

A NEW TYPE OF GENERATING VOLTMETER

by

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A THESIS

submitted to the

OREGON STATE AGRICULTURAL COLLEGE

in partial fulfillment of
the requirements for the
degree of

MASTER OF SCIENCE

July 1936

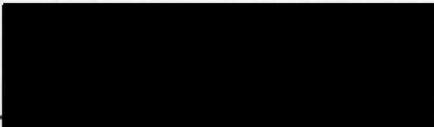
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A NEW TYPE OF GENERATING VOLTMETER

Introduction

While considerable work has been done on the generating voltmeter first developed by Paul Kirkpatrick and Iwao Miyake (4), all of the voltmeters previously described have been operated in air as the dielectric medium. Since air has a low dielectric constant as well as a low dielectric strength, it was felt that a voltmeter operating in some other medium of better dielectric characteristics might be an improvement. Such a voltmeter operating in transil oil as the dielectric is herein described.

Theory

The generating voltmeter may be compared to a two pole, separately excited, D.C. generator. However, instead of a coil revolving in a magnetic field, there are two insulated conductors rotating in a dielectric field and generating a current which is proportional to that field. The potential to be measured produces the dielectric field and hence it is directly proportional to the generated current.

The essential parts of the voltmeter are shown in Fig. 1. The potential to be measured is applied to the pole-plates A and B. The rotor is driven at a constant speed of n revolutions per second by means of a synchronous motor. The rotor segments H and K are made by cutting a metal tube longitudinally into two equal semi-cylinders,

and are insulated except through a path formed by commutator and galvanometer.

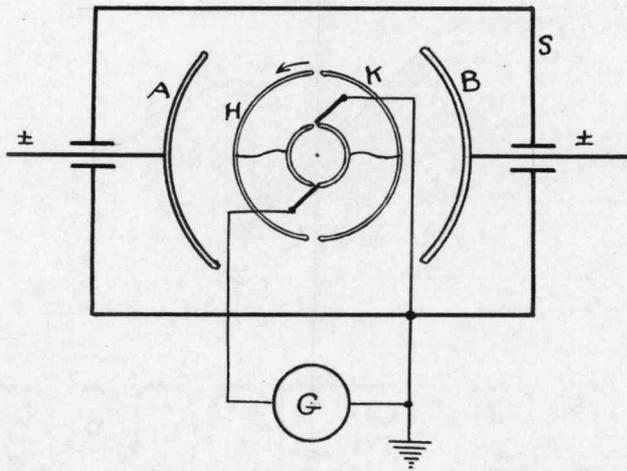


Fig. 1. Essential Parts of Generating Voltmeter.

The commutator also serves the purpose of rendering unidirectional in the meter circuit the generated current which is alternating at the segments H and K. S is a metal case which is grounded to limit the number of external potentials influencing the rotor segments to two, namely, V_A and V_B which are the potentials of plates A and B with respect to ground. Some point of the circuit connecting H and K is also held at a constant potential as indicated by the ground connection in the figure.

The following derivation of the fundamental equation of the generating voltmeter is due to Kirkpatrick. The positive charge on H due to coefficients of induction of H with respect to the surrounding conductors and their potentials is designated by Q_H . Since H and K and the case S are always practically at the same potential, the only coefficients of induction that are important are those due to the potentials of A and B and are designated by C_A and C_B . Therefore it

can be written that

$$(1) \quad Q_H = C_A V_A + C_B V_B$$

None of the quantities on the right hand side of the equation need be constants. Differentiating,

$$(2) \quad dQ_H = C_A dV_A + V_A dC_A + C_B dV_B + V_B dC_B$$

The total increase in the charge on H during one half revolution from the position indicated in the figure is the definite integral

$$(3) \quad \int_{Q_1}^{Q_2} dQ_H = \int_{V_{A_1}}^{V_{A_2}} C_A dV_A + \int_{C_{A_1}}^{C_{A_2}} V_A dC_A + \int_{V_{B_1}}^{V_{B_2}} C_B dV_B + \int_{C_{B_1}}^{C_{B_2}} V_B dC_B$$

where the upper and lower limits refer to the conditions in the initial and final positions of the rotor respectively. This may be integrated by parts by the simple formula $\int u dv + \int v du = uv$ without knowledge of the functional relations existing between potentials and capacities. This is important because it shows that the condenser current flowing between the moving plates is a function of the limit values of the applied potential existing at the instants of commutation only and is independent of intermediately existing potential values. Integrating (3) as indicated above

$$(4) \quad Q_2 - Q_1 = \Delta Q = V_{A_2} C_{A_2} - V_{A_1} C_{A_1} + V_{B_2} C_{B_2} - V_{B_1} C_{B_1}$$

Since the instrument is symmetrical

$$C_{A_1} = C_{B_2}, \quad \text{and} \quad C_{A_2} = C_{B_1}$$

so that $(5) \quad \Delta Q = C_{A_2} V_{A_2} - C_{A_1} V_{A_1} + C_{A_1} V_{B_2} - C_{A_2} V_{B_1}$

If the applied potential at the instants of commutation is constant with respect to ground $V_{A_1} = V_{A_2} = V_A$ and $V_{B_1} = V_{B_2} = V_B$

hence $(6) \quad \Delta Q = (V_A - V_B)(C_{A_2} - C_{A_1})$

The average value of the current flowing to H in a half revolution,

and therefore continually if the speed of rotation is constant, is

$$I = \frac{\Delta Q}{\Delta t} = 2n \Delta Q$$

or (7) $I = 2n(V_A - V_B)(C_{A_2} - C_{A_1})$

If the total difference of potential is $V = (V_A - V_B)$ and if C is designated as the positive difference appearing in the parenthesis $(C_{A_2} - C_{A_1})$ then the final equation for the generated current becomes

$$(8) \quad I = 2nVC$$

As mentioned before the only potential of any consequence in equation (8) is the potential difference existing at the instants of commutation, i.e. when the rotor segments are opposite the pole-plates, and is independent of potential variations taking place during the execution of the half revolution. Obviously then, if the potential to be measured is varying with a periodic variation of frequency $2n$, the generated current will have an average value which will be a measure of the instantaneous potential difference at the instants of commutation. By shifting the phase of the moving rotor with respect to the applied potential wave it is therefore possible to measure the potential of any point on the wave form. Thus the wave form of the applied potential may be traced by a point to point method.

Since Schuchard (9) has worked out the theory of the generating voltmeter in great detail and by several different methods, no attempt will be made to write further on this part of the subject; his conclusions are quoted herewith:

"In summarizing this strictly electrostatic analysis of operation, the most important results are, assuming no disturbing time constants in the connecting circuits:

1. The average current of the generating electrostatic

- voltmeter is linearly related to the applied potential value at each commutation instant, provided the applied potential is direct or has a periodicity of any even integral multiple of the rotor revolution frequency.
2. For a symmetrical construction with the shielding case grounded, the calibration is the same whether the potential applied between the electrodes be grounded at any point or be insulated, and whether the rotor circuit be grounded or insulated.
 3. Under the conditions of (2), the equation of generation is $I=2nVC$, unless modified by an additive term due to electromotive forces in the rotor circuit.
 4. Dissymmetries of construction do not affect the operation other than that the calibration constant may not remain the same for all types of use and additive terms are more likely to appear from stray charges or similar influences.
 5. The operation is unchanged whether the commutating process is instantaneous or of finite duration, as only the potential-capacity product at the beginning of the commutation process affects the average generated current (subject to the conditions of negligible time constant and charge leakage).

Construction

Figs. 2 and 3 show the essential points of the construction of the instrument. Fig. 3 was taken during development and shows a bakelite baffle that is no longer used. This baffle unfortunately hides the rotor from view.

The rotor consists of a split brass tube six inches long and one and seven-eighths inches in diameter mounted on a treated maple cylinder. The rotor shaft which carries this cylinder and the commutator is mounted in ball bearings at the top and bottom and is coupled to the motor through a simple universal joint. The commutator is of the drum type with spring brass brushes. Other types of brushes were tried but the simple spring brushes gave the most consistent and satisfactory results. A grounded brass cylinder shields

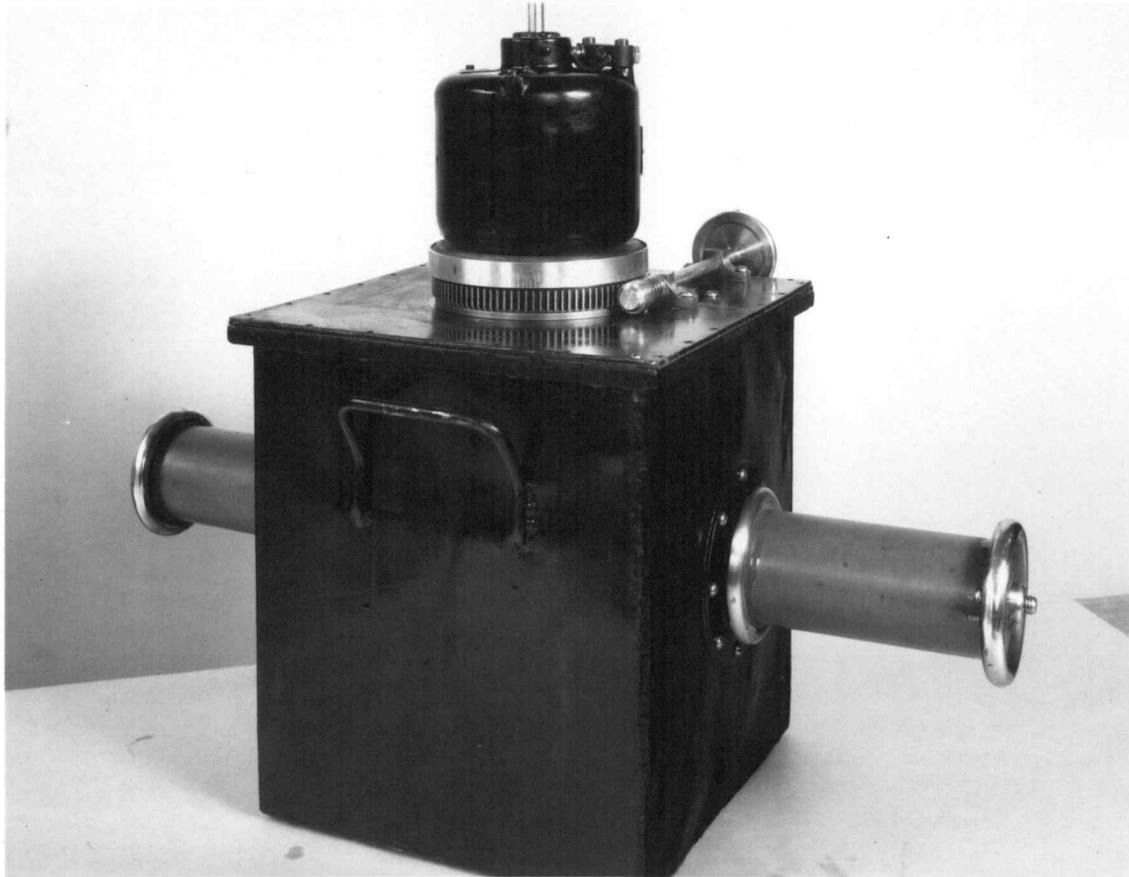


Fig. 2. Assembled Voltmeter

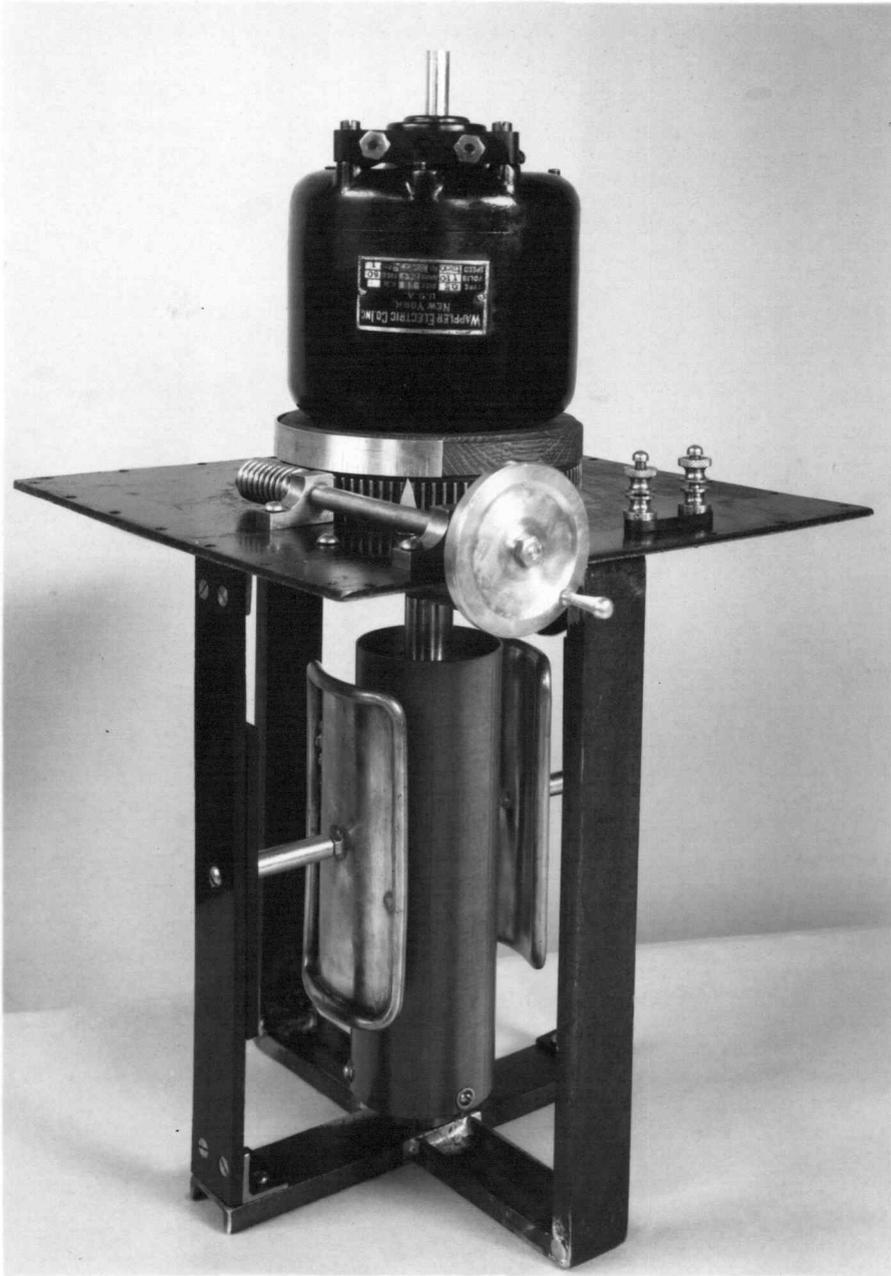


Fig. 3. Voltmeter Without Case

the leads from the rotor segments to the commutator segments from the dielectric field. The whole commutator and brush assembly is also shielded by a metal housing.

The high voltage bushings are made of three inch diameter bakelite tubing properly designed with corona guard rings on the outside and baffles on the inside to prevent the formation of ion chains in the oil. A short grounded brass tube fits tightly inside the bakelite tubing where it enters the case to shield the bakelite from heavy dielectric stress at that point. Each bushing will withstand a voltage of 105 K.V.P. to ground before sparking over on the outside.

The case is made of heavy sheet iron and when grounded makes a very efficient electrostatic shield for the rotor. A 1/4 H.P. synchronous motor mounted on top of the tank as shown in Fig. 3 drives the rotor at a speed of 1800 R.P.M.. All moving parts were sanded and polished to reduce the stirring action on the oil to a negligible amount.

In the early development of the instrument a special transformer oil having a dielectric constant of 4.5 was used as the liquid dielectric. Due to a large ion conduction, as will be discussed more in detail later, it was discarded in favor of transil oil. The transil oil used was a regular commercial brand but it was filtered and heat treated in a partial vacuum to remove air and water vapor before being put into the tank.

Experimental Operation

Since previous generating voltmeters are stated to have shown a tendency to change their calibration slightly with changing conditions, considerable attention was given to the calibration and to the constancy of calibration of this instrument. Numerous calibrations were made over a period of several months under various conditions. Some of the resulting calibration points are plotted on the calibration curve in Fig. 4. All the high voltage calibrations were made with 6.25 cm. and 12.5 cm. sphere gaps in accordance with A.I.E.E. standards; each experimental point is the average of at least five consistent values of spark-over voltage. A 180 K.V.P. testing transformer with power supplied by an alternator was used in most of the calibration work. Voltage control was obtained by varying the field excitation of the alternator. Direct current voltage for calibration purposes was obtained by charging high voltage condensers through a kenetron rectifier. The data for (c) of Fig. 4. was taken by using a 12.5 cm. sphere gap which could be shortened slowly and continuously until spark-over occurred. The voltage was set at a given value by means of an auto-transformer and then the sphere gap closed to spark-over. The spacing between the spheres was then measured with calipers to 0.1 mm. and the voltage at standard conditions obtained from sphere gap curves. The average value of the calibration constant C of the instrument as calculated from sixty experimental points was 6.60 mmf. These points, part of which are shown on the calibration curve, were taken from A.C., D.C., and one-side-grounded data. A calculation of the per cent error for each experimental point shows a distribution as

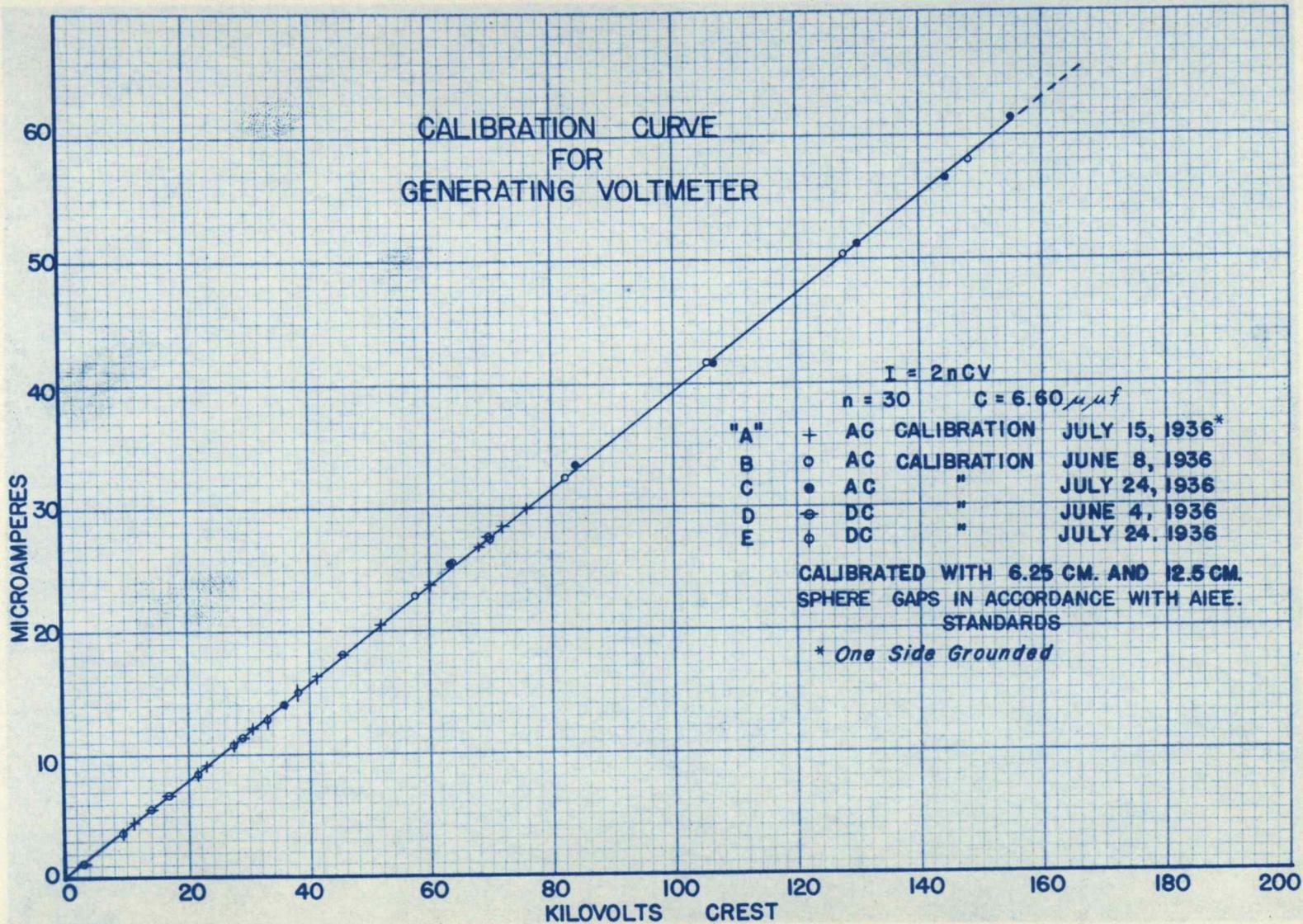


Fig. 4,

given in the table below.

<u>Per Cent Error</u>	<u>Per Cent Total Number Points</u>
0.0% - 0.5%	34%
0.5% - 1.0%	37%
1.0% - 1.5%	17%
1.5% - 2.0%	12%

This table shows a peculiar trend but it must be remembered that the sphere gap has an experimental error as high as 3%. It is restated for emphasis that each experimental point on the calibration curve is the average of at least five consistent values of spark-over voltage.

Fig. 5 shows the low voltage D.C. calibration of the instrument. The voltage for this was obtained from an over-excited 1000 volt D.C. generator shunted by a 0.01 mfd. condenser. This voltage was measured with a 0-750 volt range voltmeter which had an error of less than 0.3%. The microammeter was replaced by a wall galvanometer which had just been calibrated with a Weston standard cell and standard resistances. The calibration constant thus measured at low voltage was also 6.60 mmf. and the maximum error of any point was less than 1%. From a consideration of these results it seems quite permissible to obtain the calibration of the voltmeter at low voltages and extrapolate the curve to higher voltages.

As mentioned before the rotor was first immersed in a commercial transformer oil intended for use on comparatively low voltages and having a dielectric constant of 4.5. This high dielectric constant gave two and a half times the capacitance as transil oil did with the same clearances. This increased the constant C by the same

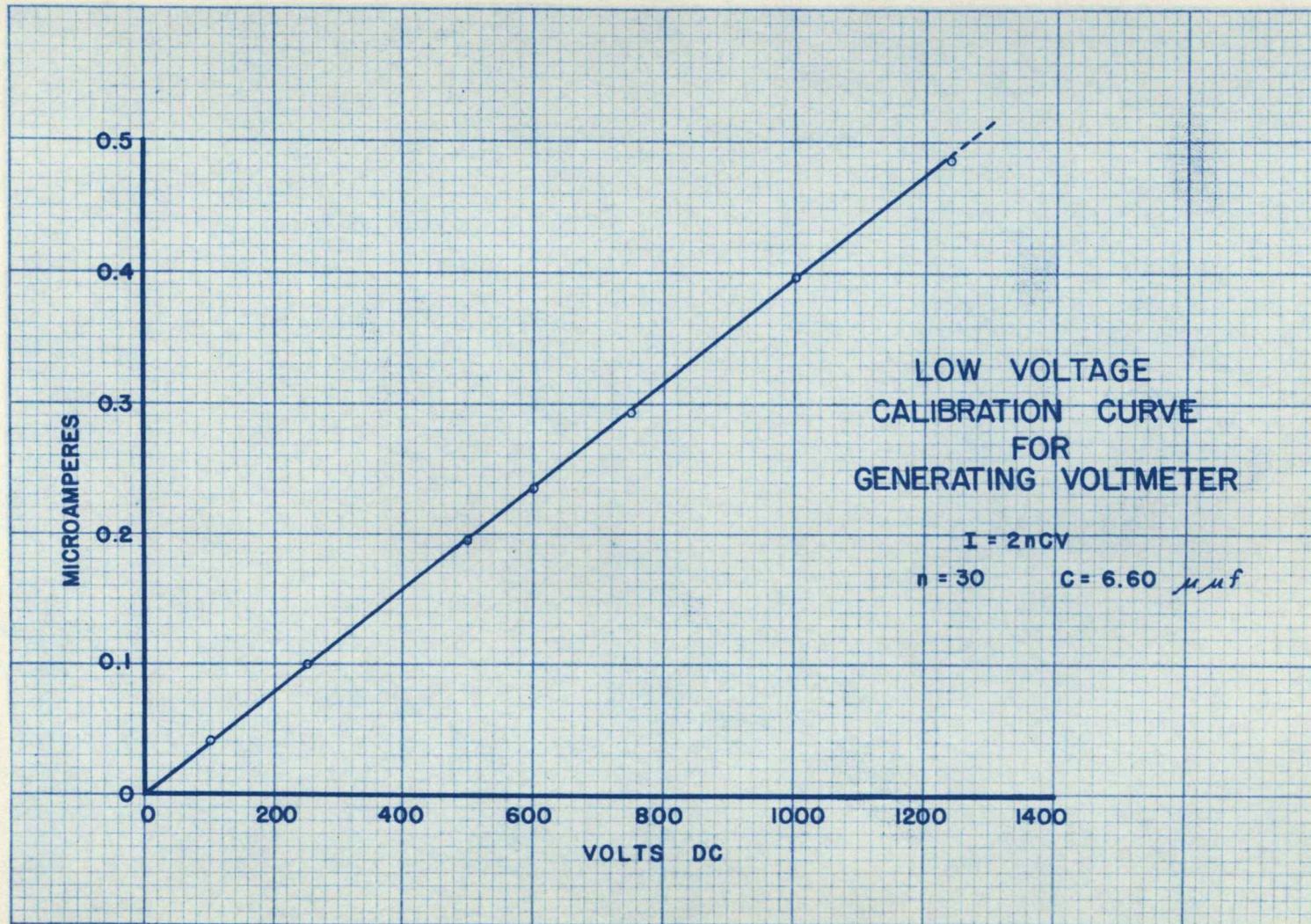


Fig. 5.

factor and thus raised the number of microampers per kilovolt. In addition it had the advantage of allowing bakelite baffles to be used without over-stressing the liquid dielectric, as both have practically the same dielectric constant. However, it had the disadvantage of a low resistivity, the effect of which was not realized until it was attempted to establish the wave form of an applied pulsating D.C. potential. Fig. 6 shows the results obtained, the broken line indicating the true wave form as traced by running the voltmeter in air and then multiplying the data thus obtained by the ratio of the dielectric constants of oil and air. In effect, the zero axis seems to have been shifted; or in other words, a negative additive term has appeared in the equation $I = 2nVC$ so that now $I = 2nVC - a$; where a is a quantity due either to stray charges or to a stray electromotive force in the rotor circuit. That this additive term is due to the former cause is most probable because the low resistivity assures an abundance of ions in the oil, and these act as stray charges. Stray electromotive forces in the rotor circuit due to the deposition of ions on the segments are not possible because each segment, while revolving at high speed, would pick up just as many positive as negative ions. The term is also of the right sign to support the theory of a space charge due to the ions. The shift in the zero axis is explained by considering the sketch in Fig. 7. The negative ions would collect around the positive plate and reduce its effective potential as far as the rotor is concerned; likewise the positive ions would collect at the negative terminal and produce the same result. During the time that the applied D.C. voltage wave shown in Fig. 6 is zero,

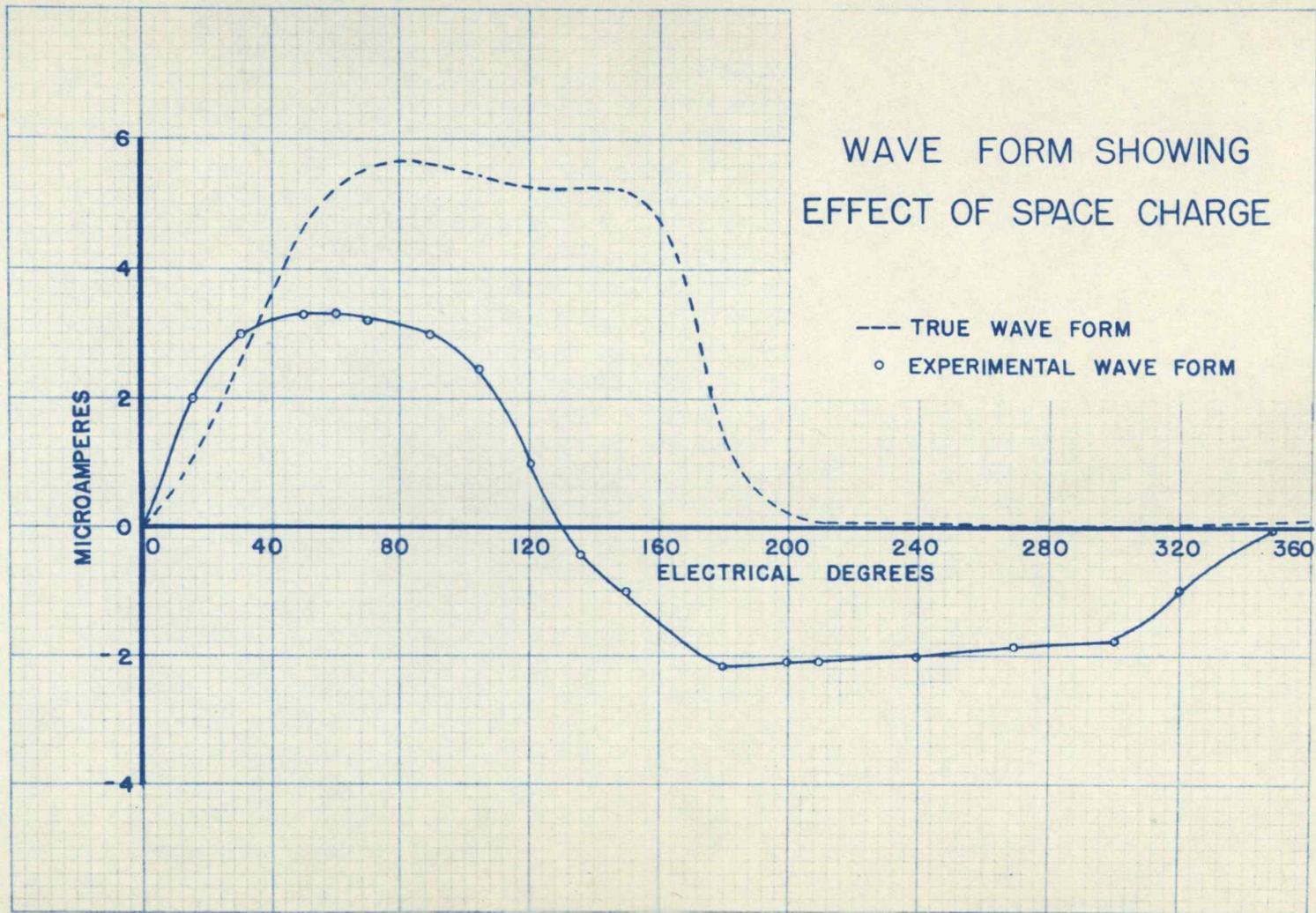


Fig. 6.

the ions are not being accelerated, and any motion is due only to their inertia so that essentially during that short period they constitute a relatively stationary space charge.

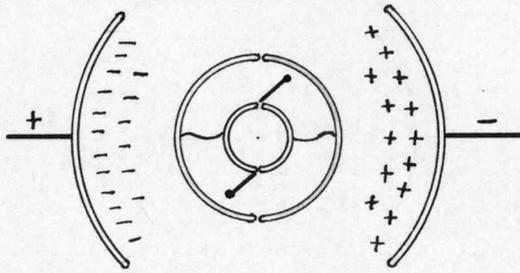


Fig. 7. Collection of Space Charge Around Electrodes.

Since the applied potential is zero, any current generated during that time is due only to the potential of the space charge. This is important because it indicates a feasible and simple method of measuring space charge in a liquid dielectric. Knowing the volume of liquid involved, it is a simple matter to calculate the amount of charge present per cubic centimeter.

Another phenomenon indicating the presence of a space charge in this dielectric was noticed. A D.C. high voltage was applied across the pole-plates long enough to produce a supply of ions and then suddenly removed. The generated current which previous to the removal of the potential was of the correct sign, suddenly reversed and gave a considerable reading in the opposite direction. This reading decreased slowly, requiring about ten seconds to reach zero. Evidently the mobility of the ions must have been rather low or their rate of recombination would have been much greater than this indicated.

On alternating current potentials, the space charge effect

does not show up at all because the ions do not have time to form in a half cycle. This suggests the additional possibility of measuring the space charge by applying first a D.C. potential of given value and then an A.C. potential having the same crest voltage. The difference between the generated currents would be due to the potential of the space charge which formed in the case of the D.C. but not in the case of the A.C.

All of this calls attention to the fact that when using the instrument as a D.C. voltmeter any ions present, if sufficient in quantity, will introduce serious error. Hence in preparing the transil oil for use in the meter, great care was exercised in processing it to remove all foreign material that might act as charge carriers. Of course the effect would be less in transil oil anyway on account of its higher resistivity. Since using the transil oil, all attempts to detect a space charge effect have failed.

The potential wave forms are traced by revolving the motor frame through 180 mechanical degrees by means of a worm gear, and taking readings of generated current every few degrees. Because $f=2n$, 180 mechanical degrees rotation is equivalent to 360 electrical degrees; this can be read to 0.2 of a degree by means of a scale mounted on the motor. The voltmeter will not follow rapid oscillations like an oscillograph, but will follow any change that takes place in the space of 0.5 of an electrical degree, if that change appears at exactly the same point of each cycle. Fig. 8 shows a tracing of the voltage wave form used in one of the A.C. calibrations. A small percentage of harmonics due to armature slots in the alter-

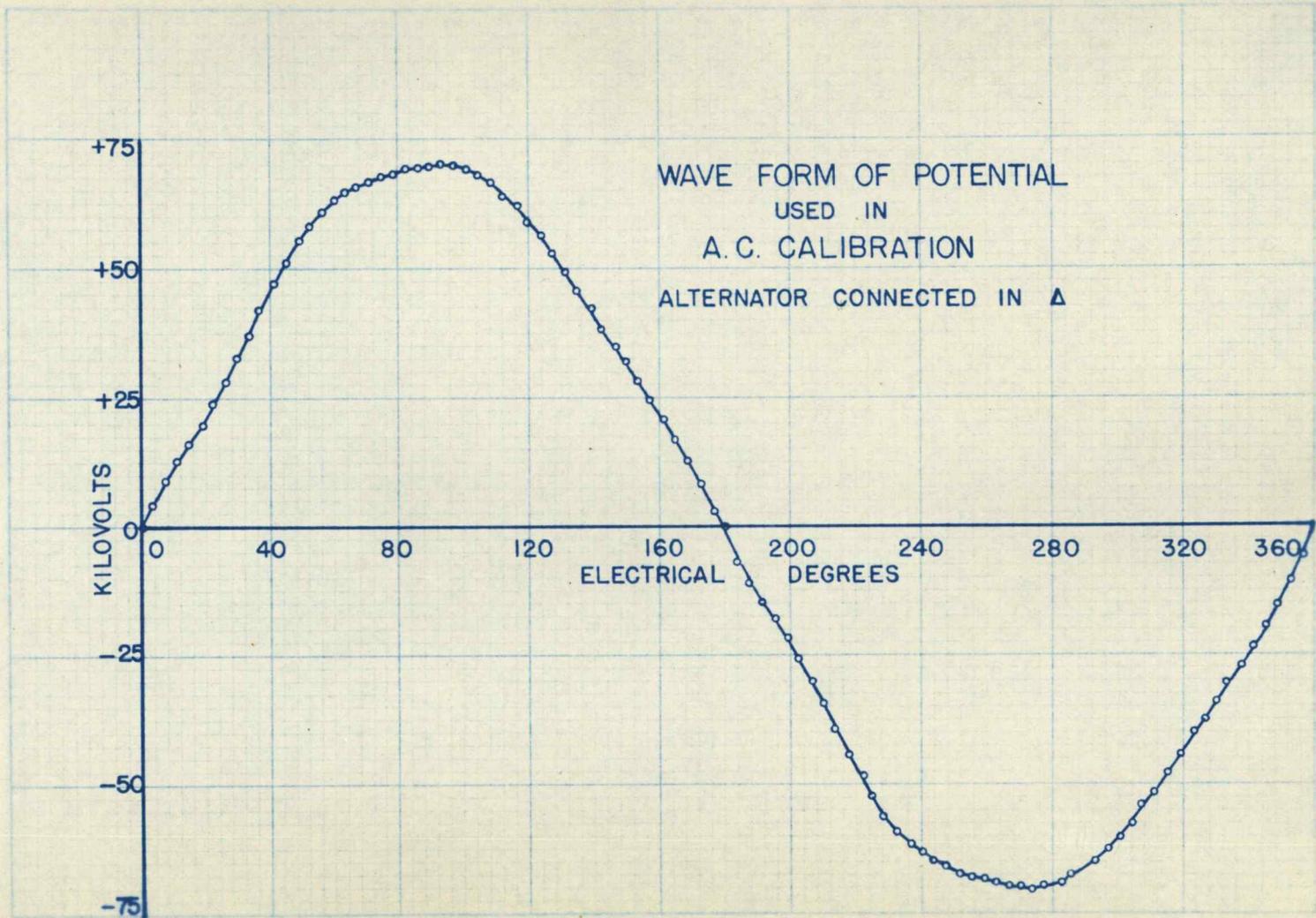


Fig. 8.

nator will be noticed. In Figs. 9 and 10 are shown the voltage and current of an X-ray machine in which the tube does its own rectifying. It will be seen that the inverse voltage is much greater than the voltage during that half of the cycle that the tube is conducting current. It is obvious from these curves why the sphere gap is definitely wrong for voltage measurements on self-rectified equipment.

Cathode ray oscillograms were taken at the same time with most of the wave form tracings and these show the reliability of the voltmeter. These are shown by the insets on the curve sheets. The oscillograph deflector plates were connected to the high voltage terminals through a voltage divider made from distilled water tube resistors. These resistors were of the order of 100 megohms, consequently the power dissipation was small.

Figs. 11 and 12 show the voltage and current wave forms with a mechanical rectifier and no storage capacitor. These were difficult to take because the waves were moving back and forth slightly due to "hunting" in the synchronous motor of the rectifier. Fig. 13 shows the voltage wave form under the same conditions as Fig. 11 except that a 0.01 mfd. storage capacitor was connected across the rectifier. In this curve points were scaled from the oscillogram and plotted with those of the generating voltmeter.

The voltage wave forms were traced by connecting the voltmeter across the X-ray tube directly while the current wave forms were taken with the voltmeter connected across a water resistor connected in series with the X-ray tube.

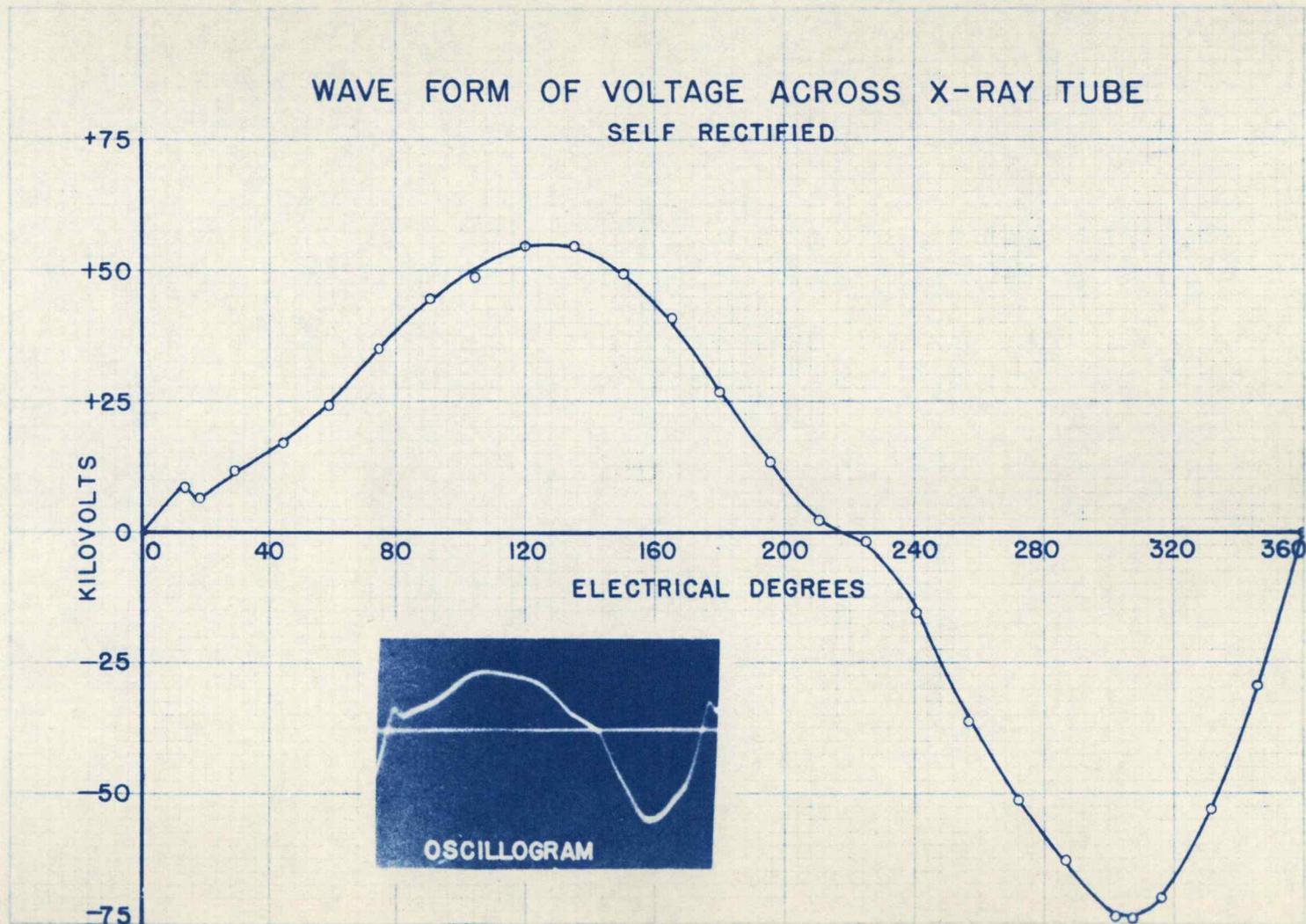


Fig. 9.

WAVE FORM OF CURRENT THROUGH X-RAY TUBE
SELF RECTIFIED 5 MA.

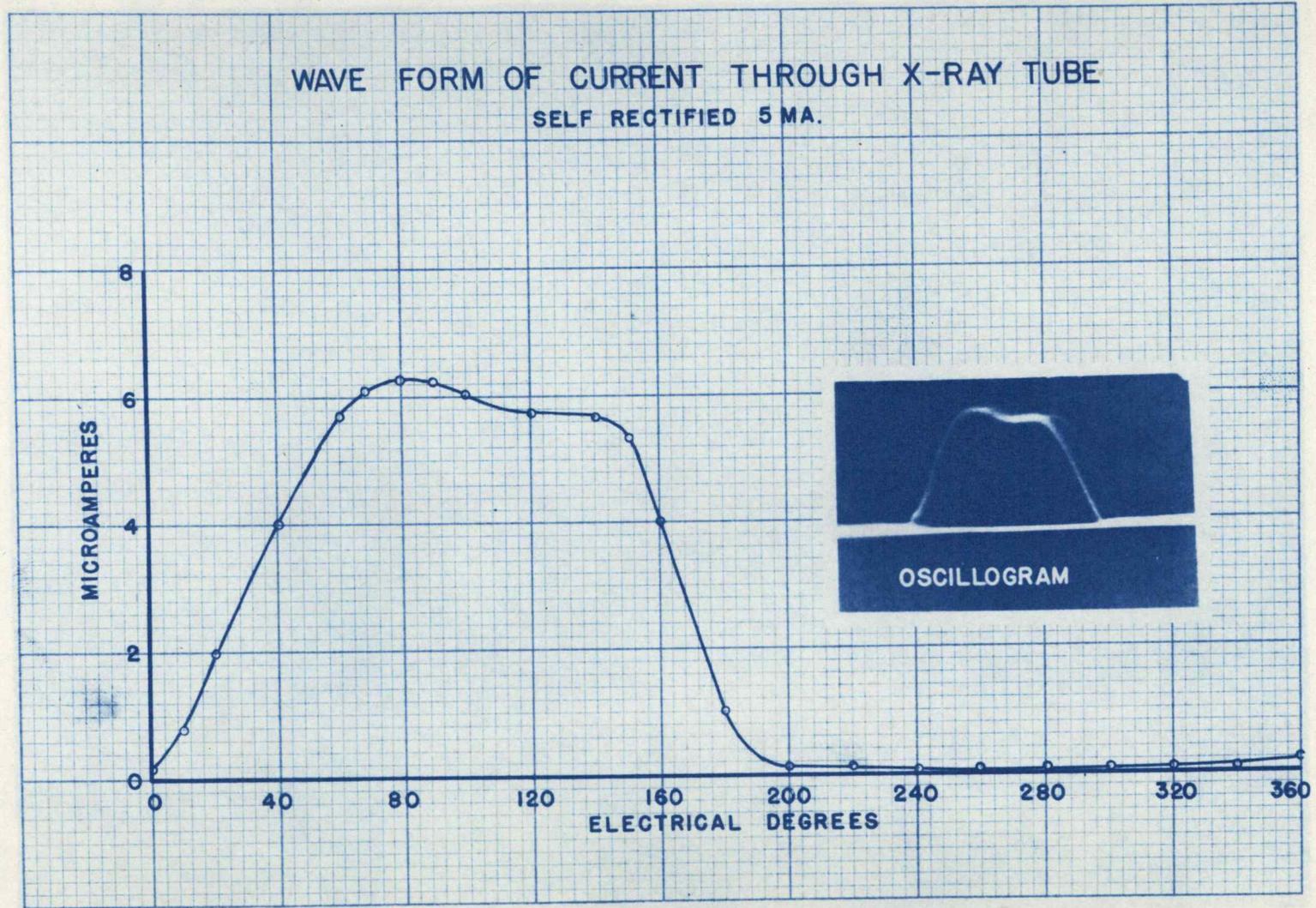


Fig. 10.

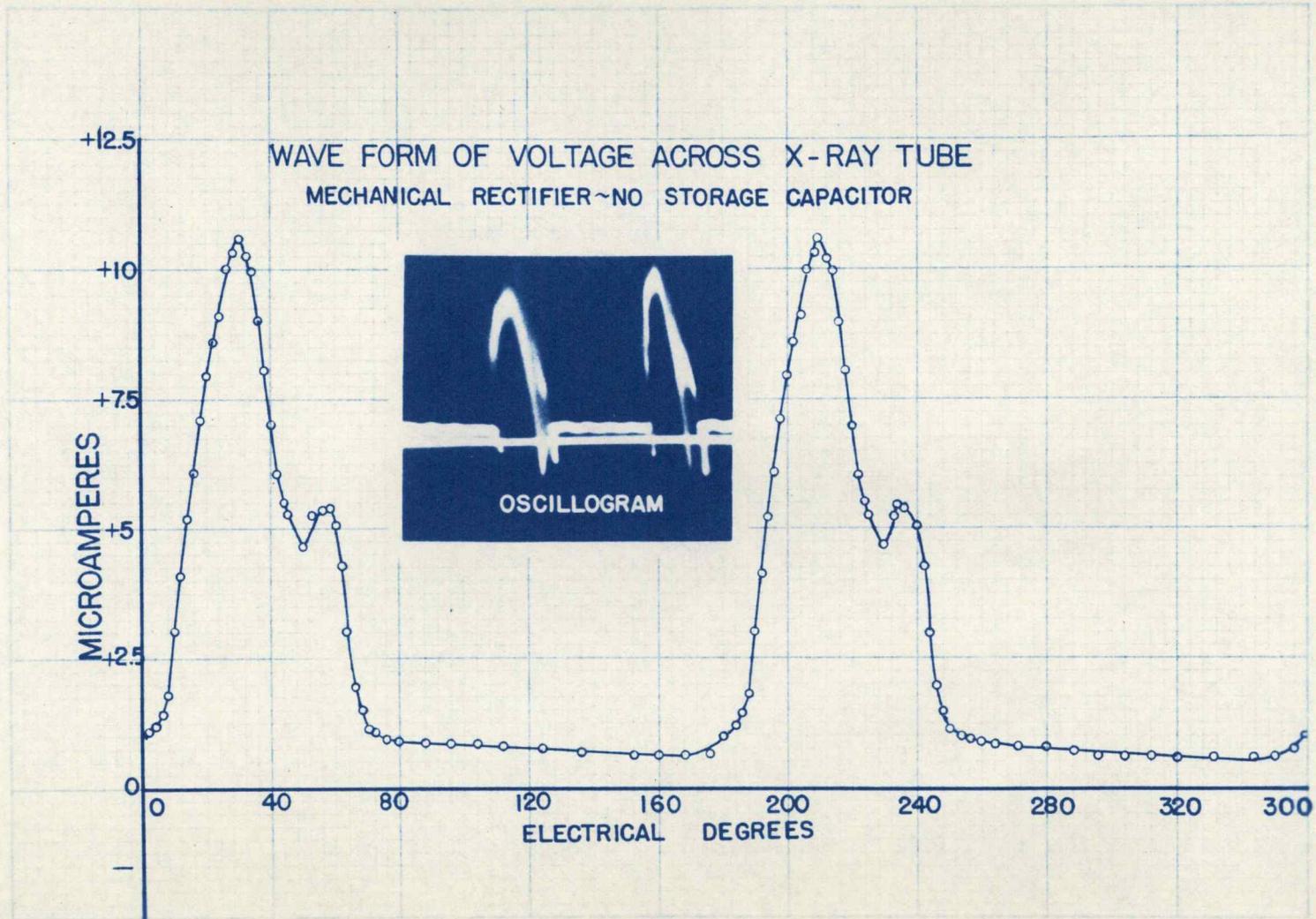


Fig. 11.

WAVE FORM OF CURRENT THROUGH X-RAY TUBE
MECHANICAL RECTIFIER~NO STORAGE CAPACITOR

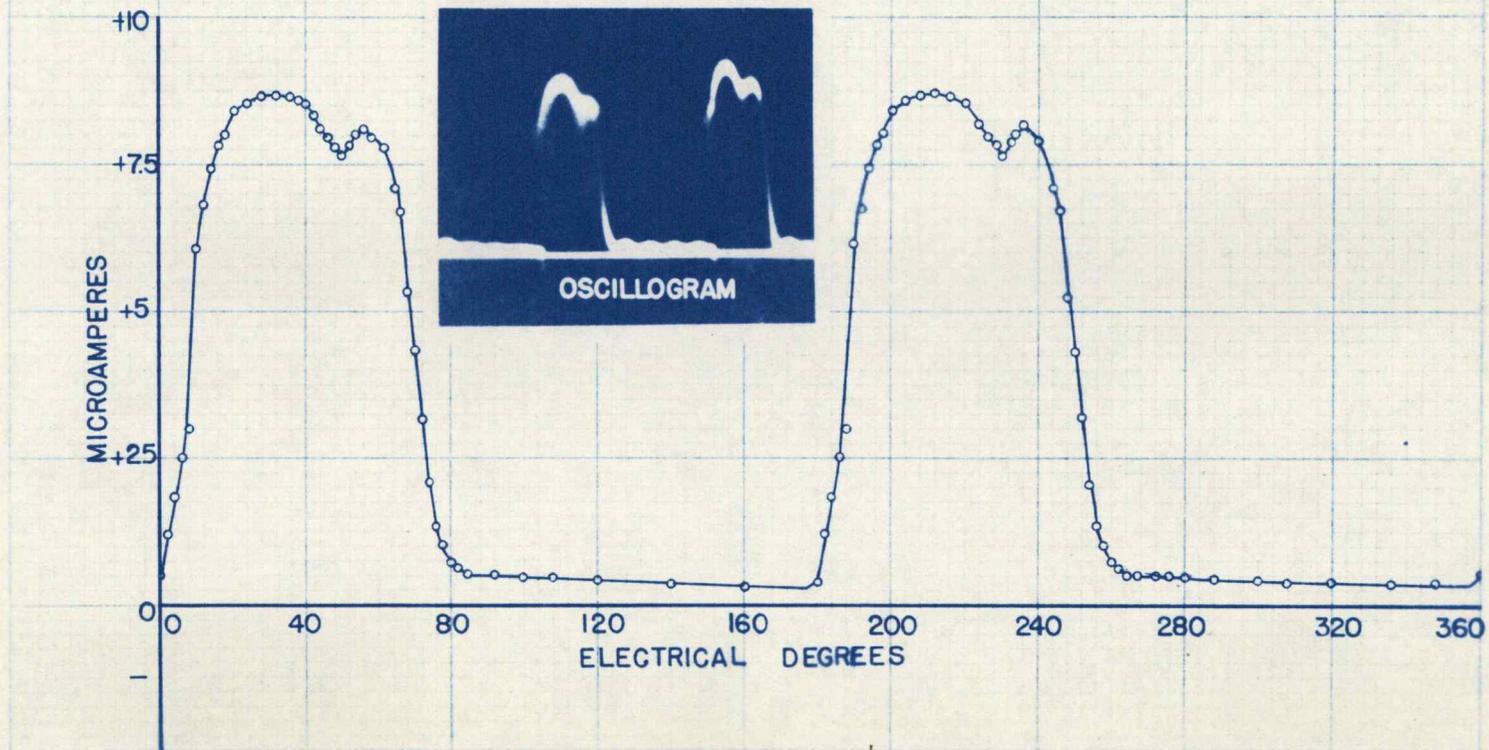


Fig. 12.

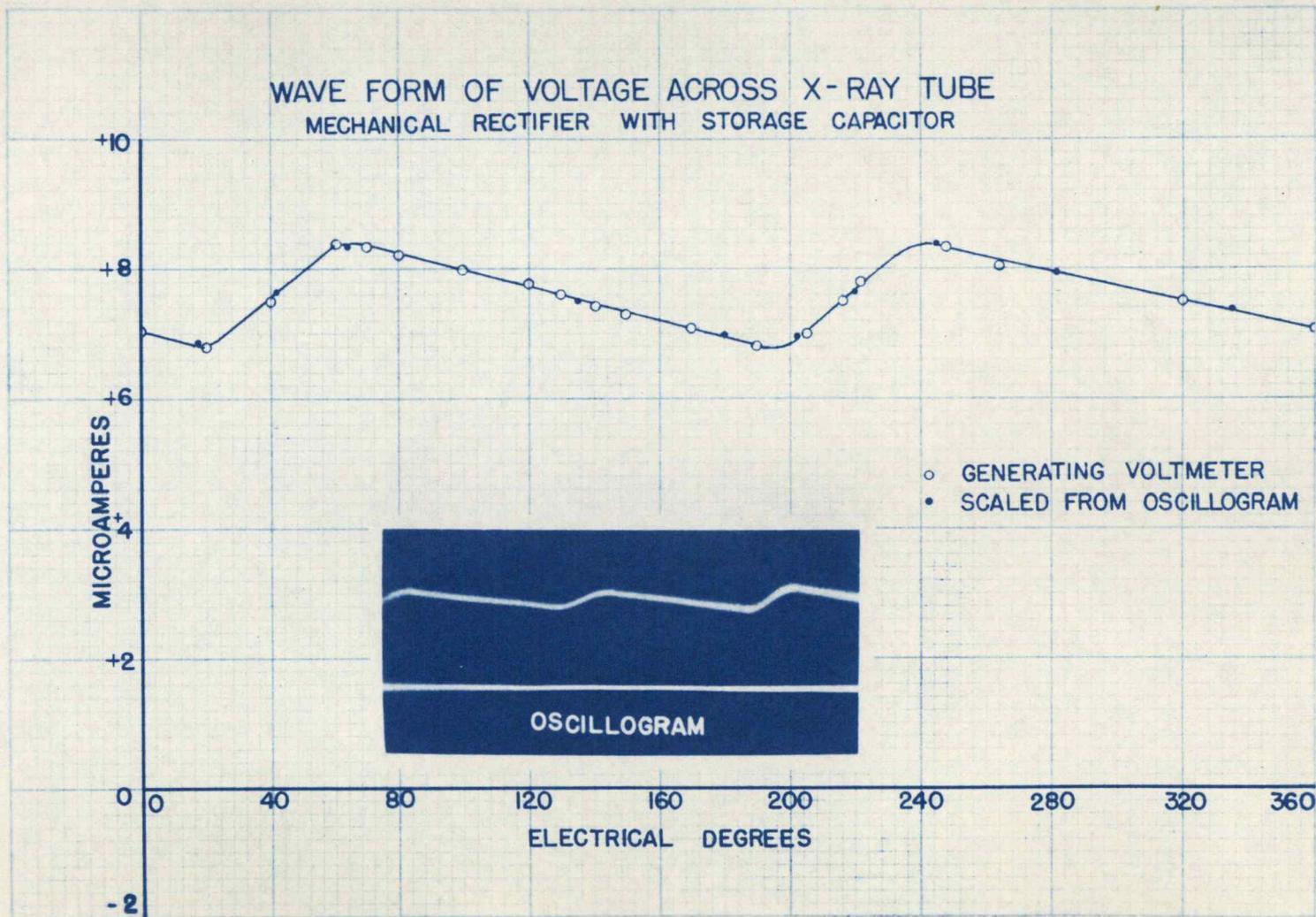


Fig. 13.

Summary

The chief results of this investigation are:

1. The generating voltmeter described will accurately measure D.C. potentials or A.C. potentials of any wave form providing they are recurring functions of a frequency which is an integral multiple of that applied to the synchronous driving motor.
2. The equation of generation is $I = 2nVC$, and since it is linear, may be extrapolated to higher values of voltage without increasing the per cent error.
3. By changing the phase of the rotor with respect to the applied potential, the voltmeter may be used for determining voltage wave forms of any kind providing they follow the limitations stated in conclusion one.
4. By immersing an instrument of the type described in any dielectric, the space charge in that dielectric may be measured.
5. The accuracy of the voltmeter is limited by the accuracy of the indicating instrument.
6. Either terminal of the voltmeter may be grounded or both insulated without affecting its calibration. Time, jarring, stray fields, or changing temperature do not affect the calibration of the instrument.
7. The voltmeter draws negligible power.
8. The indicating instrument is at ground potential and may be located at a distance from the voltmeter itself.

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