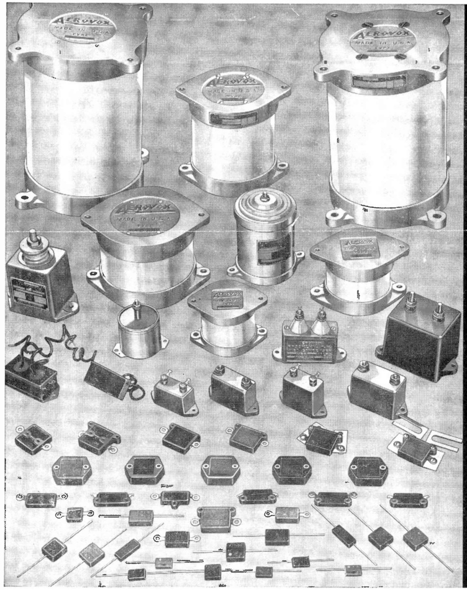

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Methods of Measuring High Voltages

By the Engineering Department, Aerovox Corporation

THE EXTENT of present applications of high-voltage equipment, together with future prospects of enlarged research, development, and applications in this field, raise interest in the methods employed in measuring high voltages. It is evident that measurement of potentials between five and several hundred kilovolts introduces problems of instrumentation, technique, and handling not encountered at low and medium voltages.

A cursory survey of high voltage measurements will indicate that several common methods of measurement are employed in the field to suit individual voltages and test conditions and, in most cases, that one system may be used to check or standardize the other. It will be the purpose of this article to describe the instruments and methods in current use in shop and laboratory, and to digest such operating and handling information as will be useful in handling high-voltage equipment.

SYSTEMS

The common systems now being used for measuring high voltages include (1) meters designed specifically for high-voltage tests, these including electrostatic kilovoltmeters and d'Arsonval type kilovoltmeters (with and without external multipliers); (2) special external multipliers, voltage dividers, and potential transformers for converting low- or intermediate-range voltmeters or milliammeters into kilovoltmeters; (3) electrometers which find their most extensive use in experimental laboratory work; (4) special spark gaps, including sphere gaps and needle-point gaps; and (5) step-up test transformers (often in conjunction with electronic rectifiers) of known turns-ratio to which known values of low primary voltage are applied. The editors do not wish to imply that these are the only systems available for the measurement of high voltages. The instruments and systems listed are the most commonly used at this time, however, and are highly practical.

MOVABLE-COIL METERS

Commercial d'Arsonval type meters, having sensitivity of 1000 ohms per volt are supplied without external multipliers for full-scale dc deflections up to 1000 volts. From 1 to

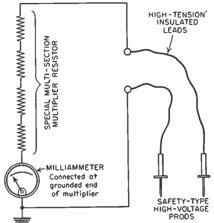

FIG. 1

5 kv. full-scale deflection, these instruments are supplied as catalog items for use with external multipliers and can be furnished for higher values on special order.

One instrument manufacturer supplies entirely self-contained portable kilovoltmeters with 0-5, 0-10, and 0-20 kv. ranges. These instruments are essentially low- and medium-range milliammeters with high-resistance series-connected multiplier resistors internally mounted. Ceramic-insulated high-voltage input terminals are provided, and well-insulated safety-type test prods and leads are included as essential accessories.

The same manufacturer also supplies special close-tolerance multipliers for use with 0-10 dc milliammeters (with thermocouples for ac operation) to measure potentials up to 25 kv., ac and dc. In the 1-25 kv. range, the multiplier current is 1 to 5 milliamperes and the accuracy of calibration of the multiplier resistance is 0.1%.

SERIES RESISTOR

Any low-range movable-coil milliammeter may be converted into a practical kilovoltmeter by connecting in series with it an appropriate high-resistance multiplier. Panel-mounted instruments on high-voltage power supply units are often so arranged. Connections are indicated in Figure 1. The value of the resistor may be determined from Ohm's Law, $R = E/I$; where R is the required multiplier resistance value (ohms), E the desired full-scale deflection (volts), and I the present full-scale current deflection (amperes).

This multiplier must have a large enough wattage rating to dissipate with ample safety factor the power (I^2R) developed by the maximum full-scale meter current flowing through it, and must be as long as possible (preferably being made up of several component resistors connected in series and imbedded in a high-grade wax) to minimize surface leakage and prevent flashover.

It is highly desirable to mount such resistors in an overlength glass tube after they have been connected together and to mount the entire assembly well clear of other circuit components. The mounting must be rigid mechanically and must not require that the pig-tail leads of the end resistors act as supports.

VOLTAGE DIVIDER

High-resistance, movable-coil voltmeters may be converted into kilovoltmeters by means of voltage divider potentiometers (see Figure 2). This is the same conventional arrangement employed in some low-voltage instruments of the electronic type, except that the resistance ratios are arranged for higher-voltage division.

CHART I
NEEDLE-GAP SPARK-OVER VOLTAGES
(At 25°C., 760 mm, 80% R.H.)

RMS KILOVOLTS	MILLIMETERS
10	11.9
15	18.4
20	25.4
25	33.0
30	41.0
35	51.0
40	62.0
45	75.0
50	90.0

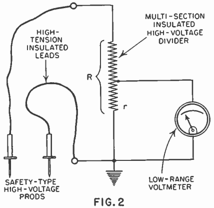

FIG. 2

In this circuit, the ratio of the fractional resistance, r, (across which the meter is connected) to the total resistance, R, corresponds to the ratio of the normal full-scale meter deflection to the high voltage applied across R. If section r is made variable, as by tap-switching, several kilovolt ranges may be provided for a single meter.

The potentiometer method has the disadvantage that the meter resistance must be considerably higher than the section resistance, r. In some instances, this will limit the total resistance value, R, which for best results must be of a high order of magnitude to prevent excessive loading of the high-voltage source. R must be capable of dissipating with ample safety factor the power (I^2R) developed by current flowing through the entire resistor; and like the series multiplier, must possess the greatest practicable length in order to minimize surface effects and prevent flashover. The highest range of an electronic voltmeter (generally 1000 volts) may be extended successfully to several kilovolts by the potentiometer method, since the vacuum-tube instrument possesses extraordinarily high input resistance and permits the highest values for R.

PRECAUTIONS WHEN USING MOVABLE-COIL METERS

Several important safety precautions must be observed when employing any of the movable-coil kilovoltmeters. The meter must be connected to the *ground* end of the multiplier or voltage-divider resistance; meters with "live" zero adjuster

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instrument is perhaps more popular in Europe than in the United States.

The safety precautions recommended in connection with movable-coil kilovoltmeters apply as well to the electrostatic instrument.

SPARK GAPS

High voltages may be measured in terms of the maximum air gap in which spark-over will occur. The accuracy of this method may be enhanced by correcting for pressure and relative humidity.

Standard voltage-measuring gaps in practical use are of two types, the *needle gap* and the *sphere gap*. The former is recommended for voltages between 10 and 50 kv.; the latter for voltages higher than 50 kv.

The following specifications for spark gaps have been set by the American Institute of Electrical Engineers (A. I. E. E. *Standards*—paragraph 2366):

NEEDLE GAP

Arrangement. Utilizes gap between points of two new needles.

Electrode Size. Needles are double long No. 00.

Electrode Support. Needles are supported axially at ends of linear conductors.

Support Size. Linear conductors are at least twice the gap length.

Electrode Clearance. The space around the needle gap must be clear over a radius equal to twice the gap length.

SPHERE GAP

Arrangement. Utilizes gap between two metallic spheres.

Electrode Size. Standard sphere diameters (for each sphere) are 62.5, 125, 250, and 500 millimeters. The curvature of these spheres (as measured by a spherometer) must not vary more than 1% from that of a true sphere of the given diameter, and the sphere diameter must not vary more than 0.1%.

Electrode Support. The spheres are supported by shanks, the maximum diameter of which must not exceed 20% of the sphere diameter. Supporting collars or similar attachments must be as small as practicable and must be separated from the spheres by a distance equal at least to the maximum active gap length.

Electrode Clearance. The space around the sphere gap should be clear, no external bodies or circuit components coming closer to the gap than a distance equal to twice the sphere diameter.

Chart I lists needle-gap spark-over distances corresponding to common RMS values of sinusoidal voltage. Chart II lists sphere-gap spark-over distances corresponding to common RMS values of sinusoidal voltage, for various sphere diameters.

Gap corrections are made for air density in accordance with Chart III. In making these corrections for a *sparking* gap, Chart II values are multiplied by the correction factor obtained from Chart III. In making air density corrections for a gap which is to be set, the required voltage is divided by the Chart III correction factors to determine (from Chart II) the correct spacing.

The relative air density values (column 1, Chart III) are determined by means of the equation:

$$\text{Relative Air Density} = \frac{0.392\,b}{273 + t} \tag{4}$$

Where b = barometric pressure (millimeters)
t = temperature (°C)

The data included in the three charts are from A. I. E. E. standards as published in the *Standard Handbook for Electrical Engineers*, Fifth Edition (McGraw-Hill Book Co.); Chart I (p. 1893), Chart II (p. 1895), and Chart III p. 1896).

CHART III
AIR DENSITY CORRECTION FACTORS FOR SPHERE GAPS

RELATIVE AIR DENSITY	Diameter of Standard Spheres in Millimeters			
	62.5	125	250	500
0.50	0.547	0.535	0.527	0.519
0.55	0.594	0.583	0.575	0.567
0.60	0.640	0.630	0.623	0.615
0.65	0.686	0.677	0.670	0.663
0.70	0.732	0.724	0.718	0.711
0.75	0.777	0.771	0.766	0.759
0.80	0.821	0.816	0.812	0.807
0.85	0.866	0.862	0.859	0.855
0.90	0.910	0.908	0.906	0.904
0.95	0.956	0.955	0.954	0.952
1.00	1.000	1.000	1.000	1.000
1.05	1.044	1.045	1.046	1.048
1.10	1.090	1.092	1.094	1.096

CHART II

SPHERE-GAP SPARKING DISTANCES IN MILLIMETERS
(25°C. and 760 mm.)

KILOVOLTS	62.5 mm. SPHERES		125 mm. SPHERES		250 mm. SPHERES		500 mm. SPHERES	
	ONE SPHERE GROUNDED	BOTH SPHERES GROUNDED	ONE SPHERE GROUNDED	BOTH SPHERES GROUNDED	ONE SPHERE GROUNDED	BOTH SPHERES GROUNDED	ONE SPHERE GROUNDED	BOTH SPHERES GROUNDED
10	4.2	4.2						
20	8.6	8.6						
30	14.1	14.1	14.1	14.1				
40	19.2	19.2	19.1	19.1				
50	25.5	25.0	24.4	24.4				
60	34.5	32.0	30	30	29	29		
70	46	39.5	36	36	35	35		
80	62	49	42	42	41	41	41	41
90	—	60.5	49	49	46	45	46	45
100			56	55	52	51	52	51
120			79.7	71	64	63	63	62
140			108	88	78	77	74	73
160			150	110	92	90	85	83
180			—	138	109	106	97	95
200					128	123	108	106
220					150	141	120	117
240					177	160	133	130
260					210	180	148	144
280					250	203	163	158
300					—	231	177	171
320					—	265	194	187
340							214	204
360							234	221

tain balance. The attraction is proportional to the square of the difference of potential. The voltage value is determined by means of the equation:

$$E = d\sqrt{\frac{25.13\,f}{kA}} \qquad (3)$$

Where E is the applied voltage
f = force of attraction (measured with the balance)
k = dielectric constant of the material separating the plates (1 for air)
A = area of the smaller plate (if the two are unequal in size)
d = separation between plates at balance

A and d must be in the same class units (inches and square inches, or centimeters and square centimeters)

There are several variations of the fundamental electrometer design, the arrangement just described being merely a rudimentary arrangement which has found frequent application in the absence of other instruments for high voltage measurements.

ELECTROSTATIC VOLTMETER

The electrostatic voltmeter, like the electrometer, utilizes electrostatic attraction between fixed and movable elements to obtain deflections proportional to an applied voltage. The movable vane in a modern electrostatic voltmeter is mounted on a pivoted spindle which rotates in jewelled bearings against the torque of a spiral spring. Suspension type instruments are also supplied for laboratory use. The electrostatic kilovoltmeter, available commercially in both portable and panel-mounting styles, is distinctive in that it draws virtually no current from the high-voltage source. However, its use is limited to dc and to low-frequency ac.

The electrostatic voltmeter is essentially a high-voltage instrument. It rarely is supplied for full-scale deflections of less than 500 to 700 volts, being commonly intended for kilovolt service. Electrostatic kilovoltmeters are supplied for use up to 100 kv., the higher ranges being obtained by means of capacitor-type multipliers. As a kilovoltmeter, this screws should never be used; metal-cased meters should be used only in emergencies and then only when mounted back of the instrument panel, and whenever practicable the meter should be mounted behind thick glass. Test leads should be provided with high-tension insulation, and test prods should be of extra long length and must be insulated by a high-grade hard sleeving throughout most of their length.

Suitable instrument fuses should be connected at the meter terminals and should be held by approved fuse holders supported by some other means than the meter case. Fuses should be provided also at the input terminals of the instrument for protection of the multiplier or divider resistor. A few designers favor paper meter cards over the popular metal scales.

POTENTIAL TRANSFORMERS

Standard potential transformers are available for converting low- or intermediate-range voltmeters (and some milliammeters) into kilovoltmeters. These instruments are step-down transformers designed to reduce the maximum high potential to be measured to the lower full-scale value of an available voltmeter. The transformer turns ratio is the factor whereby the meter deflection is multiplied.

A typical potential transformer is the Weston Model 311 which steps down 4.5 or 9 kilovolts to 150 volts maximum. This unit is supplied for 25 or 50 to 133 cycle operation and is capable of handling 15 or 25 volt-amperes.

Makeshift potential transformers may be any such units whose turns ratio will furnish the required step down of voltage, whose input winding is capable of handling the high voltages and passing safely the attendant current, and whose insulation is capable of withstanding the high voltage. It is highly desirable that the input winding have as high a dc resistance value as possible, in order to minimize loading of the high-voltage source.

Disadvantages of the potential transformer are its relative weight and bulk, low-resistance input, and restricted maximum input potentials.

TURNS RATIO OF H.V. TRANSFORMER

When the line voltage and turns ratio of the transformer in a high-voltage power supply circuit are known, high potentials delivered by the supply unit may be determined with sufficient accuracy for many applications by means of the following formulae:

$$E_s = 1.414\ E_p \left(\frac{N_s}{N_p}\right) \tag{1}$$

for alternating voltage delivered directly by the transformer secondary.

$$E_s = 1.414\ F E_p \left(\frac{N_s}{N_p}\right) \tag{2}$$

for direct voltage by rectification.

E_S is the high-voltage value, E_P the RMS reading of a primary voltmeter connected in parallel with the transformer primary and the supply line, and N_S/N_P the transformer turns ratio. In the dc formula, F is a factor governed by the type of rectifier employed — i.e., F is 1 for simple half- or full-wave rectification, 2 for a voltage doubler, 4 for a voltage quadrupler, etc., etc. The second formula assumes that the power supply is either unloaded, or negligibly loaded (as by a high-resistance bleeder).

ELECTROMETER

The electrometer is an instrument which makes use of basic principles for the measurement of potentials, and is most successfully employed at high voltages. The active portion of this instrument consists essentially of two metallic plates, one stationary and one movable, arranged in parallel relationship with each other and connected to the source of high voltage. Electrostatic attraction, which causes one plate to be drawn toward the other, is proportional to the applied voltage. The displacement of the movable plate, with respect to its position of rest, thus is likewise proportional to the applied voltage, and the instrument may be employed as a voltmeter for either ac or dc indications.

An elementary electrometer consists of a simple balance, as shown in Figure 3. In this arrangement, a movable metal plate is carried from one end of a beam; a weight pan from the other. The movable plate is suspended above a parallel-mounted stationary plate, and the two are connected to the source of high voltage. An insulating safety stop prevents the two plates from meeting.

Electrostatic attraction tends to draw the plates together, the force of this attraction being measured in terms of the weights which must be placed in the weight pan to main-

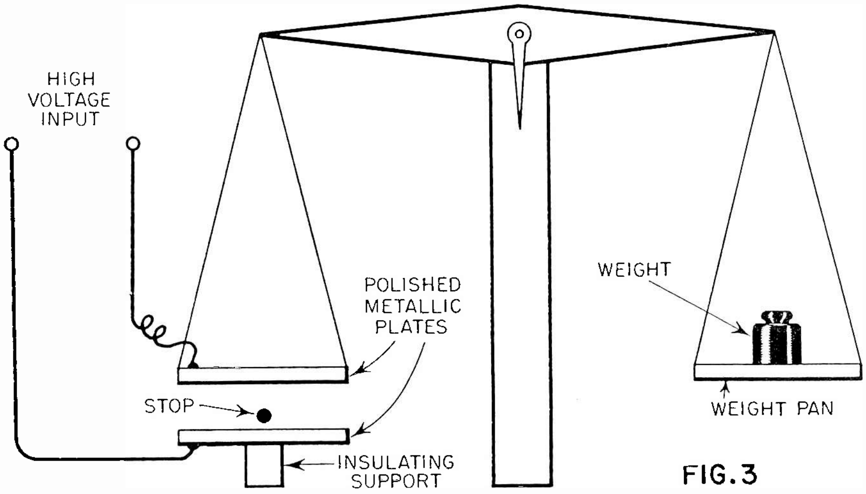

FIG.3