Doyle

Crest Voltmeters.
CREST VOLT METERS

BY

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# CREST VOLTMETERS

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O 0 o
1. Purpose of Thesis.

The use of high voltage for power transmission is becoming more and more general. Not only are larger amounts of energy being transmitted but the distances traversed are greater. This is rendered feasible only through the employment of higher operating voltages. High operating voltages require particularly good insulation in both the transformers connected to the line and in the line itself.

The purpose of this thesis is to study the various methods of testing the insulation of apparatus and materials particularly with respect to the methods of measuring high voltage. A new instrument for use in high voltage tests is described and its operation is analyzed.

2. Acknowledgements.

The greater part of the work described in this thesis, particularly the development of the crest voltmeter, was done at the Electrical Testing Laboratories, New York City. Acknowledgement is hereby made for the use of the material so obtained. Thanks is due to Dr. C. H. Sharp of the Laboratories to whom credit should be given for the fundamental idea and to Dr. I. Langmuir of the General Electric Research Laboratory, Schenectady, who furnished the hot cathode rectifier used in the tests described.

The qualities to be possessed by an insulator for high voltage service are many and diversified. It should have considerable mechanical strength. It should have high insulation resistance. It should have high dielectric strength. The mechanical strength may be determined by the regular mechanical tests. The insulation resistance may be determined with a battery of dry cells and a sensitive galvanometer. The dielectric strength can only be determined by subjecting the insulation to a voltage at least as high, if not higher, than that which it will be subjected to in service.

4. Types of High Voltage Tests.

High voltage tests may be divided into two classes, "pressure" tests and "puncture" tests. The first are of a routine character and are made on completed apparatus for the purpose of ascertaining whether or not the material and workmanship entering into the apparatus is first class, it having been previously determined that the type of material would be suitable for the service. "Puncture" tests, on the other hand, are made on samples of insulation for the purpose of learning its ultimate dielectric strength. As the tests are necessarily destructive, they are generally made on comparatively small samples of the materials, for example a puncture test on high voltage cable is made on a sample not more than ten feet long.

5. Production of High Voltages.

High voltage for test purposes may be produced in a number
of different ways. The most common one is that of using an alternator in connection with a step-up transformer. The alternator is generally a standard frequency machine (25 or 60 cycles) although frequencies as high as 100 000 and 200 000 cycles have been used in special cases. Voltage regulation is usually effected through control of the alternator field current or by means of a voltage regulator connected between the alternator terminals and the transformer primary terminals. The connections for the two methods are shown in fig. 1, (a) and (b). An alternative method is the "potentiometer" method. It is shown in fig. 1 (c).

Within the last few years a number of tests have been described which are intended to duplicate more or less completely the effect of "impulse currents". Hayden and Steinmetz¹ have used the method shown diagramatically in fig. 2 (a). The scheme is to use the transient voltage induced in the secondary of a transformer when the primary is thrown across a direct current source. A similar scheme has been used by Chernyshoff and Butman². It is shown in fig. 2 (e). It differs mainly in nicety of construction, arrangements being had whereby successive impulses in the same direction may be produced. Imlay and Thomas³ have used the connections shown in fig. 2 (b). Creighton⁴ has made use of the "oscillation transformer". It is practically a Tesla coil. The arrangement is shown in fig. 2 (c). Peck's "impulse generator"⁵ is shown in fig. 2 (a).

¹. Bibliography No.1.  2. Bibliography No.2.  3. Bibliography No.3  4. Bibliography No.4.  5. Bibliography No.5.
Fig. 1.

Methods of Regulating Voltage
Fig. 2.

Impulse Tests.
In addition to the methods indicated above there are several others which have been used from time to time. The induction coil has been used in certain instances. High voltage direct current has been suggested for such cases as underground cable systems where the capacitance is high. For a discussion of the various methods available for the production of high voltage direct current see "Methods of Obtaining High-potential Direct Current" by S. Thomson. 6. Characteristics of High Voltage Waves.

The assumption is generally made that the wave form of normal frequency testing equipments is sinusoidal, both at the terminals of the alternator and the high tension winding of the step-up transformer. As a general rule there is no reason for making such an assumption for there are a number of factors which cause the wave to depart from a sine curve. Sine waves at no load are only obtained where considerable care is exercised in the design of the alternator. Fig. 3 shows the wave form of a number of alternators and distribution systems which have come to the attention of the writer. Fig. 3 (a), (b) and (c) show the wave forms of three generators used by as many wire and cable manufacturers for testing their product. Fig. 3 (d) shows that of the life test alternator at the Electrical Testing Laboratories. Although this machine is used primarily for tests of incandescent lamps, it is also used for such high voltage tests as are made at the Laboratories. Fig. 3 (e) and (f) are the 25 and 60 cycle system wave forms of one of the large central stations in New York.

Even in cases where the alternator gives a good wave at no

1. Bibliography No. 23.
load there is a possibility that the wave shape will change with load, particularly a load of high capacitance. This effect is a composite one. It is partially due to the effect of armature reactions produced by the load currents and the exciting current of the testing transformer. Resonance between the effective inductance of the alternator and the transformer and the capacitance of the load may magnify harmonics existing in the voltage wave. Fig. 4 shows some very good examples of such effects. The alternator in question was loaded to its rated capacity with rubber insulated wire. The various curves show the wave forms under different conditions of load. It should be noted that the transformer high tension waves were of the same shape as those shown.

The method of regulation also has its effect on the wave form. Fig. 5 shows the effect of regulating the voltage by putting resistance in series with the transformer primary winding and by using a poorly designed voltage regulator.

While the above methods give a definite wave of constant amplitude under a given condition, the "impulse" tests do not. It is very difficult to obtain the wave shape of the voltage waves directly, but they may be calculated in certain cases from the constants of the circuit. Fig. 6 shows some representative curves for the various tests described above. From them it will be seen that successive alternations do not have the same amplitude.

Direct current test voltages may be more or less constant, depending on the arrangement used. A proper arrangement of condensers and inductances will make the voltage fluctuations negligible.

Variation of Generator Waveform with Load.

Fig. 4.

(a) No Load
(b) 8% Load
(c) 16% Load
(d) 24% Load
(e) 32% Load
(f) Full Load
Arc Effect Negligible.

Arc Effect Predominant.

Calculated Oscillation Transformer Waves.

(Proc. A.I.E.E. Sept. 1915)

Calculated "Impulse Generator" Waves.

Fig. 6.
Continuous Oscillation and Harmonic Waves
7. Measurement of High Voltages.\(^1\)

Two general methods are available for the measurement of high voltages, (a) the indicating instrument and (b) the spark gap. The indicating instrument method may take a number of forms. It may be a voltmeter connected to some form of ratio device, such as a voltage transformer, a voltmeter coil in the high tension winding or taps in the same winding. It may be connected to the primary terminals of the transformer or it may even be used directly on the high tension voltage through a series resistance. High range electrostatic voltmeters are also available in ranges as high as 200,000 volts.

Spark gaps may be used up to the highest attainable voltages. They have been calibrated directly to voltages of the order of 250,000 volts and calibration curves have been calculated for voltages as high as 1,000,000 volts.

In standard frequency tests any of the above methods may be used. The indicating instrument method is the most convenient one, for one has an indication of the voltage at all times. However the indications of the voltmeter are proportional to the virtual value of the voltage while the break down of insulation depends on the maximum value of the voltage. The spark gap is the only method which operates on the maximum value of the wave, but although it is capable of giving accurate indications, it is very inconvenient to use for it gives no indication of the value of the voltage before it arcs over. Its use has been very aptly compared with the use of fuses for the measurement of currents. Extreme care must be exercised in using the spark gap in testing apparatus of high capacitance. Destructive

\(^1\) Bibliography No. 6.
oscillations are very likely to be set up when arc over occurs.

The spark gap is the only available method for measuring "impulse" voltages. Even here it is not entirely satisfactory for the question of the comparative dielectric spark lags of the gap and the material being tested enters.

Practically no difficulties occur in measuring high direct current voltages. Electrostatic voltmeters give entire satisfaction and it is possible to use D'Arsonval type instruments with series multipliers where enough power is available.


From the above it will be seen that while stresses in insulating materials are proportional to the maximum value of the voltage those instruments which are the most convenient to use all give indications proportional to the virtual value. Allowance could be made for this if the wave were sinusoidal or if it remained constant for a particular equipment. Unfortunately such is not the case. A field therefore exists for an instrument which will either indicate the maximum or crest value of the voltage or which will give the crest factor (i.e. the ratio of the crest value to the virtual value).

III DEVELOPMENT OF CREST VOLTMETERS.

A. Wave Tracers.


Wave tracers may be considered as the fore runners of the crest voltmeter. Not only will they all give readings proportional to the crest value of the wave, but a number of them have been used
as crest voltmeters. A study of the various types is interesting in view of the later developments.

Wave tracers are of two types, the contactor type and the vibrator type. The former includes the devices of Joubert, Mershon and Duncan. The latter includes the oscillographs of Blondel, Duddell and Irwin.


Mershon's method is shown diagramatically in fig. 7 (a). It consisted primarily of a contactor on the shaft of the alternator which makes contact momentarily. The voltage to be investigated was opposed to a direct current voltage through this contactor and a telephone receiver. The direct current voltage was varied until no sound could be heard in the receiver. The indication of the d.c. voltmeter was a measure of the a.c voltage at the instant of contact. By shifting the contactor around the shaft the entire wave shape could be obtained.

Rosa's wave tracer is an elaboration of the fundamental idea. The principal difference is the addition of a recording pencil which indicates the position of the sliding point of the potentiometer.


Duncan devised a method which enabled a number of waves to be investigated at the same time with a single contactor. The contactor was in series with the fixed coils of a number of dynamometers which were connected to a d.c. source. The moving coils of the met-

1. Bibliography No. 9. 2. Bibliography No. 11. 3. Bibliography No. 10
ers are connected to the various voltages to be investigated, (See fig. 7 (b) for connections). The torque of each meter is equal to the product of the direct current and the alternating current at the instant contact is made. During the rest of the cycle the torque is zero. The meters are calibrated by passing direct current through the moving coils while the contactor is still operating. The complete curve is taken by shifting the phase of the time of contact.


Joubert's method is shown in fig. 7 (c). He used the same type of contact as Mershon and Duncan, but the voltage is run to a condenser. The contactor connected the condenser to the circuit for an instant and at the instant of breaking the circuit, the condenser was left with a charge proportional to the voltage at that instant. The voltage of the condenser was determined by discharging it through a galvanometer (as in the case of the General Electric wavemeter) or by an electrometer connected across its terminals (as used by Ryan).

13. Oscillographs. 

The essential idea of all oscillographs is to cause a small mirror to follow the variations in a current, no matter how rapidly they may occur. This has been produced by different inventors in various ways. Blondel mounted the mirror on a soft iron strip placed between the poles of a powerful electromagnet. The current to be investigated passed through small coils close to the pole pieces of the magnet. The interaction of the two fields

1. Bibliography No. 7  
2. Bibliography No. 11  
3. Bibliography No. 8  
4. Bibliography No. 12
caused the iron strip to twist, thereby deflecting a beam of light which had been thrown on the mirror.

Duddell mounted the mirror on two conducting filaments placed between the poles of a similar electro-magnet. Current was sent through the two strips in series. The interaction of the current and the magnetic field deflected the strips in opposite directions thereby turning the mirror.

Irwin has produced a similar effect by thermal means. He has two strips carrying direct current. The alternating current is sent through the same strips, but in such a manner as to increase the direct current in one strip while it diminishes it in the other. As a consequence one strip is heated by the alternating current while the other is cooled by virtue of the same current. One strip is lengthened while the other is shortened. These movements are conveyed to the mirror by suitable means and the general effect is the same as the electro-magnetic oscillograph.

In every case there are two methods of recording the movement of the mirror. One is photographic, the plate or film being moved across the path of the beam of light. The other is visual and is the one which is the most convenient for crest voltmeter work. The beam of light is thrown on a translucent screen and the width of the band of light may be noted or it may be resolved into a curve by the equivalent of a rotating mirror.


The following is a discussion of all of the types of crest voltimeters which have been described in the technical press. Each is described and its principal advantages and dis-advantages enumerated.

15. Sharp-Farmer Crest Voltmeter.

This device is an adaptation of Ryan's modification of Joubert's method to high voltage measurements. It is shown in fig. 8. A number of high voltage condensers are connected in series and a low voltage variable condenser is connected between one end of the series and ground. The other end of the series is connected directly to the high voltage source. A synchronous rectifier with very narrow segments rectifies the drop across the low voltage condenser and delivers it to an electrostatic voltmeter. By shifting the phase of rectification the voltmeter may be supplied with voltage at the maximum value of the wave. As it is insulated during the balance of the alternation, it holds the charge so obtained and indicates the maximum value of the wave continuously. Owing to imperfect insulation in the voltmeter, it is often necessary to shunt the voltmeter with a condenser which acts as a reservoir to supply the leakage during the time the voltmeter is insulated.

By the use of a double pole switch it is possible to throw the voltmeter directly across the low voltage condenser. This gives virtual voltages and enables one to get crest factor directly. During this reading the shunting condenser must be cut out.

1. Bibliography No.15.
Fig. 8.
CREST VOLTMETERS.
The principal advantages of the Sharp-Farmer device are (1) it may be calibrated on either alternating or direct current, (2) it gives crest factor as well as crest voltage, (3) it may be used on a condenser multiplier, a voltmeter coil or a voltage transformer, (4) it has no frequency error and (5) it indicates the crest voltage at the instant of reading.

It suffers from the following disadvantages, (1) it requires a synchronous motor and takes considerable power from either the alternating or direct current circuit, (2) it is limited to comparatively low fundamental frequencies, (3) it must be shifted to obtain the crest reading, (4) the contact device is liable to give trouble and (5) the electrostatic voltmeter is rather sluggish.


Chubb and Fortescue have described a form of crest voltmeter which is entirely different from any of the wave tracers which have been described. They have made use of the fact that the average value of the charging current of a condenser is proportional to the maximum value of the voltage impressed on the condenser. The reasoning is as follows.

If the frequency of the circuit is \( f \), the time to pass from a positive to a negative maximum will be

\[
T = \frac{1}{2f}
\]

During this time the condenser current will have increased from zero to a maximum and decreased to zero again. Its average value equals the total charge divided by the time, i.e.

1. Bibliography No. 16.
\[ i_{av} = \frac{2VC}{1 - \frac{1}{2f}} = 4fVC \]

or \[ V = \frac{i_{av}}{4fC} \]

The average value of the current is read on an instrument of the D'Arsonval type. In order to eliminate the reversed currents of alternate half cycles, the reversed currents are short circuited by a synchronous contactor, (see fig. 8). The readings must therefore be multiplied by 2 and the final formula is

\[ V = \frac{i_{av}}{2fC} \]

By using a suitable condenser the method may be made an absolute one.

The advantages of the method are (1) connection is made directly to the high voltage source, (2) the indications of the instrument are steady and (3) absolute values may be obtained.

The disadvantages are (1) calibration can only be effected by calculation, (2) a synchronous motor is required, (3) there is a considerable chance for trouble from stray electrostatic fields, (4) the indications vary directly with the frequency and (5) virtual values must be obtained from a separate instrument.

17. G.E. Wavemeter as a Crest Voltmeter.¹

While no one has described the use of the General Electric wavemeter as a crest voltmeter, it has been used by the writer in such a capacity to very good advantage. The results of these tests will be found later in this thesis. Its advantages are (1) the in-

¹ Bibliography No. 11.
indicating instrument is well damped, (2) there is practically no frequency error and (3) it may be calibrated directly on direct current.

Its disadvantages are (1) it requires a synchronous motor, which requires considerable energy and (2) it must be adjusted to locate the crest value of the wave.


Whitehead and Gorton in their investigation of corona have made use of the modification of the Chubb-Fortescue method shown in fig. 8 (c). The synchronous contactor of the original scheme has been replaced by a pair of mercury arc rectifiers. During one half cycle the charging current of the condenser is allowed to pass thru the ammeter while the following half cycle of current is shunted around the ammeter by the second rectifier.

The advantage of this method over the original one is that the device requires no adjustment to locate the maximum value of the wave. In addition it may be used on practically any frequency. The ammeter may be very nearly dead-beat and will follow any ordinary fluctuations of voltage.

The disadvantages of the original method remain with the exception of those pertaining to the motor and contactor. In many cases the necessity of having two independent direct current sources will prevent its use. Another disadvantage of such an arrangement has been pointed out by Chubb. The arrangement will not give a correct indication on a voltage wave having more than one maximum per cycle. Fig. 9 (copied from Chubb's paper) shows the voltage and

Fig. 9
Source of Error in Whitehead-Gorton Crest Voltmeter

Figure 6
Source of Error in Whitney's
Dilution (Creath Method)
current through a condenser on such a wave. It will be noted that the current passes through zero whenever the voltage has a maximum or a minimum value. This produces a number of negative loops in the current wave. These negative loops can not pass through the ammeter as they are by-passed by the second rectifier. On the other hand the corresponding positive loops in the next half cycle will pass through the ammeter. The accuracy of the method depends on the equation given on page 24, i.e. the crest voltage is proportional to the algebraic average of the current. Consequently the indication of the meter will be in error by an amount equal to twice the area of the negative loops in the first half cycle. In certain instances errors as high as 46 percent have been observed.

19. Westinghouse Crest Voltmeter.\(^2\)

Chubb has taken the previous method and made a very practical outfit out of it. It is now being supplied by the Westinghouse Company as a crest voltmeter with high voltage testing equipments. The mercury arc rectifiers have been replaced with two hot cathode rectifiers. They are small bulbs filled with mercury vapor and containing a filament and a grid. They resemble the DeForest audion. The filaments are heated by currents from two small transformers. The condenser bushing of the testing transformer serves as the condenser whose charging current is to be measured.

This device has the same advantages and disadvantages as the Whitehead-Gorton arrangement, with the exception of the excitation of the rectifiers. The latter method is vastly superior to the

1. Bibliography No. 22. 2. Bibliography No. 19.
original one. The use of the condenser bushing has some slight disadvantages. Its capacitance changes with voltage and the outfit must be calibrated as a unit. It is also probable that there would be a change of capacitance with frequency. The question of checking the meter under working conditions is not without its difficulties. The only available method is the sphere gap. While it is accurate if corrections be made for air density, it can not be used when testing loads of high capacitance, for reasons enumerated above, (see p. 15).

On the other hand it is under just such conditions that voltage with double peaks are most likely to be encountered. The device fails under those conditions where it is most needed.

20. Simplex "Peak Reading Voltmeter".

The use of the oscillograph as an indicating instrument for observing maximum values was first suggested by Robinson and Ball. Lloyd later suggested its use for measuring crest values of voltage waves. Middleton and Dawes have perfected such an instrument based on the oscillograph principle and have used it to a considerable extent in the testing of wire and cables. The meter is essentially an oscillograph element arranged for switch board mounting. Switches are provided for calibrating the meter and for connecting it to a voltage transformer. The maximum value of the voltage is determined from the width of a band of light on a translucent screen.

The advantages of this type of meter are (1) it is easily calibrated and (2) it is dead-beat. Its disadvantages are (1) it is

1. Bibliography No. 18.
necessary to have a reasonably constant d.c. voltage for excitation and calibration, (2) the meter gives only crest values - if virtual values are desired they must be obtained with another meter., (3) it is difficult to read peaks such as that shown in fig. 4 (a) and (4) it must be used on a voltage transformer.

IV. SOME NEW TYPES OF CREST VOLTMETERS

A. General.

The following types of crest voltmeter are based on what the writer believes is an entirely different principle than that of any other crest voltmeter. A condenser is put in series with an electric valve and is connected across the voltage to be investigated. The voltage charges the condenser to the maximum voltage of the wave and the valve prevents the condenser from losing its charge. The voltage of the condenser is measured by one of several methods. The distinction between the two types is entirely one of voltage measurement.

B. "Type A" Crest Voltmeter.


The meter consists primarily of a hot cathode rectifier and an electrostatic voltmeter. The two are connected in series on the voltage. The mode of operation is most easily understood from a study of fig. 10. In this figure "e" and "i" are the voltage across and the current through a condenser on a distorted voltage wave. If a perfect electric valve be placed in series with the condenser, it will allow current to pass without any voltage drop as long as the

1. Bibliography No. 20.
Fig. 10.

Cycle of "Type A" Crest Voltmeter
Case of Type A Great Voltmeter
current is in one direction. If the current tries to reverse, the valve interposes an infinite resistance in the circuit and the current ceases (see "A" fig. 10). However this reversal of current through the condenser can only occur when the voltage across the condenser is not changing, i.e. when \( \frac{de}{dt} = 0 \), or in other words when the voltage wave has a maximum or a minimum value. Since the current is trying to change from a positive to a negative value, it must be a maximum point in the voltage wave. If the valve has infinite resistance (as will be the case with a perfect valve) and the condenser has perfect insulation, the condenser will remain charged to this voltage indefinitely if a higher voltage is not impressed on the circuit. If there be a higher maximum in the voltage wave (as shown at C') the current will remain at zero until the voltage B' is reached (B' = A') when the current will suddenly increase from B to B" following the curve B"DC until the maximum point C' of the voltage wave is reached. This voltage will be held on the condenser for no voltage smaller than C' can send current through the valve.

22. Description.

Fig. 11 (a) shows the arrangement usually employed. "K" is a hot cathode rectifier of the kenotron type\(^1\), manufactured by the General Electric Company. It was rated at 10 000 volts 5 milliamperes by Dr. Langmuir of the G.E. Research Laboratory. It consists of a tungsten filament cathode and a tungsten plate anode in a highly evacuated bulb. The filament is heated to incandescence by a cur-

\[^1\] Bibliography No. 21.
(a) A.C. Excitation.

(b) D.C. Excitation.

Fig. 11.
Connections. "Type A" Crest Voltmeter
rent of approximately 3.5 amperes.

"V" is an electrostatic voltmeter of the Ayrton and Mather type manufactured by Robt. W. Paul. It is a double pivoted instrument and has a range of 60 to 250 volts. The scale is remarkably uniform for a meter of this type.

The connections are indicated in the figure. The voltmeter is in series with the kenotron across the voltage. The filament is heated with current from the transformer "T" which should be connected to the same source as the high voltage transformer whenever possible. As shown the voltmeter indicates crest voltage. Closing the switch "S" short circuits the kenotron allowing the voltmeter to indicate virtual volts.

The condenser "C" is put in multiple with the voltmeter for practical reasons which have been mentioned on page 21. It is a subdivided mica condenser having a range of 0.001 to 1.000 microfarads.

23. Checks of Device and Application to Testing.

The "Type A" crest voltmeter has been tested and used under a number of different conditions. The following is a summary of the more important work. Unless stated to the contrary, the work was done at the Electrical Testing Laboratories.

24. Checks Against Oscillograph.

This work was done at the plant of one of the prominent manufacturers of wire and cable near New York City. The original purpose of the tests was to determine the shape of the high voltage testing transformer wave under all of the conditions ordinarily encountered. The transformer was rated at 50 kva. 1100 to 12 500 , 25 000
or 50,000 volts. It was connected directly to an engine-driven alternator of 55 kva. capacity. During the test the transformer secondary was connected for 12,500 volts and was loaded with a number of thousand foot coils of No. 8 AWG. copper wire with 5/32 inch rubber insulation. Primary and secondary voltage wave shapes were obtained from voltage transformers connected across the two windings. The crest voltmeter was connected to the secondary of the voltage transformer across the high tension winding. Table 1 shows the comparative crest factors obtained by the two methods.

TABLE 1.

<table>
<thead>
<tr>
<th>Wave</th>
<th>Percent Crest Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fig. 4-a Crest Voltmeter</td>
<td>Oscillograph</td>
</tr>
<tr>
<td>&quot; 4-b</td>
<td>145</td>
</tr>
<tr>
<td>&quot; 4-c</td>
<td>155</td>
</tr>
<tr>
<td>&quot; 4-d</td>
<td>163</td>
</tr>
<tr>
<td>&quot; 4-e</td>
<td>169</td>
</tr>
<tr>
<td>&quot; 4-f</td>
<td>139</td>
</tr>
<tr>
<td>Average</td>
<td>153</td>
</tr>
</tbody>
</table>

It is to be noted that the above tests were made with a Kelvin multicellular voltmeter which showed considerable friction around the zero position. The above tests are not as reliable as some described later.

25. Check Against Wavemeter.

The following tests were made on a special generator from which various distorted waves could be obtained. It consists of three sine wave generators in the same frame. The first has a frequency of 60 cycles; the second, 180 cycles and the third, 300 cycles. The voltages could be varied independently while the phases of the second and third machines could be adjusted by shifting the armatures.
in their cradles. Inasmuch as the generator voltage was 120, the voltmeter was connected directly to the generator terminals. The indication of the crest voltmeter was checked by two independent methods, (1) using a G. E. wavemeter as a wave tracer and (2) calibrating the wavemeter as a crest voltmeter and reading virtual volts on another meter of the dynamometer type. The set-up employed is shown in fig. 12. The procedure was as follows: A wave of the desired shape was produced by adjusting the voltages and phases of the generators. Crest and virtual voltages were obtained with the "Type A" device. The wave was then traced with the wavemeter. At the maximum point of the wave the wavemeter voltmeter was read simultaneously with a dynamometer voltmeter. From the readings so obtained three separate calculations could be made of the crest factor.

Fig. 13 shows the three waves investigated. The crest factors are shown in table 2.

**TABLE 2.**

<table>
<thead>
<tr>
<th>Wave</th>
<th>Percent Crest Factor.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Crest Voltmeter</td>
</tr>
<tr>
<td>Fig. 13-a</td>
<td>121.8</td>
</tr>
<tr>
<td>&quot; 13-b</td>
<td>143.5</td>
</tr>
<tr>
<td>&quot; 13-c</td>
<td>209.0</td>
</tr>
</tbody>
</table>

From the above it will be seen that there is a very satisfactory agreement between the various methods. As will be shown later it is impossible for this type of meter to give an indication higher than the true value if it is connected correctly. The variations in the case of wave 13-c may be attributed to errors in reading the several
Fig. 12.  
Connections for Wavemeter  
Check of "Type A" Crest V.M.
Fig. 13.
Waves used in Check of "Type A" Crest Voltmeter
FIG. 16

WAVE OBSERVED METER OR
"FREE WAVE" WAVE OF METEOR
instruments.

As a matter of interest the calibration of the G.E.Wavemeter as a crest voltmeter at different frequencies has been included as fig. 14. The calibration was made by running the synchronous motor on sources of different frequencies, direct current being impressed on the terminals where alternating current was ordinarily used. Simultaneous readings were taken of the voltmeter used with the wavemeter and that across the direct current source. During this test the capacitance of the condensers employed was approximately 6 mf. while the resistance of the voltmeter was about 15 000 ohms.

26. Checks at High Frequencies.

Dushman has stated that the kenotron operated just as satisfactorily at 100 000 cycles as it does at the lower commercial frequencies. While no opportunity was obtained to make checks at such frequencies, a few tests were made at frequencies as high as 4 000 cycles. The crest voltmeter was connected to a Vreeland Oscillator and crest and virtual voltage readings taken. The Vreeland Oscillator is a generator of pure sine waves. The ratios of the two sets of readings should therefore have been 1.41. Values as high as 1.6 were observed. This is accounted for by the fact that it is practically impossible to get the oscillator to give a steady voltage. Even with the voltmeter connected for a virtual reading one could see sudden "kicks". The readings indicate that these kicks were considerably larger than would be suspected and that the kenotron was sensitive to each one.

27. Application of Crest Voltmeter to Test Problems.

The "Type A" crest voltmeter has been applied to the solut-
ion of test problems with considerable success. They are included both to show the utility of the device and to suggest other uses to those who may be interested in such a device.


At the same time that the checks reported on page 33 were made, a complete set of readings of the crest factor were taken under all conditions of load. The results are given below.

TABLE 3.

Variation of High Tension Crest Factor with Load.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Current, Amperes</th>
<th>Percent Crest Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary</td>
<td>Secondary</td>
</tr>
<tr>
<td>Alternator only</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>&quot; and transf'r</td>
<td>3.20</td>
<td>0</td>
</tr>
<tr>
<td>One coil of wire</td>
<td>2.45</td>
<td>0.28</td>
</tr>
<tr>
<td>Two coils &quot; &quot;</td>
<td>4.70</td>
<td>0.57</td>
</tr>
<tr>
<td>Three &quot; &quot; &quot;</td>
<td>8.0</td>
<td>0.94</td>
</tr>
<tr>
<td>Four &quot; &quot; &quot;</td>
<td>16.4</td>
<td>1.61</td>
</tr>
<tr>
<td>Five &quot; &quot; &quot;</td>
<td>16.0</td>
<td>1.70</td>
</tr>
<tr>
<td>Six &quot; &quot; &quot;</td>
<td>17.5</td>
<td>1.85</td>
</tr>
<tr>
<td>Seven &quot; &quot; &quot;</td>
<td>20.5</td>
<td>2.10</td>
</tr>
<tr>
<td>Eight &quot; &quot; &quot;</td>
<td>23.4</td>
<td>2.37</td>
</tr>
<tr>
<td>Nine &quot; &quot; &quot;</td>
<td>26.3</td>
<td>2.63</td>
</tr>
<tr>
<td>Ten &quot; &quot; &quot;</td>
<td>29.8</td>
<td>2.94</td>
</tr>
<tr>
<td>Eleven&quot; &quot; &quot;</td>
<td>34.0</td>
<td>3.30</td>
</tr>
<tr>
<td>Twelve&quot; &quot; &quot;</td>
<td>----</td>
<td>3.61</td>
</tr>
</tbody>
</table>

Note: Each coil consisted of 1000 feet of No. 8 AWG. copper wire with a 5/32 inch wall of rubber insulation. All tests were made at 12,500 volts (high tension). The above tests show the variation which may exist in a high voltage test without its being suspected. A study of the amps. per thousand feet of wire would have shown that some trouble existed but the only definite information is that obtained from the crest factors. The results are shown graphically in fig. 15.

29. Check of Sphere Gap on Distorted Voltage Wave.

The following test was made for the purpose of showing the
**Fig 14.**

G.E. Wavemeter as Crest Voltmeter.

**Fig 15.**

Variation of Wave Distortion with Load.
application of the crest voltmeter to high voltage testing. Distorted waves were produced by operating a 60 cycle, 110 to 246 400 volt testing transformer from a 220 volt 25 cycle circuit through a small variable ratio auto transformer having considerable magnetic leakage. A sample wave from this combination is shown in fig. 5 (c). A 25 centimeter sphere gap was connected to the secondary of the transformer, the crest voltmeter and an ordinary iron vane voltmeter being connected to the primary taps. The results of the test are given below.

**TABLE 4.**

Check of 25 Cm. Sphere Gap on a Distorted Wave.

<table>
<thead>
<tr>
<th>Sphere Gap (Inches)</th>
<th>L.T. Volts by R.M.S. Crest VM.</th>
<th>H.T. Kilovolts (Max) by Crest Sphere VM. Gap</th>
<th>H.T. Kilovolts (Max) by Crest Sphere VM.</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6</td>
<td>65</td>
<td>122</td>
<td>272</td>
</tr>
<tr>
<td>5.2</td>
<td>70</td>
<td>132</td>
<td>298</td>
</tr>
<tr>
<td>6.0</td>
<td>75</td>
<td>145</td>
<td>330</td>
</tr>
</tbody>
</table>


The crest voltmeter has been used to determine the maximum voltage induced in the primary winding of a high tension ignition magneto when the interrupter opened the circuit. During this test a high resistance was used as a multiplier, the crest voltmeter being tapped across a section of it. On operating the magneto at various speeds the required readings were obtained. Owing to the fact that this work was not done by employees of the Electrical Laboratories no data can be presented. It should be particularly noted that in such tests as those described above it is necessary to use a resistance type of multiplier. It is obvious that a condenser type would be of absolutely no use.
C. "Type B" Crest Voltmeter.


There are a number of instances where the "Type A" crest voltmeter will not be as useful as one which will not only indicate the crest voltage but will show fluctuations in this value. A modification of the above scheme has been devised which offers advantages for certain purposes. The general arrangement is shown in fig. 16. It will be noted that it differs from fig. 11 (a) only in the substitution of a galvanometer "G" and a high resistance "R" for the electrostatic voltmeter. With the latter arrangement, the voltage charges the condenser to a maximum value, the charge being gradually dissipated in the resistance "R" during the remainder of the cycle. It would seem at first thought that such an arrangement would be very susceptible to changes in frequency and wave form, but the tests made so far do not indicate any such state of affairs.

32. Description.

The valve is the same one described above. The galvanometer is a Paul "Unipivot", pointer type instrument. It is portable and has a sensitivity of 1 microampere per division with an internal resistance of 50 ohms. The series resistance is a "Megohm Box" consisting of ten 100 000 ohm coils connected in series. The condenser is a standard mica condenser.

33. Tests of "Type B" against "Type A.

"Type B" has been compared with "Type A" under a number of different conditions of frequency and wave form. The results of these tests are shown in table 5 and fig. 17.
Fig. 16.

Connections "Type B" Crest Voltmeter.
Fig. 1E
TURBO CHARGE CONTROLLER
### TABLE 5.

Check of "Type B" against "Type A" Voltmeter.

<table>
<thead>
<tr>
<th>Frequency Cycles</th>
<th>Crest Factor Percent</th>
<th>Crest Voltmeter Ind. Type A</th>
<th>Crest Voltmeter Ind. Type B</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>140.0</td>
<td>122.5</td>
<td>91.8</td>
</tr>
<tr>
<td>62</td>
<td>138.5</td>
<td>94.5</td>
<td>70.0</td>
</tr>
<tr>
<td>62</td>
<td>138.5</td>
<td>103.3(?)</td>
<td>75.0</td>
</tr>
<tr>
<td>62</td>
<td>138.5</td>
<td>106.5</td>
<td>80.0</td>
</tr>
<tr>
<td>62</td>
<td>138.5</td>
<td>120.0</td>
<td>90.0</td>
</tr>
<tr>
<td>62</td>
<td>130.2</td>
<td>94.5</td>
<td>72.0</td>
</tr>
<tr>
<td>62</td>
<td>135.7</td>
<td>130.2</td>
<td>99.0</td>
</tr>
<tr>
<td>62</td>
<td>156.0</td>
<td>125.0</td>
<td>90.5</td>
</tr>
<tr>
<td>125</td>
<td>140.0</td>
<td>101.0</td>
<td>75.0</td>
</tr>
<tr>
<td>125</td>
<td>140.0</td>
<td>118.0</td>
<td>90.0</td>
</tr>
<tr>
<td>125</td>
<td>140.0</td>
<td>133.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

### 34. Effect of Condenser Capacitance on Indications.

Experience has shown that the capacitance of the condenser, across which the galvanometer and its series multiplier is connected, may have an effect on the indication of the galvanometer. Table 6 shows this effect. It will be noted that the lower the fundamental frequency, the larger is the limiting value of the capacitance.
Fig. 17.

**Check of "Type B" Crest Voltmeter against "Type A" Voltmeter**

- +25 Cycles.
- O 62 "
- • 125 "

**Indications "Type A" Voltmeter**

- 140
- 130
- 120
- 110
- 100
- 90
- 80
- 70
- 60
- 50
- 40
- 30
- 20
- 10
- 0

**Indications "Type B" Voltmeter**

- 0
- 10
- 20
- 30
- 40
- 50
- 60
- 70
- 80
- 90
- 100
### TABLE 6.

Effect of Condenser Capacitance on Indications of "Type B" Crest Voltmeter.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Capacitance</th>
<th>Crest Voltmeter Ind.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycles</td>
<td>Microfarads</td>
<td>&quot;Type A&quot;</td>
</tr>
<tr>
<td>25</td>
<td>0.1</td>
<td>122.5</td>
</tr>
<tr>
<td>25</td>
<td>0.2</td>
<td>122.5</td>
</tr>
<tr>
<td>25</td>
<td>0.4</td>
<td>122.5</td>
</tr>
<tr>
<td>25</td>
<td>0.5</td>
<td>122.5</td>
</tr>
<tr>
<td>25</td>
<td>0.9</td>
<td>122.5</td>
</tr>
<tr>
<td>62</td>
<td>0</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.001</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.002</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.005</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.010</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.015</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.020</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.030</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.044</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.05</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.07</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.10</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.15</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.20</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.5</td>
<td>122.3</td>
</tr>
<tr>
<td>62</td>
<td>0.9</td>
<td>122.3</td>
</tr>
<tr>
<td>125</td>
<td>0</td>
<td>118.0</td>
</tr>
<tr>
<td>125</td>
<td>0.005</td>
<td>118.0</td>
</tr>
<tr>
<td>125</td>
<td>0.05</td>
<td>118.0</td>
</tr>
<tr>
<td>125</td>
<td>0.10</td>
<td>118.0</td>
</tr>
<tr>
<td>125</td>
<td>0.2</td>
<td>118.0</td>
</tr>
<tr>
<td>125</td>
<td>0.3</td>
<td>118.0</td>
</tr>
<tr>
<td>125</td>
<td>0.5</td>
<td>118.0</td>
</tr>
<tr>
<td>125</td>
<td>0.9</td>
<td>118.0</td>
</tr>
</tbody>
</table>
D. Conclusion.

35. Characteristics to be Desired in a Crest Voltmeter.

A study of the various types of crest voltmeters and of the purposes for which they may be used shows that the ideal instrument should have the following characteristics.

(a) It should be portable and require very little energy to operate it. This would serve a two-fold purpose. It makes the meter available for the use of inspectors and it would enable it to be used in cases where the available power is small.¹

(b) It should be easily calibrated and should require no adjusting while it is being used. The first is of prime importance where it is necessary to convince an inspector that the indication of the meter is correct. The second characteristic would eliminate contact devices which have always proven a source of trouble. The wave form is very likely to change with load and it would be very difficult to obtain the crest reading in certain cases before puncture had occurred.

(c) It should be possible to operate the meter directly from the high tension bus or through a voltage transformer.

(d) It should be available for high (radio) frequencies. The use of the oscillation transformer and impact tests is becoming general and it is necessary to have a method which can be used in such tests.

(e) It should not be necessary to make a correction for frequency, nor should there be a possibility of the meter giving erroneous readings on any form of wave.

¹. See §30, page 41.
(f) The meter should follow fluctuations in the voltage. Under certain conditions the circuit may be very sensitive to slight changes in frequency. If the voltmeter does not respond to these changes, the actual voltage on the material may be considerably lower than the meter indicates.

(g) The meter should give crest factor as well as crest voltage. By so doing one has a better knowledge of the conditions existing in the circuit and anything abnormal will be discovered earlier.

36. Comparison of Types "A" and "B".

A comparison of the characteristics of the "Type A" and the "Type B" crest voltmeter with those of the previous section shows that the "Type A" measures up to the standards very well. It has a low power consumption, the kenotron filament taking about 16 watts. This energy may be taken from any circuit, however. There are no moving parts other than the instrument. It is easily calibrated on either alternating or direct current. It is portable and has no frequency error. Crest factor may be obtained as easily as crest voltage. On the other hand it is impossible to get an electrostatic voltmeter which will compare at all favorably in damping with an instrument of the D'Arsonval type. It will either be too sluggish from overdamping or it will oscillate back and forth. The "Type A" from its mode of operation can not follow fluctuations in the voltage. It must be watched for this reason. The principal advantages of the "Type B" over the "Type A" is the employment of the D'Arsonval movement, affording better damping and the ability to follow voltage
fluctuations. The ability to read virtual volts has to be sacrificed. The qualities of portability, etc. are common to both types.

37. Possible Further Applications of "A" and "B" Crest Voltmeters.

It is possible that the quality of holding the maximum voltage for an appreciable time may enable the "Type A" device to be used as a transient voltage recorder. Very little work has been done so far along this line, but it is hoped to do so later.

It will be seen that the omission of the condenser from the "Type B" set up makes an instrument which will read the average value of a wave. This in connection with a dynamometer type voltmeter affords a method for easily determining form factor.

38. Summary.

The need of a crest voltmeter has been shown. The various types so far proposed have been studied and their limitations noted. Some new types are described in detail. It is felt that they possess advantages over the earlier types, particularly for the testing of electric cables and for high voltage special work.
PART II.

Appendix 1. Directions for Setting Up and Using the "Type A" Crest Voltmeter.

1. Adjustments.

The apparatus should be connected as shown in fig. 11. The kenotron filament may be heated with either alternating or direct current. If the former it should preferably be taken from the same source as the voltage to be investigated. All wires should be so arranged as to afford no chance for grounds. It is well to use bare wires so that any faults will be perfectly definite and so be quickly located.

In the absence of any other method of checking up the relative polarities of the two voltages, the following method may be used. Connect up the apparatus and take a reading of crest voltage. Reverse the direction of current through the filament and take another reading keeping the other conditions as before. That connection which gives the lower crest voltage is the correct one to use.

The capacitance of the shunting condenser may require adjustment when the set up is first made owing to the insulation of the various parts changing. The capacitance should be entirely cut out and gradually increased. As this is done the crest voltage indication will increase for a time and then gradually decrease, due to the limitations of the kenotron. The capacitance should be cut down to a value slightly lower than that causing the drop in voltage.

2. Using the Crest Voltmeter.

In using the voltmeter for "pressure tests" it is well to
read the virtual volts from time to time by shortcircuiting the kenotron. If it is desired to check the crest value without allowing the voltmeter indication to drop back to the virtual value, it can be done by momentarily increasing the capacitance of the shunting condenser. This will disturb the potential of the condenser and it will take the voltmeter an appreciable time to reach a maximum indication again.
Appendix 2.
Kenotron Characteristics and their Effect on the Operation of the Crest Voltmeter.

The kenotron is a development of the Research Laboratory of the General Electric Company and its characteristics have been described at length by the various members of its staff. They are repeated here in so far as they have an effect on the operation of the crest voltmeter.

The kenotron is an electric valve very similar to that invented by Dr. Fleming. It has a heated filament and a metal plate anode. It differs from the Fleming valve in that its operation is due to a pure electron discharge, whereas the latter depends on the presence of a minute quantity of gas for its operation.

If a constant voltage be applied between the anode and the cathode and the temperature of the filament be raised gradually, the current through the valve will increase according to the Richardson equation

\[ i = a\sqrt{T} e^{-\frac{b}{T}} \]

where \( a \) and \( b \) are constants for the particular metal used, \( T \) is the absolute temperature of the filament and \( e \) is the base of the Napierian system of logarithms. The above equation will hold if the voltage is high enough to overcome the "space charge voltage". This differs with changes in the dimensions of the filament and plate and it limits the current to a value

\[ i_s = k \sqrt{\frac{V}{r}} \]

1. Bibliography No. 21.
where $k$ is a constant depending on the dimensions of the kenotron and $V$ is the impressed voltage. Fig. 18 shows the variation of current through a kenotron with filament temperature and voltage.

The effect of the above characteristics on the crest voltmeter can be best seen from a study of the three cases,

(a) when operating on direct current

(b) when operating on alternating current with a perfectly insulated voltmeter

(c) when operating on alternating current with a poorly insulated voltmeter.

Both the Richardson effect and the space charge effect can be replaced by equivalent resistances. The first limits the current to a constant value, i.e. $R' = k E^{-1}$. On the other hand current as limited by the space charge varies as the $1.5$ power of the voltage so the "space charge resistance" $R'' = k' E^{0.5}$. Since the two effects can not exist simultaneously, they will be replaced in the following discussion by a resistance $R^o$.

If direct current be impressed on the crest voltmeter (of the "A" type) with perfect insulation, the electrostatic voltmeter will gradually become charged to the impressed voltage. The value of $R^o$ will have no effect other than to limit the time for the voltmeter to become fully charged. If the insulation of the voltmeter be low (or if the meter be of the "B" type) the resistance $R^o$ enters directly. The final indication of the voltmeter can not exceed $\frac{R}{R+R^o}$ of the impressed voltage, where $R$ is the insulation resistance of the voltmeter.

If alternating current be impressed on a voltmeter
FIG. 18.

VOLT-AMPERE CHARACTERISTICS OF A KENOTRON

(V = 129)
(V = 114.5)
(V = 107)
(V = 87.5)
(V = 77.5)
(V = 67.5)
(V = 55.5)
(V = 47)
(V = 35)

140 MILLIAMPERES.

130

120

110

100

90

80

70

60

50

40

30

20

10

0

2100 2200 2300 2400 2500

DEGREES-KELVIN

(G.E. Review Mar. 1915)
having perfect insulation, the final indication is independent of
the resistance of the valve. Rectification occurs in the valve and
the behavior of the voltmeter is the same as if direct current were
impressed on the circuit. On the other hand where the insulation is
low it is practically impossible to predetermine the performance of
the crest voltmeter on alternating current. The following case has
been worked out for the case of sine waves and a perfect valve. The
circuit is shown in fig. 19 (a). "K" is a kenotron, "S" is a switch
which may be used to short circuit "K", "C" is a condenser which has
a voltmeter in shunt with it and "R" is the shunting insulation re-
sistance. If a sine wave of voltage be impressed on the circuit
("S" being closed) current will flow through the circuit and will
divide as indicated in fig. 19 (b), where "e" is the voltage, "i_r" is
the leakage current and "i_c" the current through the condenser.
If "S" be opened, current will pass through the valve as long as it
is positive. As soon as it reaches a zero value it will be inter-
rupted. This will occur when the instantaneous values of "i_r" and
"i_c" are equal but of opposite sign. The time when this will
occur is found as follows.

Let \( e = E \sin pt \) \hspace{1cm} (1)

Then \( i_r = \frac{E}{R} \sin pt \) \hspace{1cm} (2)

and \( i_c = CE \cos pt \) \hspace{1cm} (3)

Equating (2) and (3) and placing the negative sign before the second
member of the equation,

\[
\frac{E}{R} \sin pt = - CE \cos pt \tag{4}
\]

or \( \tan pt = -CR \)
LAB 4. CHECK INPUT SIGNAL EFFECT ON TRANSISTOR ZIP Vb
As soon as the time $t'$ is reached (where $t' = \frac{\arctan(-CR)}{p}$)
the condenser begins to discharge and the voltage of the condenser
follows the equation

$$e = \sin \arctan(-CR) \epsilon \frac{t-t'}{CR}$$

This will continue until the condenser voltage is the same as the
line voltage (as shown at "b" in fig.19-b) when the line voltage
will again be able to send current through the valve. As a conse-
quence, the voltage on the condenser and voltmeter will vary as in-
dicated by the heavy line. If the voltmeter is an electrostatic
meter, the indication will be the root mean square of this voltage,
whereas a D'Arsonval instrument (such as would be used with the
"Type B") would give an average reading.

It is obvious that the shape of this curve will depend
on the capacitance, insulation resistance, frequency, etc. The high-
er the insulation resistance, the nearer the crest voltage will the
point "b" occur.

The limitations of the kenotron are most pronounced in
trying to develop a transient voltage indicator.

Let $t = \text{duration of maximum value of a transient volt-
age } E$

and $C = \text{the capacitance of the condenser}$

The average current which will have to pass through the kenotron
will be

$$i = CE/t$$

Particular care must be taken that this current does not approach
the saturation current of the valve and that the space charge volt-
age is low compared with E.

If the filament of a kenotron be heated with direct current and a high resistance voltmeter (preferably a megohm resistance and a galvanometer) be connected between the negative end of the filament and the anode it will be found that the cathode will be at a potential of from 1 to 2 volts above the anode. If the lead to the cathode be transferred to the positive end it will be found that the voltmeter will indicate the voltage consumed by the filament, the relative polarities of the anode plate and the filament remaining as before. In all of the tests which have been made by the writer the first effect has never been noticed except in those cases where voltage impressed on the valve was zero. The other effect is always present and must be guarded against. The test is very simple and has been given in Appendix 1. In every case the difference between the two maximum voltage readings has been found to equal the filament voltage.

Where it is necessary to use alternating current of a frequency different from the voltage being tested, this effect can not be eliminated. A correction must therefore be applied. If alternating current of the same frequency but having a phase difference is used, the effect can be made almost negligible. The voltage on the valve is the resultant of the filament voltage and the test voltage. By reversals the two can always be kept within 90° of each other. Assuming that they are 90° apart and that the filament voltage is 12% of the test voltage gives a resultant of

$$100 + 0.12 = 101.4$$

or an error of 1.4%. 
Appendix 3. Possibility of Using Other Valves.

During the investigation, of which this thesis is a summary, a number of attempts were made to use valves other than the kenotron. One of the first valves used was a small DeForest audion. It gave results about 1 percent low on sine waves. No tests were made on distorted waves.

Another fairly satisfactory valve was made by the Edison Lamp Works of the General Electric Co. It consisted of two coiled filaments supported one half inch apart from opposite ends of a lamp bulb, which had been well evacuated. Readings with this valve were 3 percent low on sine waves and 5 percent low on waves similar to that shown in fig.13 (c).
Appendix 4. High Voltage Multipliers.

While the crest voltmeter has been used directly on voltages as high as 100,000 by Peek, the device is most satisfactory when used at low voltages (less than 500 volts). Since crest factor is generally desired on a high tension wave, it is necessary to reduce the voltage without changing its wave form. Work has shown that the voltage from a tertiary coil on the transformer has the same wave shape as the secondary voltage within a very small percentage. However, few transformers have this coil and since voltage transformers for high voltages are prohibited by their large size and high cost, other means must be provided.

A volt box arrangement is immediately suggested. The general scheme is shown in fig. 20 (a). Two impedances are connected in series between the voltage and ground, the voltmeter being tapped off between the common point and ground. In general the impedances may have inductive or capacity reactance or they may be pure resistances. It is not necessary that the impedance be uniformly distributed. It may be "lumped" as shown in fig. 20 (b). The ratios of the reactance to the resistance of the two sections must be the same however or the voltage across the low voltage section will have a different wave form from that of the line.

Certain types of multipliers have advantages for specific cases. The condenser type takes a large leading current, but very little energy current. Its use is limited to comparatively low frequencies. The resistance type dissipates considerable power at high

1. Bibliography No. 22.
(a) Distributed Impedance.

(b) Lumped Capacity

(c) Air Condenser with Guard Ring.

FIG. 20

HIGH VOLTAGE MULTIPLIERS.
voltages, but may be used to very good advantages in cases where the loss of power is not objectionable or where the presence of a condenser would change the conditions of the test. There seems to be no use for the reactance type of multiplier at any but the lower voltages. Here it has no advantages over the voltage transformer and would not be used.

The principal advantage of the condenser type outside of the low power consumption, is the ease with which it may be constructed. Sharp and Farmer\(^1\) have used one consisting of a series of glass plate condensers connected in series and immersed in a tank of oil. It is possible in an emergency to use several sheets of galvanized iron with air as the dielectric. Whenever a train of condensers are connected in series there is a possibility that they will puncture and the entire voltage be impressed on the low voltage condenser. A film cut out (such as is used with series incandescent lamps) in parallel with the low voltage condenser will protect the voltmeter etc. but there would be a question as to the admittance of that section. There is also a possibility that the admittance of the high voltage section may change with voltage due to corona or change in capacitance.

A condenser with air as a dielectric may be made free of the above objections if it is properly designed. Such a condenser is shown in outline in fig. 20 (c). It consists of a central plate condenser surrounded with a guard ring which is connected to earth. The relative dielectric flux densities are such that the guard ring will always arc over sooner than the center plate. The guard ring

\(^1\) Bibliography No. 15.
also eliminates any fringeing of the lines at the edge of the center plate and thereby makes the capacitance of the center part inversely proportional to the spacing.

The following design has been made for an air condenser to be used with the "Type A" crest voltmeter described on page 31. The conditions to be met are,

(a) Device to operate at 200 000 volts(max.) to ground.

(b) Crest factor to be obtained with an accuracy of 0.5%.

The voltmeter has a capacitance of 1.6 \times 10^{-10} \text{ farads}, while its maximum indication is 250 volts. If crest factor is to be determined with an accuracy of 0.5 percent, the capacitance of the voltmeter should not be more than 0.2 percent of the low voltage condenser to allow for errors in reading the instrument. The low voltage condenser must have a capacitance of not less than

\[
\frac{1.6 \times 10^{-10} \text{ farads}}{0.2 \%} = 8 \times 10^{-8} \text{ farads}, \text{ or approximately } 0.1 \text{ mf.}
\]

The capacitance of the high voltage section will be

\[
\frac{250 \times 0.1}{200 \text{ 000}} = 1.25 \times 10^{-4} \text{ microfarads.}
\]

Experiments having shown that the ultimate dielectric strength of air is 30 kilovolts(max) per centimeter, the minimum spacing allowable for 200 000 volts would be 6.67 cm, or using a factor of safety of 2.5, the spacing would be 16 centimeters.

The edges of the plates must be turned up to eliminate flux concentration. A convenient form both from the standpoint of calculation and construction is cylindrical sides and spherical corners. Peek has stated that corona will not form before spark over where
S/r is less than 5.85,
S being the distance between center lines of the cylinders and r being the radius. For the present case the limiting radius is 4.15 cm. but as the 25 cm. sphere gap has been adopted as a standard size r = 12.5 will be used.

The capacitance of parallel plates is given by the following equation where "C" is in microfarads, and the area "A" and spacing "s" are in sq.cm. and cm. respectively.

\[ C = \frac{8.84 \times 10^{-8}}{s} A \]

Hence for a capacitance of 1.25 x 10^{-4} microfarads with a spacing of 16 cm. the area must be 22 600 sq.cm. or since 150 by 150 cm. is a convenient size, the latter will be used.

The following tables have been worked out to show the capacitance and spark over voltage of the various parts of the condenser. The work has been done by the aid of the tables and formulae contained in Peek's "Dielectric Phenomena in High Voltage Engineering". It will be noted that the capacitance of the guard circuit becomes more and more prominent at the greater spacings and that the guard ring will always divert the arc overs away from the plates.
TABLE 7.

Variation of Capacitance of Air Condenser with Spacing.

<table>
<thead>
<tr>
<th>Operating Voltage</th>
<th>Spacing Cm.</th>
<th>Capacitance, Farads x 10⁻¹²</th>
<th>Plates</th>
<th>Cylinders</th>
<th>Spheres</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 000</td>
<td>0.4</td>
<td></td>
<td>4980</td>
<td>462</td>
<td>20</td>
<td>5462</td>
</tr>
<tr>
<td>10 000</td>
<td>0.8</td>
<td></td>
<td>2490</td>
<td>330</td>
<td>12</td>
<td>2832</td>
</tr>
<tr>
<td>20 000</td>
<td>1.6</td>
<td></td>
<td>1245</td>
<td>234</td>
<td>11</td>
<td>1490</td>
</tr>
<tr>
<td>40 000</td>
<td>3.2</td>
<td></td>
<td>622</td>
<td>165</td>
<td>10</td>
<td>797</td>
</tr>
<tr>
<td>60 000</td>
<td>4.8</td>
<td></td>
<td>415</td>
<td>136</td>
<td>10</td>
<td>561</td>
</tr>
<tr>
<td>80 000</td>
<td>6.4</td>
<td></td>
<td>311</td>
<td>119</td>
<td>9</td>
<td>439</td>
</tr>
<tr>
<td>100 000</td>
<td>8.0</td>
<td></td>
<td>249</td>
<td>107</td>
<td>9</td>
<td>365</td>
</tr>
<tr>
<td>150 000</td>
<td>12.0</td>
<td></td>
<td>166</td>
<td>88</td>
<td>8</td>
<td>262</td>
</tr>
<tr>
<td>200 000</td>
<td>16.0</td>
<td></td>
<td>124</td>
<td>78</td>
<td>8</td>
<td>210</td>
</tr>
<tr>
<td>300 000</td>
<td>24.0</td>
<td></td>
<td>83</td>
<td>65</td>
<td>7</td>
<td>155</td>
</tr>
<tr>
<td>400 000</td>
<td>32.0</td>
<td></td>
<td>62</td>
<td>60</td>
<td>7</td>
<td>129</td>
</tr>
<tr>
<td>500 000</td>
<td>40.0</td>
<td></td>
<td>50</td>
<td>52</td>
<td>6</td>
<td>108</td>
</tr>
</tbody>
</table>

TABLE 8.

Variation of Spark-over Voltage of Condenser with Spacing.

<table>
<thead>
<tr>
<th>Operating Voltage</th>
<th>Spacing Cm.</th>
<th>Spark-over Voltage, Kv. (Max.)</th>
<th>Plates</th>
<th>Cylinders</th>
<th>Spheres</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 000</td>
<td>0.4</td>
<td></td>
<td>12</td>
<td>12</td>
<td>9</td>
</tr>
<tr>
<td>10 000</td>
<td>0.8</td>
<td></td>
<td>24</td>
<td>23</td>
<td>17</td>
</tr>
<tr>
<td>20 000</td>
<td>1.6</td>
<td></td>
<td>48</td>
<td>47</td>
<td>32</td>
</tr>
<tr>
<td>40 000</td>
<td>3.2</td>
<td></td>
<td>96</td>
<td>94</td>
<td>62</td>
</tr>
<tr>
<td>60 000</td>
<td>4.8</td>
<td></td>
<td>144</td>
<td>134</td>
<td>90</td>
</tr>
<tr>
<td>80 000</td>
<td>6.4</td>
<td></td>
<td>192</td>
<td>177</td>
<td>115</td>
</tr>
<tr>
<td>100 000</td>
<td>8.0</td>
<td></td>
<td>240</td>
<td>218</td>
<td>140</td>
</tr>
<tr>
<td>150 000</td>
<td>12.0</td>
<td></td>
<td>360</td>
<td>312</td>
<td>191</td>
</tr>
<tr>
<td>200 000</td>
<td>16.0</td>
<td></td>
<td>480</td>
<td>400</td>
<td>228</td>
</tr>
<tr>
<td>300 000</td>
<td>24.0</td>
<td></td>
<td>720</td>
<td>552</td>
<td>275</td>
</tr>
<tr>
<td>400 000</td>
<td>32.0</td>
<td></td>
<td>960</td>
<td>681</td>
<td>310</td>
</tr>
<tr>
<td>500 000</td>
<td>40.0</td>
<td></td>
<td>1600</td>
<td>800</td>
<td>325</td>
</tr>
</tbody>
</table>
There are cases where the condenser type of multiplier can not be used. The resistor type may be of use in such cases. Several forms are available. One is the water tube resistance. If such a one is used provision must be made for the water boiling. A convenient form is a U tube connected at top and bottom with special cooling on one branch. The low voltage section must be in the same tube for otherwise the variation in the temperature of the water would affect the calibration of the unit.

Hull has described a very compact resistance which he has used as a multiplier for a d.c. voltmeter on 100 000 volts. It consists of 1000 voltmeter resistance coils each having 10 000 ohms resistance. They are mounted on hard wood lattices, 100 to a lattice, the 10 lattices being spaced three inches apart and individual coils 1/2 inch apart. The whole outfit is immersed in a tank of oil. If the capacitance of the various coils against earth can be made negligible this arrangement should be very convenient for crest voltmeter work.

A comparison of the kva. of the air condenser and the kw. of the resistor type is of interest. The air condenser when set for 200 000 volts 60 cycles takes a total of 3.2 kva. Assuming that Hull's type of resistance could be used for the same voltage, it would consume 2 kw.

As has been suggested there is no field for an inductance type multiplier. At first sight it would seem that it might be used with an oscillation transformer which has a natural frequency of from

100 000 to 300 000 cycles. Such is not the case. If an inductance were made up of 10 000 turns of No.20 AWG. copper wire each turn having a diameter of 30 cm. the inductance with the separate turns touching each other would only be 3.3 henrys. At 100 000 volts 200 000 cycles the current would be 0.048 amperes or a total of 48 kva. As the output of an oscillation transformer is limited to a value considerably below this the arrangement is out of the question.
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