors of the ratio method but is also an effective reading and gives no indication of wave shape and maximum value.

The calibration of the sphere gaps was thought to be dependent only on the maximum voltage and it was the aim of the authors to obtain the calibrations in terms of maximum of the voltage of the high-tension winding, and then reduce the results to effective values, assuming sine wave shape of voltage.

A very satisfactory method of measuring the maximum of the voltage wave was to rectify the capacity current taken by an air condenser and measure the average value of the rectified current with a d'Arsonval galvanometer. The details of this method will probably be of interest.

Fig. 1 shows diagrammatically the apparatus and circuits necessary to calibrate the gap in terms of the maximum voltage.

The air condenser is shown in Fig. 2. It was constructed of wood carefully turned to dimensions and coated with tin-foil and lead sheeting. The central and high-voltage member was 60 cm. (23.6 in.) in diameter and 458 cm. (15 ft.) long. The outside or ground member with the flared ends had a total length of 240 cm. and internal diameter of 162.8 cm. (5.34 ft.) It was divided into three sections; the middle or working part was 47.7 cm. (18.8 in.) long and the end sections or guard rings were each of equal length in the cylindrical part and were flared with toroidal surfaces having a radius of 47.7 cm. (18.8 in.). The capacity of the central section was figured and found to be $2.657 + 10^{-11}$ farad.

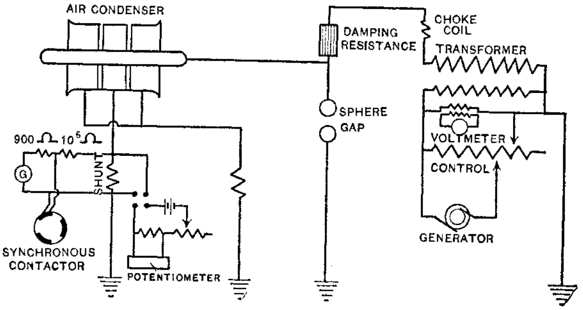

FIG. 1

The central section of the outside member was connected to ground through a non-inductive resistance which served as a shunt to measure its charging current. The guard ring sections were connected together and grounded through a resistance of such a value that the time constants of the center and ends would be approximately the same, and there would be no cause for leakage between the three sections. Across the resistance between ground and the central section, was connected the galvanometer circuit consisting of a megohm of series resistance and a d'Arsonval galvanometer shunted with a synchronous contactor. The contactor was driven by a six-pole synchronous motor and arranged with three equal brass segments which short-circuited two brushes during every alternate half cycle. The brushes were connected to a long lever so that they could be readily shifted in phase. A maximum deflection of the galvanometer in this case indicates commutation at the zero points of the current wave, and this maximum deflection was proportional to the average charging current of the condenser section and also proportional to the maximum voltage impressed upon the condenser.

If Q is the quantity required to charge the condenser to any maximum potential V, the passage of $2Q$ is required to change the potential from $+V$ to $-V$ for the symmetrical periodic charge. While the potential changes from $-V$ to $+V$, the reversal of current is suppressed in the instrument by the shunting effect of the synchronous contactor. The steady deflection of the instrument is therefore caused by a unidirectional pulsating current. The average value of the condenser current (disregarding sign) is equal to the quantity flowing, in coulombs per second.

$$I = 4\,Q f = 4\,C\,V f \qquad (1)$$

where C = Capacity of condenser.
f = Frequency.
V = The maximum voltage.
and I = The average value of the condenser current.

The steady current deflection (d) of the galvanometer is

$$d = K\,I \qquad (2)$$

where K is the instrument constant in divisions per ampere. From (**1**) and (**2**)

$$V = \frac{d}{4\,C\,K f}$$

In all cases the value of K was obtained by applying the battery voltage to the galvanometer circuit while the contactor was running.

In order to make sure that the contactor was making good contact at all times, frequent check tests were made with the contactor running, and still to make sure that currents for equal deflections were in the ratio of 2 to 1. The galvanometer was critically damped so as to obtain quicker readings, and to eliminate errors due to overshooting and swinging which would occur with voltage variations and phase shifts. With the instrument under-damped it was difficult to distinguish between voltage variations and false setting of the brushes. When over-damped the proper position of the brushes for the maximum reading could readily be found, when the voltage was steady, but the response to quick changes in voltage was not sufficient, and it

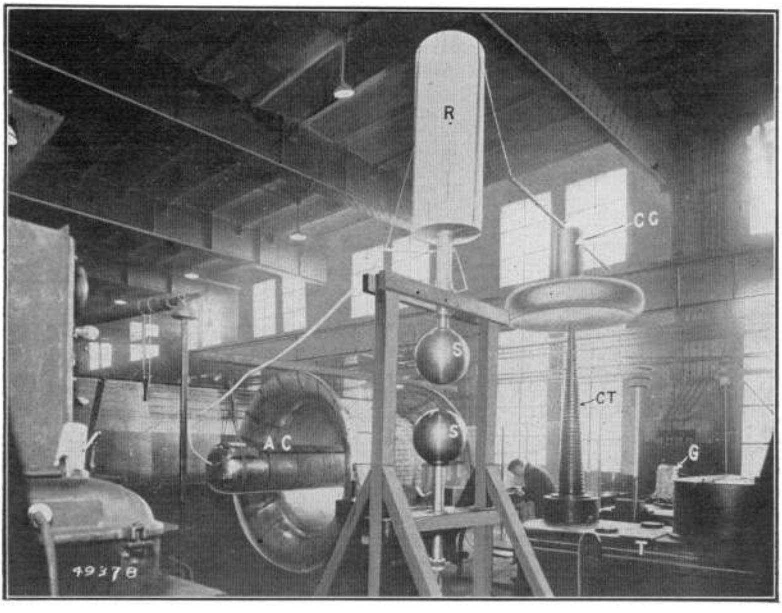

FIG. 2. [CHUBB AND FORTESCUE]

T—Transformer; C T—Condenser terminals; C C—Choke coil; R—Resistance; S S—Sphere gap; A C—Air condenser; G—Galvanometer.

was impossible to tell whether the breakdown of the gap was due to a surge of voltage or not. Throughout the work, all wiring, instruments, switches, resistances in the circuit, and the contactor were shielded with grounded coverings of tin-foil or wire screen in order to remove static troubles. Serious errors were introduced when any part of circuit was left unshielded, but the strong static field had no bad effects when the shields were properly grounded. There was an appreciable capacity between the high-tension terminal and the ground side of the condenser, and in order to prevent errors due to this additional condenser current, through the measuring shunt, it was necessary to place a grounded network of wires between the condenser and the high-potential circuits. Before each test a high voltage was applied, with the condenser disconnected and short-circuited, to find out if there were any static or electromagnetic troubles which would give a deflection of the galvanometer. If no such troubles were present the high-tension lead was connected to the condenser and tests made as follows:

The gap was opened two or three cm. beyond the breaking point. Voltage was then applied to the condenser and gap. After the maximum deflections of the galvanometer had been carefully observed, the sphere gap was very slowly closed until breakdown occurred. The maximum value of the voltage was then worked out from the galvanometer readings and a direct-current calibration made after each test. The relation between this maximum voltage and the separation of the spheres was then plotted.

In the later tests the contactor was driven with a 30-h.p. induction motor instead of a synchronous motor. By making this change both positive and negative maxima could be observed, and no shifting of brushes was necessary, as the adjustment for maximum deflection was obtained each time the rotor of the motor had slipped a pole pitch. At 60 cycles, the motor slipped less than one revolution (6 poles) per minute, so that with the critically damped galvanometer, accurate observations of the two maxima could readily be made. At lower frequency the per cent slip was of course greater, but the frequency of galvanometer maxima was about the same.

Tests were made at frequencies ranging from 25 to 60 cycles with two high-voltage transformers, each excited from two different sources of power.

The authors hoped to calibrate the 37½-cm. and 50-cm. spheres to 500 kv. (effective) on a third and larger transformer, but lack of time and a great volume of commercial testing delayed these tests.

It was assumed that a good test on the 25-cm. spheres up to the voltage corresponding to a diameter separation could be made on the 300-kv. transformer and the calibrations of the larger gaps obtained by extrapolation and the theory of proportional fields.

If the calibration of the 25-cm. spheres showed a constant surface intensity throughout, and if the larger set agreed within the same range of voltage, such an extrapolation could not be questioned. The results, however, show increasing intensity with an increase in separation, and show the air between the larger spheres to be apparently weaker than between the small spheres for the same ratio of separation.

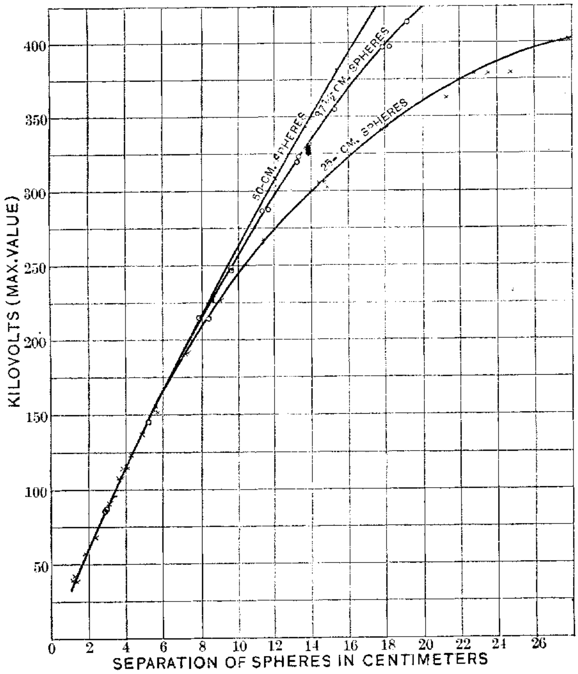

FIG. 3

The increase of surface intensity with increase in separation has been observed by several experimenters, but not satisfactorily explained. The relative weakness of the air gaps between the large spheres is probably due to the effect of neighboring bodies.

Extraneous objects at constant distances from the gaps will of course weaken the gap between the larger spheres more than that between the smaller spheres. Quantitative tests of the effect of extraneous objects will be made later.

The results of the tests show frequency and wave shape to have no appreciable effect upon the calibration.

TABLE I

25-CM. SPHERES

d_1	d_2	d	E ratio kv.	f cycles per sec.	Gap cm.	$K \times 10^{-3}$	V kv.	Remarks Test No. 36
32	37	69	24.8	25	1.31	658	39.6	
32.5	36.5	69	24.8	"	1.19	"	39.6	
76.5	82	158.5	58.5	"	3.10	"	90.9	
76.5	82.5	159	58.5	"	3.10	"	90.9	
96.6	102.5	199.1	75	"	3.86	"	114	
97	102.3	199.3	75	"	4.07	"	114.3	
98.5	102.2	200.7	75	"	4.06	"	115.1	
131.5	135.5	267	100	"	5.52	"	152.8	
131.5	137	268.5	100	"	5.56	"	154	
118.5	122	240.5	90	"	4.92	"	137.8	Damping not good brush tightened
106	108.5	214.2	80	"	4.38	"	122.6	
92.5	94.5	187	70	"	3.79	"	107.2	
92.5	94	186.5	70	"	3.76	"	106.8	
60.5	60	120.5	47.3	"	2.34	"	69	
49.2	49.6	98.8	34.6	"	1.82	"	57	
								Test No. 38
42	45.5	87.5	100	25	5.71	218	151	
42.5	45.5	87.5	100	"	5.68	"	151	
53.5	57.5	111	125	"	7.29	"	191	
54	57.5	111.5	125	"	7.32	"	192	
63.5	68.5	132	150	"	9.02	"	227	
63.3	68.8	132.1	150	"	9.08	"	227	
74	79.6	153.6	176	"	11.37	"	265	
75	80	155	175	"	11.36	"	268	
85	92.5	177.5	200	"	11.17	"	306	
85	92.5	177.5	202	"	14.67	"	306	
85.5	92.5	178	200	"	14.43	"	307	
95.3	103.5	198.8	225	"	17.80	"	343	
96.2	103.6	199.8	225	"	18.02	"	345	
106.3	114	220.3	251	"	23.56	"	381	
106.2	114	220.2	251	"	24.73	"	381	Surge of voltage
106.2	113.6	219.8	249	"	23.55	"	380	
112.5	121.5	234	264	"	27.85	"	404	
102	110.5	212.5	240	25.2	21.28	"	363	
112	121	233	260	25	27.58	"	402	
105.5	115	220.5	250	"	22.79	"	381	
84.5	93	177.5	200	"	14.88	"	303	
62.3	70.1	132.4	150	25.2	9.20	"	225	
41.5	49	90.5	100	"	5.56	"	154	
41.2	49.5	90.7	100	"	5.66	"	155	

TABLE II

37½-CM. SPHERES

d_1	d_2	d	E ratio kv.	f cycles per sec.	Gap cm.	$K \times 10^{-3}$	V kv.	Remarks
								Test No. 40
25	25.2	50.4	50	25	3.04	214	87.5	
24.6	25.3	49.9	50	"	2.98	"	86.4	
41.4	41.7	83.1	100	"	5.26	"	144.1	
41.5	42.5	84	100	"	5.24	"	145.6	
61	62	123	150	"	7.96	"	215.5	
60.3	62.4	122.7	150	"	8.44	"	214.8	
70.8	73	143.8	176	"	9.61	"	249.2	
70.2	72.5	142.7	175	"	9.70	"	247.5	
81.6	83.8	165.4	201	"	11.38	"	287	
81.8	84.3	166.1	202	"	11.69	"	288	Quick rise of voltage
81.2	84	165.2	201	"	11.99	"	286.6	
91.8	95	186.8	225	"	13.35	"	323.7	
91.6	94	185.6	225	"	13.27	"	321.7	
101.5	104	205.5	250	"	15.40	"	356.3	
101	104.3	205.3	250	"	15.29	"	356	
112.5	116.5	229	275	"	18.12	"	398	
112.5	116.5	229	274	"	17.88	"	398	
118	121	239	286	"	19.18	"	415	
41.2	42.5	83.7	100	"	5.27	"	145.2	

TABLE III

50-CM. SPHERES

d_1	d_2	d	E ratio kv.	f cycles per sec.	Gap cm.	$K \times 10^{-3}$	V kv.	Remarks
								Test No. 45
28.1	26.3	54.4	61	24.75	3.45	214	96.5	
28.1	26.2	54.3	60	25	3.38	"	95	
45.3	43.6	88.9	100	25	5.68	"	155	
45.3	43.7	89	100	25	5.68	"	156	
66	64.1	130.1	150	25.25	8.66	"	226	
65.8	65.2	131	150	24.75	8.66	"	231	
88.6	88	176.6	200	25	12.23	"	308	
88.8	88.1	176.9	201	25	11.99	"	309	Frequency unsteady
88.7	88	176.7	201	25	12.17	"	308	
99.4	99	198.4	225	25.25	13.88	"	344	
99.7	99	198.7	225	25.25	13.80	"	344	
109.4	109	218.4	249	25.25	15.43	"	378	
108.8	109.2	218	249	25	15.32	"	381	Guard ring discharges through shunt
87	89.2	176.2	202	25.25	12.20	"	303	

Fig. 3 shows the calibration curves obtained for each of the three sets of spheres and Tables I, II and III show the results for

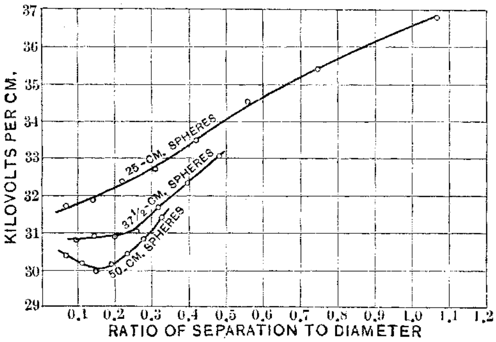

Fig. 4

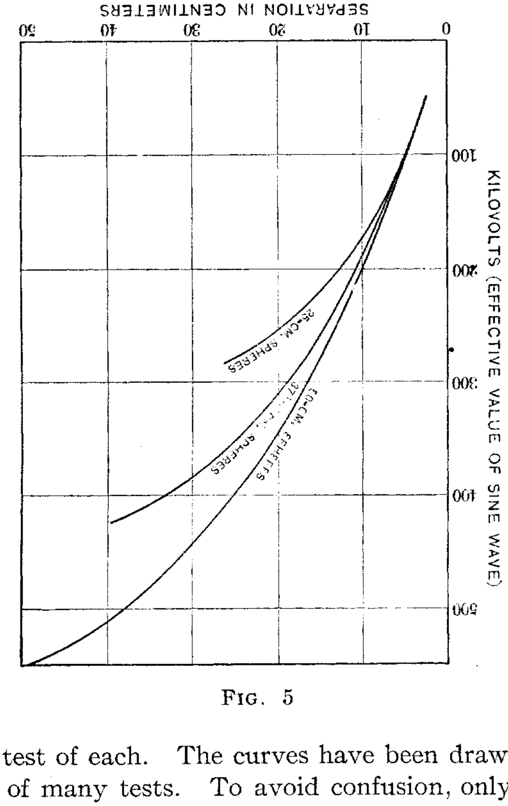

Fig. 5

a 25-cycle test of each. The curves have been drawn weighing the points of many tests. To avoid confusion, only the points of the tests shown in the tables are plotted.

Fig. 4 shows the relation between surface density and the ratio of separation for the three curves of Fig. 3.

Fig. 5 shows the calibration for the three gaps extended and expressed in terms of effective values of a sine wave voltage. These curves have been derived from the curve for the 25-cm. sphere.

The authors regret that limitation of time makes it necessary to show extrapolated curves in place of direct calibration for the high-voltage results. However, the curves will serve as a basis for comparison until the direct calibration can be completed.