A VACUUM TUBE VOLTMETER

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INTRODUCTION

This thesis is intended to present a survey of the field of vacuum tube voltmeters being concerned primarily with that particular type of instrument that measures the potential difference between negative and positive peak magnitudes of the voltage wave.

Its most general application will be found in high frequency voltages or in radio circuits. The student, radio experimenter or service man with only a limited knowledge of vacuum tube theory will find the principles and construction of this instrument easily understood.

Although much has been written on vacuum tube voltmeters, there is practically nothing about this particular circuit.

VACUUM TUBE VOLTMETERS

For some time the need for a convenient means of measuring small alternating voltage has been felt, particularly in the field of communication engineering. There are two reasons why the usual type of electro-magnetic voltmeter is unsuitable. (1) A comparatively large amount of current is required to operate the device. (2) Its calibration is greatly affected by frequency. Both of these defects are characteristic and it is probable that they can never be materially reduced. A second type, the electrostatic voltmeter, although not subject to either of the above disadvantages it has others. The adjustment of this type is very difficult and an optical system is required for voltages below 25 volts. Its sensitivity is relatively low and its high inertia makes rapid potential fluctuation and automatic recording impossible. Furthermore, it is affected by temperature. (1)

The vacuum tube voltmeter appears to possess many of the advantages of the above two and none of their major disadvantages.

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(1) F. Muller, E.M.F. Measurements with the Aid of Electron Tubes, Electro-chemical Society Transactions Vol. 62 page 117-24, September 1932.

It draws only an infinitesimal amount of current from the line, and the calibration made at 60 cycle holds true for all frequencies likely to be encountered. (1)

A device possessing these two important characteristics will have numerous applications.

(a) By measuring the potential drop across an inductance or capacity of known value, the current may be calculated if the frequency is known. Extremely small currents may be measured by this means.

(b) Direct measurement of high frequency resistance.

(c) Measurement of amplification produced by triode amplifiers.

(d) Measurement of signal strengths in wireless telegraphy.

(e) Determination of the Power factor of a condenser.

(f) It is particularly valuable in the measurement of stray magnetic fields. Because of the instrument's great sensitivity, the search coil may be composed of only a few turns, an important factor where space is limited. Also, since the instrument draws no current, the field is not altered by the presence of the search coil. (2)

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(1) C.M. Jansky, jr. and C.B. Feldman, A.I.E.E. Journal Vol. 47, page (126-132), February 1928.

(2) E.B. Moullin, A Direct Reading Thermonic Voltmeter and Its Applications, I.E.E. Journal Vol. 61 page 245-303, Feb.23

It has been stated that one of the important advantages of the vacuum tube voltmeter was the fact that it draws no power from the line. In ordinary work, the small amount drawn by the common voltmeter is of no consequence. However, in electrochemistry we find that the vacuum tube voltmeter has opened up new fields. Some examples of conditions under which the current drawn by the magnetic type of voltmeter is far too great are listed below.

(a) When using very small electrodes or extremely weak solutions.

(b) When measuring potentials of small corrosion cells in determining anode and cathode micro areas on the surface of metals.

(c) When measuring the potentials of metals in solutions containing unrelated ions.

(d) When determining the effect on potential upon the introduction into the solution of a trace of foreign metal.

(e) When determining the metal and gas potential in poorly buffered solutions.

(f) In measuring "motor electric" effects.

(g) In determining changes in potential of electrodes (notably gas electrode) during operation of a cell. (1)

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(1) F. Muller, E.m.f.-measurements with the aid of electron tubes, Electro-chemical Society Transactions, Vol. 62, page 117-24, Sept. 1932.

VACUUM TUBE FUNDAMENTALS

A thorough understanding of the fundamental principle of vacuum tube operation is essential to a complete knowledge of the operation of the vacuum tube voltmeter. According to the modern theory of matter all materials are made up of electrons and protons. Electrons, small negative charges of electricity rotate in orbits about the central nucleus the proton, a positively charged body. Although electrons are strongly held to the nucleus, it is possible to dislodge some. These free electrons then attach themselves to a new atom which has also lost an electron. In conductors, electrons are not so firmly held by the proton, and consequently at any one instant there is a considerable number of free electrons within the conductor. If now a potential is applied to the conductor, the electrons, being negatively charged, will be attracted to the point of positive potential. This flow of electrons constitutes the electric current. It will be noticed that the electron flow is from negative to positive, while one generally accepted conception of the flow of current is from positive to negative. This is an unfortunate circumstance, and is due to the fact

that the direction of current flow was arbitrarily chosen as being from positive to negative long before the electron theory was formulated. It is therefore necessary to remember that electron flow takes place in the direction opposite to current flow.

At the surface of the conductor, the free electrons, due to their high velocities, are continually passing into the medium surrounding the conductor. Since the point from which the electron emerged becomes positive due to the loss of this electron, it is immediately attracted back into the metal. If however, an electrostatic fields of sufficient intensity surrounds the conductor, the attraction may not be great enough to cause the escaping electron to be drawn back into the conductor. At the pressure of the atmosphere an enormous voltage would be required to cause the electron to leave its parent metal. Even in high vacuum, the potential required to remove only a few electrons is excessive.

Heating a material greatly increases the activity of its electrons, so that many more acquire velocities sufficient to take them beyond the bounds of the metal. This process is known as thermionic emission. It is quite similar to that taking place upon the boiling of water. On application of heat, the internal vapor pressure of the water becomes greater than the opposing atmospheric pressure, and the water passes off into the atmosphere.

Figure 1 will show how the process works.

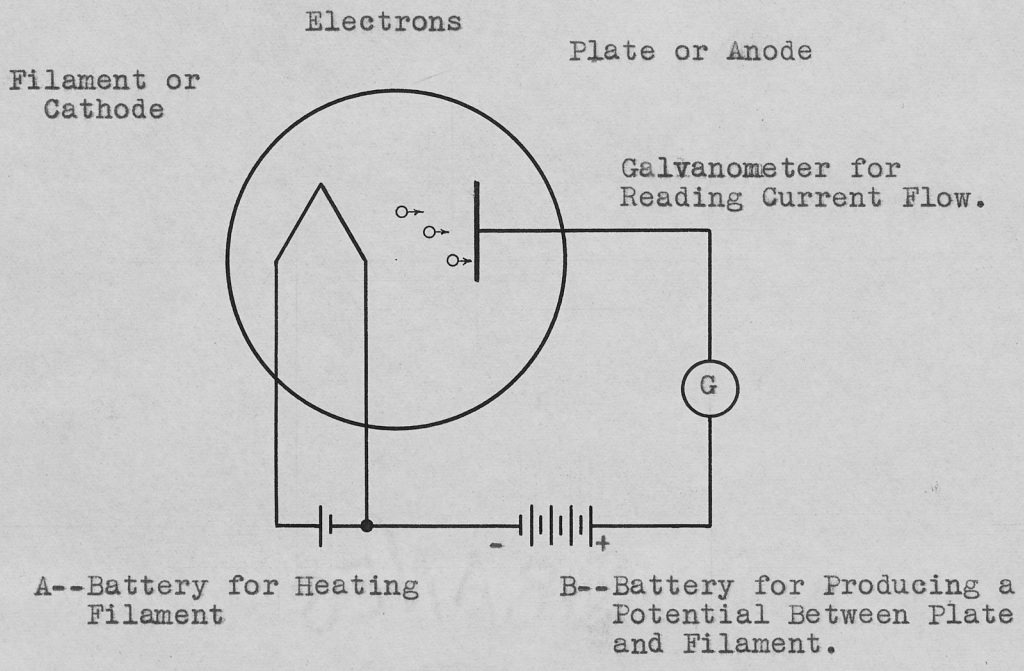


Figure 1

The filament being heated red hot by the A battery thermionic emission of the electrons takes place. Since the plate is held positive by the B batter, these emitted electrons are attracted to it. The flow of these negative charges thru the space between the filament and plate, thru the galvanometer and thru the B battery back into the filament again, constitutes the flow of electric current and will be registered by the galvanometer.

At a given filament temperature, a given number of

electrons are emitted. If the plate voltage is sufficiently high, all electrons liberated will be drawn over to the plate, and an increase in plate potential will not result in an increase of electron flow. When a condition has been reached such that all electrons freed are drawn over to the plate, the operation is said to be "emmission limited".

On the other hand, if the plate voltage is held constant and the filament temperature increased, more electrons will be emitted. These will form a negative cloud around the filament and electrons leaving the surface will be repelled and driven back. This negative cloud is known as space charge and when the plate potential is insufficient to prevent the formation of this cloud, the electron flow is said to be "space charge" limited.

This control of electron flow by space charge suggests another means of control. If we introduce a negative electric field between the filament and plate it might be supposed that the flow of electrons can be controlled. Such is the case. Fig. 2 shows the grid interposed between the filament and plate. It is given a negative charge by the "C" battery. This negative charge is known as the negative bias of the grid. By applying sufficient negative bias we may prevent the flow of electrons to the plate, all those emitted being driven back. As long as the grid does not become positive, no current will flow in the grid circuit.

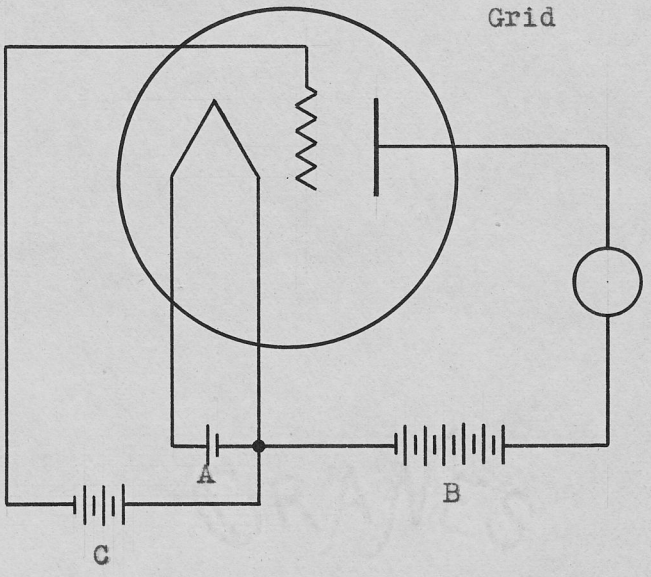


Figure 2.

The static characteristic curve figure 3, obtained by

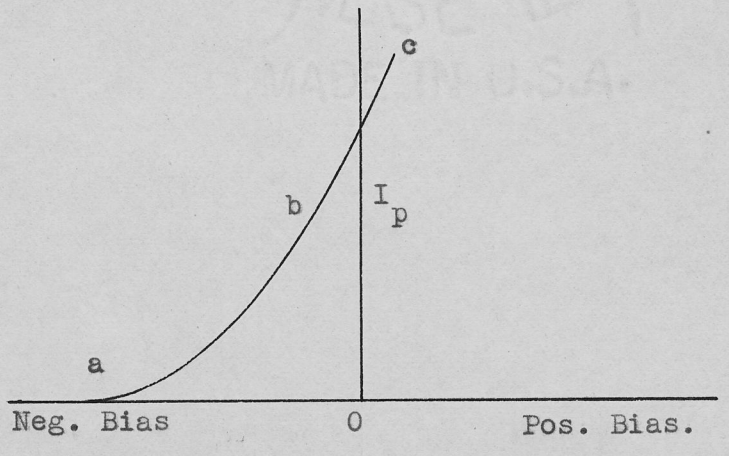


Figure 3.

holding the filament temperature and plate voltage constant, and varying the grid potential, is very important, and is fundamental in the operation of one type of vacuum tube voltmeter. For that portion of the curve between a and b, the plate current varies approximately as the square of grid potential. That part between b and c is essentially a straight line.

DETECTOR TYPE OF VOLTMETER

A common connection of a vacuum tube voltmeter is shown in figure 4.

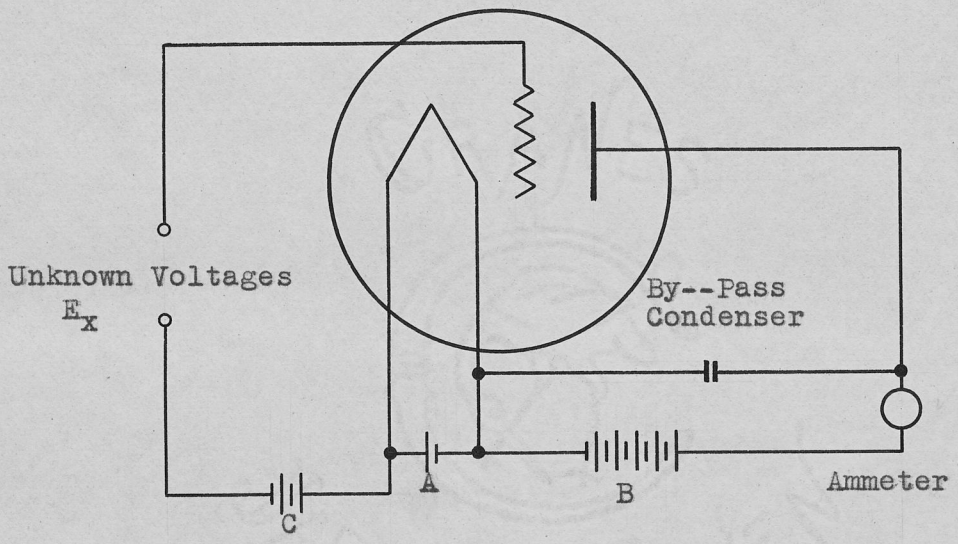


Figure 4.

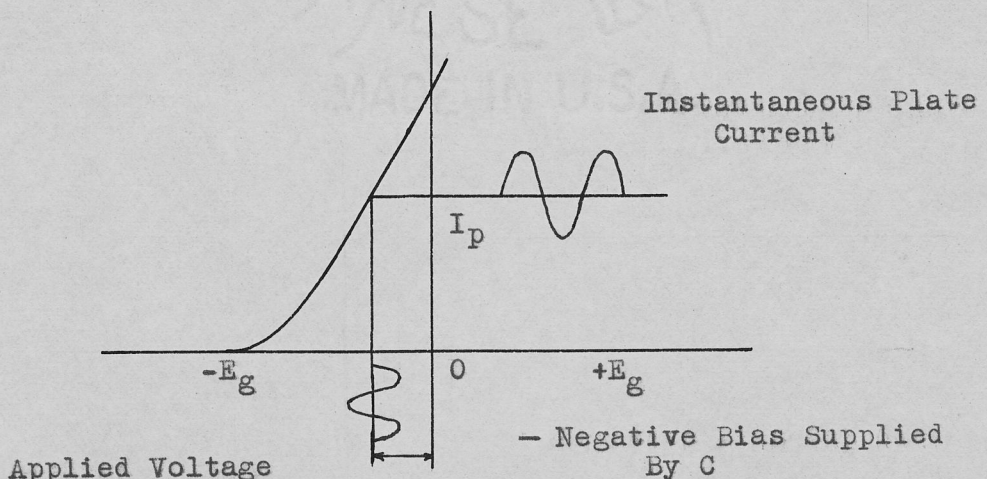


Figure 5.

Figure 5 shows the operation of this circuit. With the bias shown, the entire wave falls on the straight portion of the characteristic curve. The wave of I_p is therefore an exact reproduction of the shape of the applied voltage wave. If the bias is increased to the value shown in figure 6, the wave will fall on the square law portion of the curve.

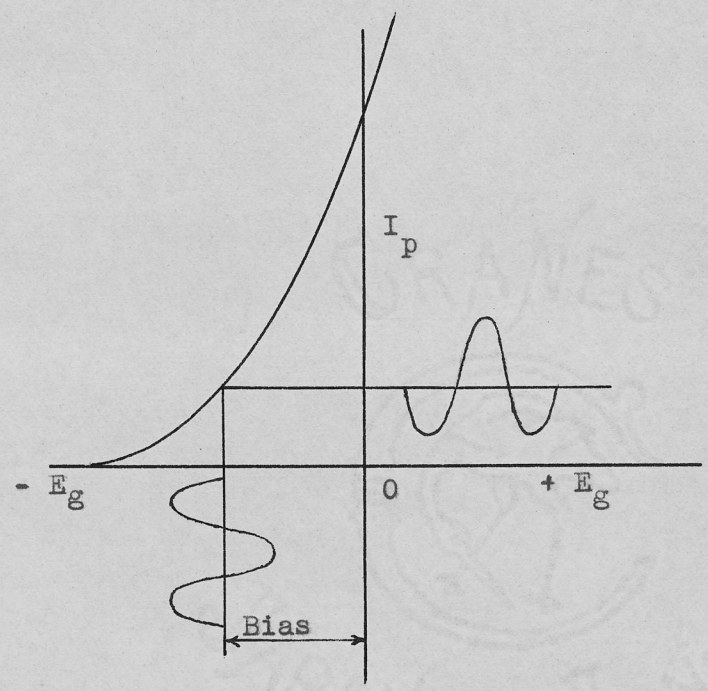


Figure 6.

It is noticed that the positive and negative alternations of I_p are different indicating the presence of even harmonics.

The current thru the milli-ammeter is a measure of the

input voltage. Since no definite relation can be formulated between the input voltage and the plate current, a calibration curve is required. As the characteristic curve is that of some power of E_g, the calibration curve when plotted on log--log paper is a straight line. (1)

High accuracy can be obtained with this type of voltmeter by using the correct grid bias; by the best possible vacuum; by low plate voltage; by small grid -- cathode capacity; by careful insulations and shielding in the grid circuit. (2)

Such voltmeters have been developed which read currents less than 10^{-10} amps.; resistance greater than 10^{10} ohms and e.m.f.'s of the order of microvolts in circuits of very high resistances or in systems from which only an infinitessimal current may be drawn. (3)

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(1) Terman, Measurements in Radio Engineering page 19.

(2) F. Muller, E.m.f. measurements with the aid of electron tubes, Electro-chemical Society Transactions Vol. 62 page 117 - 124. September 1932.

(3) K.G. Compton and H.E. Haring, A Compensated Thermionic Electrometer, Electro-chemical Society Transactions, Vol. 62, page 124 - 127, September 1932.

THE CREST VOLTMETER

The value of alternating voltage or current with which the engineer is usually concerned is the effective or R.M.S. value. This basic affords a comparison with direct current for energy a heating effect. This is the important figure when considering materials classed as conductors. However, when considering insulators, it is the maximum or crest value of the wave which is significant. The maximum potential which insulation can stand is largely influenced by the peak value of the applied voltage wave. This is particularly true of a gaseous failure such as insulator flashover in air. Sudden failure of a solid dielectric often shows no evidence of heating, seeming to be a mechanical process. If current flow following rupture is prevented, the failure appears to be a piercing action similar to that made by a bullet. An explanation of this phenomenon is that the initial path is established as a result of the displacement of electrons out of their stable orbits. The hidden stress is sufficient to tear electrons away from their nucleuses and place them in the orbits surrounding other nucleuses. This action takes place almost instantaneously, and the sudden transfer of electrons produces an

ionized path thru which the dynamic currents then flow. Electron displacement of this type is dependent upon the instantaneous value of stress, and the crest value of voltage becomes the determining factor.

Although present day commercial equipment is so designed that it produces a good sine wave, certain types of loads may give waves far from sine shape. This distortion is notably true in the case of saturated magnetic circuits and high capacitance. It is necessary, therefore, to measure the crest value of the high voltages produced by testing transformers and for some other applications.

In testing cables at stresses near the breakdown value, the internal losses give rise to wave distortion of such extent that the crest value of the impressed potential must be measured.

A common means of measuring the crest value of an alternating voltage wave is by the sphere gap, since the breakdown of the air gap between is dependent primarily on the maximum value of impressed potential. While the sphere gap provides a good standard for checking, obviously a continuous reading is not obtained. Its use as a measuring instrument may be compared to measuring steam pressure with an adjustable safety valve, or to measuring the current with a fuse. The measurement itself destroys the continuity of the test. (1)

(1). Miner, Crest Voltmeters and Their Characteristics, Elec. Journal Vol. 22, page 571-7, December, 1925.

THEORY OF THE VACUUM TUBE CREST VOLTMETER

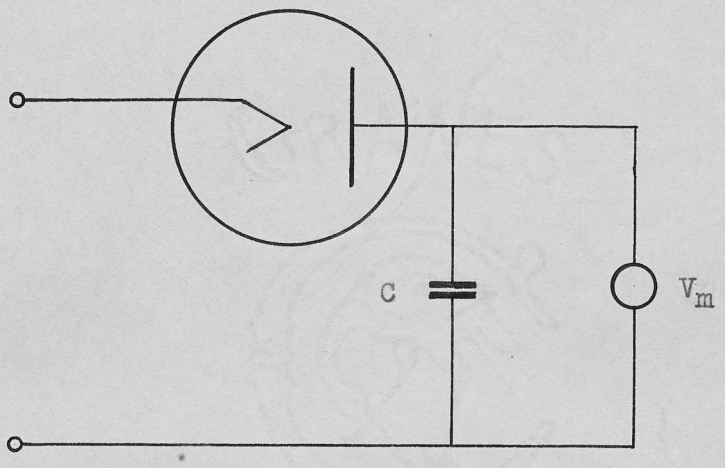


Figure 7.

Consider the circuit shown above. Under ideal conditions, the tube would be perfect in that current may flow one way but not in the other, and the condenser will have zero loss, thereby no leakage. Current will flow into the condenser during the first quarter cycle, and its charge increases until it is equal to the crest value of the applied voltage wave. During the next quarter cycle, the

wave being still positive, conditions are such that current may flow into the condenser but it will not do so since it has been assumed that the first quarter cycle was sufficient to charge the condenser. During the negative half-cycle, current will not flow from condenser back thru the tube since the latter acts as a one way valve. The potential of the condenser therefore does not change. If we now connect a voltmeter which draws no current, across the condenser, it will read the maximum or crest value of the applied wave.

The factors to be considered in actual operation are (1) internal voltage or drop in the voltage of the rectifier which alters the voltage applied to the condenser, and (2) leakage. The first factor is dependent upon the type and connection of tube used. Leakage is present to some degree in all apparatus, its allowable limit being dictated by the purpose for which the instrument is used. Thus if the high crest value obtained under transient conditions is to be measured, the leakage must be practically zero. If the leakage is too great, the voltage applied to the condenser will not be maximum value, or the charge will not be held long enough to give a reading. Furthermore, the condenser capacity must be small enough to allow complete charging during the rise of the wave to crest voltage without causing drop in the rectifier due to the charging current.

Some leakage is of advantage for ordinary use, particularly when rapid readings of varying potentials are made. If the leakage were very small, too much time would be required between readings to prevent a previous reading from having effect on subsequent lower readings.

The vacuum tube used must withstand high voltages with very little leakage, and its internal drop and losses at the low current values required must be small.

Two factors affecting the voltage delivered by the tube are (1) the initial velocity of electrons emitted from the hot cathode, and (2) the drop in the cathode filament due to the flow of current required to maintain its temperature. The first is of the order of one volt and tends to give a too high reading. The second factor is eliminated by using a tube with indirectly heated cathode. The calibration of such an instrument by a sine wave is found to hold true for all shapes except those having an extremely sharp peak, such shape giving a reading too low.

This type of crest voltmeter is important in that it is not affected by atmospheric conditions. A continuous indication is given during the adjustment and application of the voltage. No unnecessary stress, such as occurs with the sphere gap on flashover, is produced by this instrument. (1)

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(1) J.R. Craighead, Measurement of the Crest Values of Alternating Voltage by the Kenotron, Condenser and Voltmeter. G.E. Review, Vol 22, pages 104-9, February, 1919.

THE VOLTAGE DOUBLING VACUUM TUBE VOLTMETER

The apparatus constructed in the preparation of this thesis was of the voltage doubling type giving crest values. The device is accurate, compact, permanent in calibration and inexpensive. No batteries are required, the power necessary for operation being taken from an ordinary 110 volt outlet.

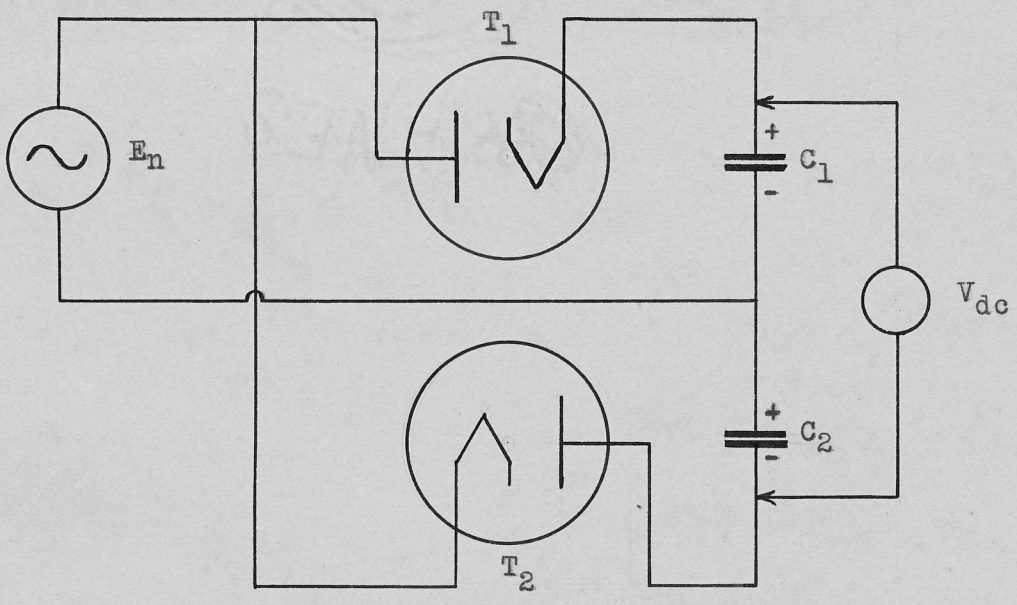


Figure 8.

Figure 8 shows the fundamental circuit of the crest

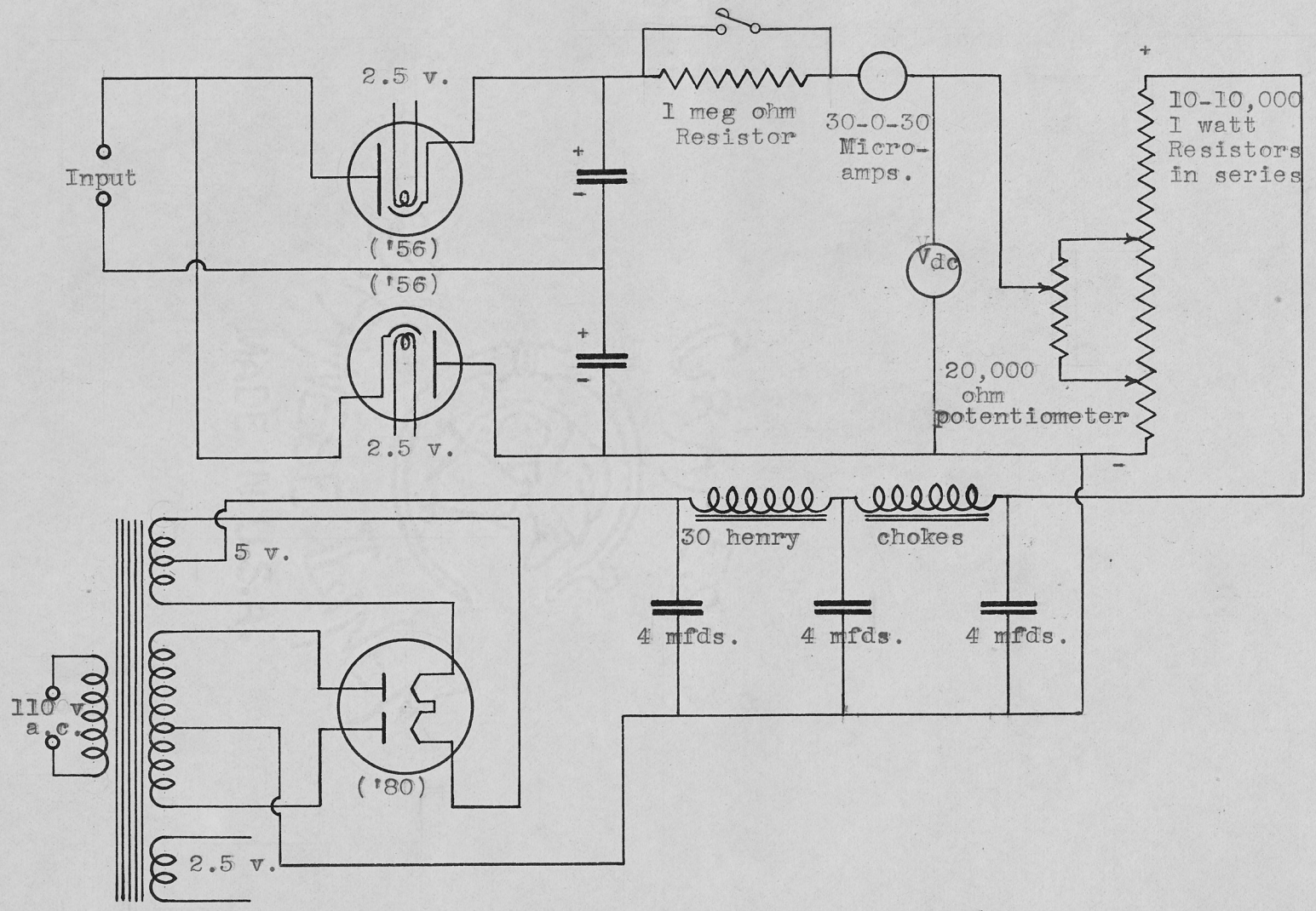

Input
2.5 v.
('56)
('56)
2.5 v.
1 meg ohm
Resistor
30-0-30
Micro-
amps.
Vdc
10-10,000
1 watt
Resistors
in series
20,000
ohm
potentiometer
30 henry
chokes
4 mfds.
4 mfds.
4 mfds.
5 v.
110 v.
a.c.
('80)
2.5 v.

Figure 9.

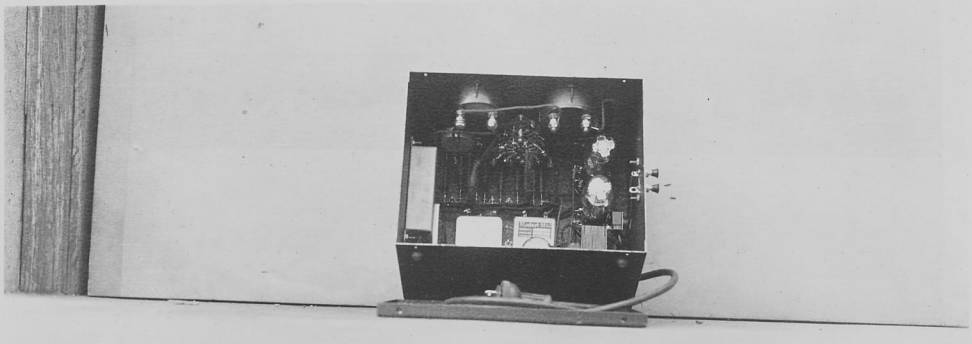




Fig. 10

doubling voltmeter. During the positive alternation, the plate of T_1 being at a higher potential than the cathode, T_1 will pass current and charge condenser C_1 to a value equal to the crest value of the positive half-cycle. This was explained on page 15. During this time no current flows thru T_2 as its plate is at a lower potential than the filament. However during the negative half-cycle, the plate of T_2 will be at a higher potential than its filament, and condenser C_2 will change to a value equal to the negative peak. A voltmeter, V_{dc}, which takes no current will then indicate the potential between positive crest and negative crest.

Figure 9 shows the circuit diagram of the complete device. The doubling circuit is identical with that already discussed. The tubes are type 56 having the grid connected to the plate, thereby greatly reducing the impedance of the tube. A 30 micro-ampere D.C. meter having a center zero is used to indicate when the opposing D.C. voltagesupplied by the type 80 rectifier is just equal to the double peak voltage across condenser. There is no advantage in having a center zero as direct current can flow only in one direction being blocked by the tube and condenser. The high resistance in series with the meter prevents damage by too high a current. Figure 10 gives photographic views of the instrument completed.

The operation is as follows. With input connected, the

potentiometer is adjusted until a counter D.C. voltage is impressed across the condensers which is just equal to the charge on the condensers. When this point is reached, no current will flow in the circuit and the micro-ammeter will read zero. Due to the large protective resistance in series with the meter, it is difficult to determine the exact point at which there is no current flow. When there appears to be no current flowing, the resistance is shorted out and a finer reading may be made. The reading of the D.C. voltmeter under conditions of zero current gives the double crest value of input wave.

ELIMINATION OF EFFECT OF HARMONICS

Vacuum tube voltmeter using triodes are subject to considerable error due to the non-linear impedance of the tube. The effect of these harmonics is neutralized by the use of two diodes operating so as to be voltage doubly. Consider the triode characteristic of figure 3, a portion of which is reproduced here.

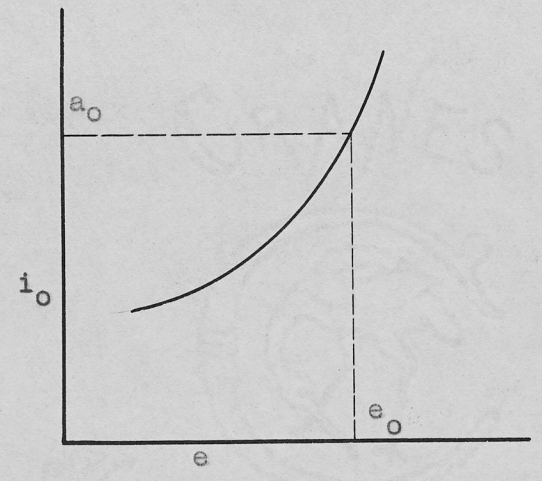


Figure 11.

The formula of any curve may be approximated by the use

of Taylor's series:

$$i = a_o + a_1(e-e_o) + a_2(e-e_o)^2 + a_3(e-e_o)^3 + \cdots$$

Applying this to the characteristic curve of the triode vacuum tube, figure 3:

$$i_p = I_o + K'(e_g-E_c) + K''(e_g-E_c)^2$$

All terms beyond the squared one have been dropped since the curvature of the characteristic is not too marked.

Let $e_g = E_c + E \sin \theta$

then $i_p = I_o + K' E \sin \theta + K'' E^2 \sin^2\theta$

Thus, we see from the $(K'' E^2/2) \cos 2\theta$ term, obtained by expanding $K'' E^2 \sin^2\theta$, that the second harmonic of the fundamental input frequency appears in the plate circuit. To determine the effect of the harmonic, differentiate i_p with respect to θ

$$\frac{d\, i_p}{d\, \theta} = K' E \cos \theta + 2 K'' E^2 \sin \theta \cos \theta$$

Setting $\frac{d\, i_p}{d\, \theta} = 0$

$$K' E \cos \theta + 2 K'' E^2 \sin \theta \cos \theta = 0 \quad (A)$$

if $K'' E^2/2 K' E = p$

then $\cos \theta = 0; \quad \theta = \pi/2, 3\pi/2$

also $\cos \theta = \pm \sqrt{1 - 1/16\ p^2}$

The curve of formula (A) takes the form of figure 12.

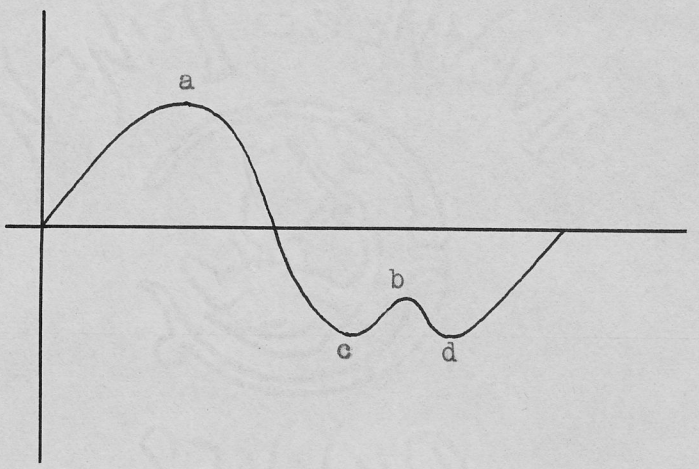


Figure 12.

The points "a" and "b" represent the first two roots; the points "c" and "d" represent the second set of two roots. If $1/16\ p^2$ is greater than 1, roots "c" and "d" do not exist. For the limiting condition where $16p^2 = 1$ or $p = 1/4(25\%)$, roots "b", "c", and "d" merge into one. Since p is generally less than 1/4 in practice, only the case of one maximum and one minimum need be investigated.

$$e_{max} = K(I_o + k' E \text{ Sin } \pi/2 + k'' E^2 \text{ Sin}^2 \pi/2)$$

$$e_{max} = K(I_o + k'E + k'' E^2) \qquad (B)$$

$$i_{max} = I_o + k' E + k'' E^2 \qquad (C)$$

From (C) it can be seen that the maximum peak value, $I_o + k' E$, of the plate current wave is increased by the value $k'' E^2$ due to second harmonic distortion. From this it can be seen how harmonic distortion introduces error into the usual type of vacuum tube voltmeter--since more than a "true" value of bias will be required on the grid to reduce this increased maximum peak value back down to the false zero.

Since the value of the minimum peak is--

$$e_{min} = K(I_o + k' E \text{ Sin } 3\pi/2 + k'' E^2 \text{ Sin}^2 3\pi/2$$

$$= K(I_o - k' E + k'' E^2)$$

--and as the meter measures

$$e_{max} - e_{min} = 2 k'E$$

--it is seen, for this case if the second harmonic in the plate circuit does not exceed 25% of the fundamental, that the voltage doubling vacuum tube boltmeter will indicate correctly twice the amplitude of the fundamental component.

Thus, we have a vacuum tube voltmeter which incorporates all the desirable qualities of compactness, cheapness, accuracy, and permanency of calibration. (1)

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(1) Vacuum Tube Voltmeter, paper presented by C. T. Coffey at A.I.E.E. Convention April 18, 1936 at Clemson, S.C.

METHOD OF CALIBRATION

One of the greatest advantages of vacuum tube voltmeters is that a calibration made at audio or power frequencies holds with negligible correction up to the highest radio frequencies. Regular sixty cycle voltage was used in calibration. The wave was assumed sinusodial. Thus

$$E_{peak} = \sqrt{2}\, E$$

or

$$2E_{peak} = 2\sqrt{2}\, E$$

$$\text{Discrepancy (in \%)} = \frac{(\text{Instrument peak voltage}) - \sqrt{2}\, E}{\sqrt{2}\, E} \times 100$$

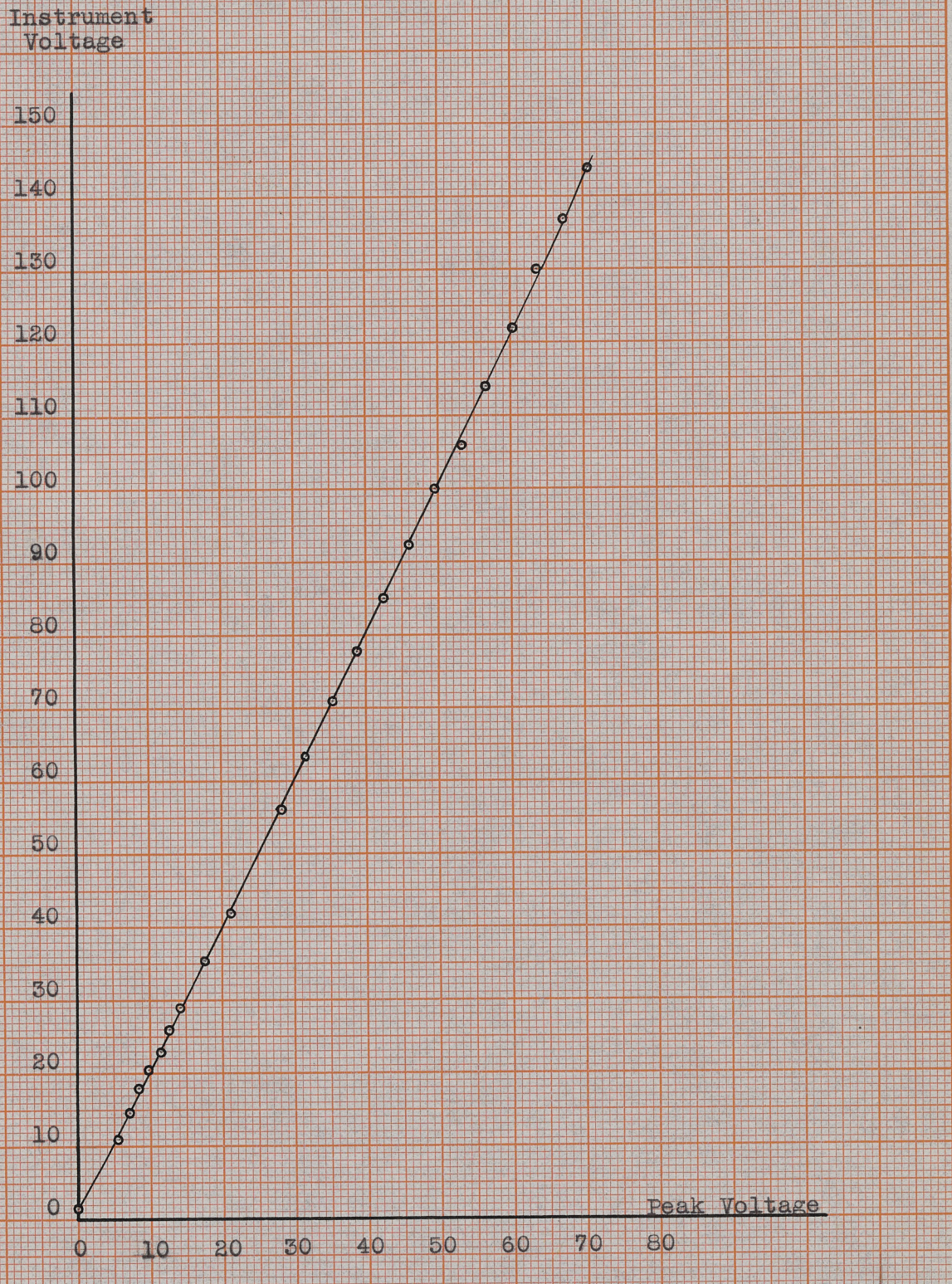
One difficulty was encountered in the construction of the device. The instrument was originally wired so that the 20,000 ohm potentiometer was shifted across each of the ten 10,000 ohm resistors. This arrangement would not give a complete range of back-D.C.-voltages accross the two condensers, but left a few voltages that could not be obtained. For example with the yaxley switch set on position 1 the highest voltage obtainable was 28 volts and the lowest voltage obtainable with the yaxley switch on position 2 was 32 volts. This skip was due to the 30,000 ohm voltmeter.

This difficulty was overcome by rewiring the yaxley switch so that as the potentiometer is moved from one end of the bank of resistors to the other end it is paralleled with 20,000 ohms instead of 10,000 ohms resistance.

DATA

Standard 2 E Effective	Calculated Peak	Cal. 2 Peak	Instrument Reading	% Disc.
0.0	0	0	1.5	
8.0	5.66	11.32	12.0	+ 6.00
10.0	7.07	14.14	14.7	+ 4.66
12.0	8.50	17.00	18.00	+ 5.88
14.0	9.91	19.82	20.5	+ 3.43
16.0	11.38	22.65	23.0	+ 1.54
18.0	12.73	25.46	26.0	+ 2.12
20.1	14.2	28.5	29.0	+ 1.75
25.0	17.7	35.4	35.3	- 0.28
30.0	21.2	42.5	42.0	- 1.19
35.0	24.8	49.6	49.3	- 0.61
40.0	28.3	56.6	56.1	- 0.89
45.0	31.8	63.7	63.5	- 0.31
50.0	35.4	70.7	71.0	- 0.42
55.0	38.9	77.8	77.8	- 0.39
60.0	42.5	84.9	85.0	- 0.12
65.0	46.0	92.0	92.3	+ 0.32
70.0	49.6	99.2	100.0	+ 0.80
75.0	53.1	106.2	106.0	- 0.19
80.0	56.6	113.2	114.0	+ 0.70
85.0	60.2	120.4	122.0	+ 1.41
90.0	63.7	127.5	130.0	+ 1.95
95.0	67.2	134.5	137.0	+ 1.85
100.0	70.7	141.4	144.0	+ 1.84

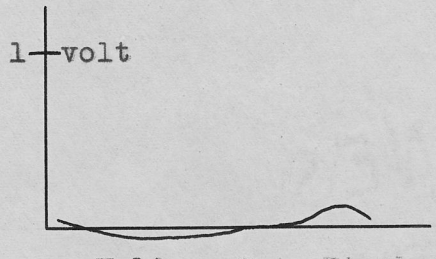
CALIBRATION CURVE



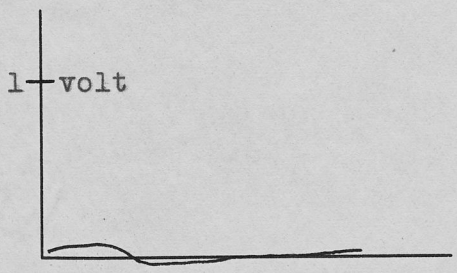
The storage condensers were tested to be sure that they are of low leakage and that the voltage across terminal is practically free from A.C.

The condensers were tested by making an oscillographic record of voltage between condenser terminals with nine volts effective value impressed on the vacuum tube voltmeter. The following oscillographic records show that there is about 0.1 A.C. volts across each condenser, and approximately the same value across both condensers.

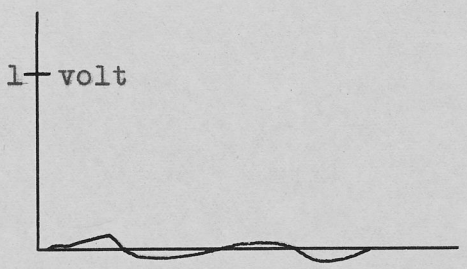
OSCILLOGRAPHIC CURVES



Voltage Wave Condenser
"A" 9 Volts Effective
Impressed.



Voltage Wave Condenser
"B" 9 Volts Effective
Impressed.



Voltage Wave Condenser
"A" and "B" in series
9 Volts Effective
Impressed.

Figure 14.

For best accuracy the back D.C. voltage should contain no A.C. component, but it would be practically impossible to get pure D.C. The filter in the rectifying tube circuit does a wonderful job. It was gratifying to find that the circuit was filtering the 120 cycle rectified voltage so that the filter output was of the order of 400 $\pm$ 0.05 volts. Following is shown the 120 cycle rectified voltage and the ripple of the filtered D.C. voltage.

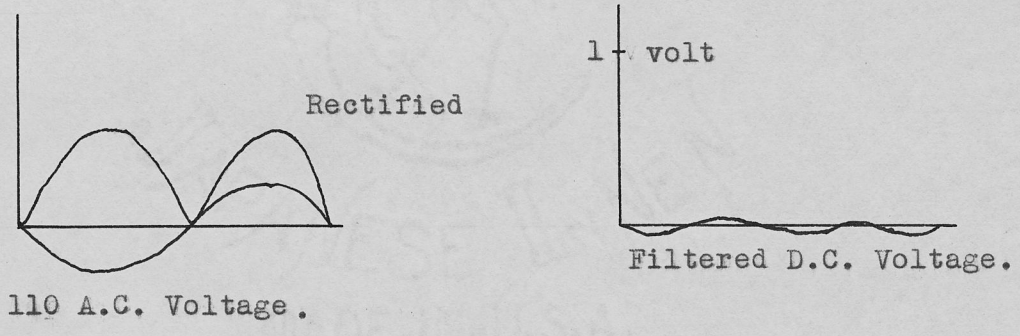


Figure 15.

CONCLUSIONS

It is seen from the data that the maximum error (exclusive of the extremely low values) was in the neighborhood of 1%. Since it was impossible to read the meter of the instrument much closer than one volt, it may be concluded that by substituting a narrow range meter with proper series resistance, the accuracy may be greatly increased.

The instrument is equipped with a center zero milliammeter. By redesigning the circuit so that the passing of the zero point will be indicated, the accuracy and ease of operation will be multiplied.

BIBLIOGRAPHY

New Form of Voltmeter for Measuring Peak Voltages, Electrical Review and Western Electrician 64: 245-6 January 31, 1914.

Sharp, C.H. and Doyle, E.D., Crest Voltmeters A.I.E.E. Proceedings 35: 129-37 February 16, 1916.

Chubb, L.W., Crest Voltmeter, A.I.E.E. Proceedings 35: 121-8 February 1916, Discussion July 1916.

Craighead, J.R., Measurement of Crest Values of A.C. Voltage by the Kenotron, Condenser and Voltmeter, General Electric Review 22: 104-9, February 1919.

Howe, Prof. G.W.O., Slide-Back Thermionic Voltmeter, Electrician 89: 32-3, July 14, 1922.

Moullin, E.B., Direct Reading Thermionic Voltmeter and its Application, I.E.E. Journal 61: 295-303, Discussion 304-7, February 1923.

Carrol, J.S., Description of a Crest Voltmeter, A.I.E.E. Journal 44: 943-8 September 1925, Discussion 45: 61-2, January 1926.

Miner, D.F., Crest Voltmeters and Their Characteristics, Electrical Journal 22: 571-7, December 1925.

Jansky, C.M., and Feldman, C.B., Two Range Vacuum Tube Voltmeter, A.I.E.E. Journal 47: 126-32, February 1928.

Moullin, E.B., Thermionic Voltmeter for Measuring the Peak

Value and the Mean Value of an Alternating Voltage of Any Wave Form, I.E.E. Journal 66: 886-95, August 1928.

Moullin, E.B., Some Developments of the Thermionic Voltmeter. I.E.E. Journal 68: 1039-51, August 1930.

Vacuum Tube Voltmeter--What It Is and How It Is Used. Radio News 12: 625-6, January 1931.

Lampkin, G.F., Simple Calibrated Vacuum Tube Voltmeter, Radio News 13: 305, October 1931

Fiske, R.M., Simple Vacuum Tube Voltmeter Radio News 13: 762, March 1932.

Detecting a Tenth of a Millionth of a Volt with a New Voltmeter, Power Plant Engineering 36: 559, July 15, 1932.

Muller, F, E.M.F. Measurements with the aid of Electron Tubes, Electrochemical Society Transactions 62 (preprint 10) 117-24, September 1932.

Compton, K.G. and Haring, H.E., A Compensated Thermionic Electrometer, Electro-chemical Society Transactions 62: 124-27 September 1932.

Pliotron and Screen Grid Applications, General Electric Review, page 331, July 1933.

Coffey, C.T., A Vacuum Tube voltmeter--Paper presented before Student A.I.E.E. Convention at Clemson College April 17, 1936.

Terman, Measurements in Radio Engineering (text).

APPROVAL

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its accpetance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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