A Portable Instrument for Measuring Insulation Resistance at High Voltage

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THERE has been an increasing trend toward measuring insulation resistance of high-voltage machines and cables at or above their rated voltage by the use of direct current. The advantage of high voltage lies in its ability to detect leakage paths which do not occur at lower voltages.[1] D-c tests are advantageous because of the elimination of capacitance-current effects. Since the resistances measured are usually quite high—of the order of megohms—if high-voltage alternating current is used to test insulation, even small load capacitances offer impedances low enough to mask the insulation-resistance effect.

Considerable information on insulation resistance, dielectric absorption, and dielectric strength resulting from the use of high-voltage direct current has been obtained from large heavy rectifier sets either permanently installed or mounted on a truck.[2] A ten-year study by Davis and Leftwich[3] indicates that through the use of high-voltage d-c testing much knowledge can be gained concerning the cause of high-voltage generator insulation failures. They report that a majority of generator failures are traceable to mechanical defects, many of which were detected and located before failure in service. Other investigations have explored the field with lower voltages of the order of 500 to 1,000 volts direct current.[4,5]

The study of insulation resistance at high voltages has been restricted by the type of equipment available, which has involved transportation problems and has been very costly. There is considerable evidence that the availability of a portable tester of suitable characteristics would greatly stimulate collection of such data throughout the industry. A suitable portable instrument of rugged construction recently has been made possible by the development of a new cold-cathode rectifier tube. Because a cold-cathode tube requires no cathode heating power, it is well adapted to those applications.

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New Cold-Cathode Rectifier Tube

Rectifier tubes employed in this test instrument belong to a new family of high-voltage rectifiers which do not require heated cathodes.[6] They are gas-filled diodes in which the cathodes are composed of an array of fine wire points. The cathode, when negative, discharges to the anode which consists of a fired-on graphite coating on the interior of the Pyrex-glass envelope.

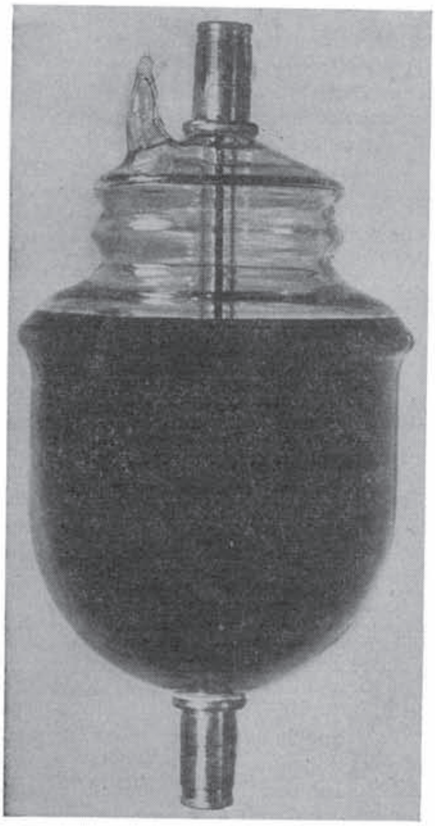


Figure 1 (above). Takktron type 60.8 high-voltage rectifier tube (cold-cathode)

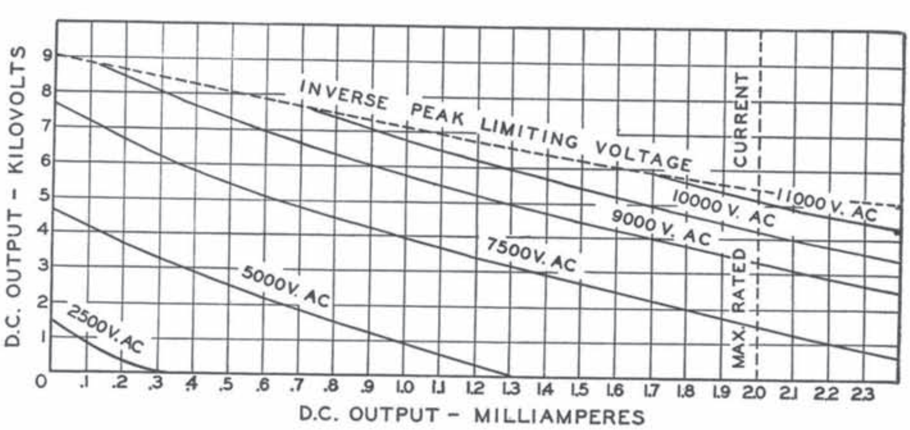
By controlling the pressure and composition of the gas, the number of points in the cathode, and the anode–cathode spacing, it is possible to provide a wide range of rectifying characteristics. Present standardized tube models will provide d-c outputs up to 25 kv and currents up to ten milliamperes in half-wave circuits.

These tubes are particularly suited for cascade voltage-multiplying circuits since no filament-transformer insulation problems are encountered.[7] Also it is possible to reverse the high-voltage output polarity merely by reversing each tube in its mounting. By use of such voltage-multiplying circuits, practical power units producing up to 200 kv have been built. Even higher voltages are feasible. Such high-voltage power units are characterized by light weight, compactness, and air insulation in the high-voltage portion of the unit. Small high-voltage transformers are used since the maximum alternating voltage required is 30 kv rms.

These tubes are not damaged if their maximum inverse peak voltages are exceeded. Under this condition soft diffuse discharges take place between the cathode and the anode without damaging the tube or its characteristics. Complete short-circuiting of the output of this type of tube, or of a power unit employing the tube, likewise has no harmful effects. The absence of a hot cathode implies no deterioration during idle periods and the ability of the tube to start instantly upon the application of power.

These desirable self-protective properties are gained from the internal resistance of the tube. This resistance has little effect on the output-voltage regulation for load currents within the current rating of the tube. Beyond this value, however, the tube resistance becomes large enough to protect both the tube and the high-voltage transformer. This tube resistance is also advantageous in that it

Figure 2. Voltage–current characteristics of Takktron type 60.8 tube



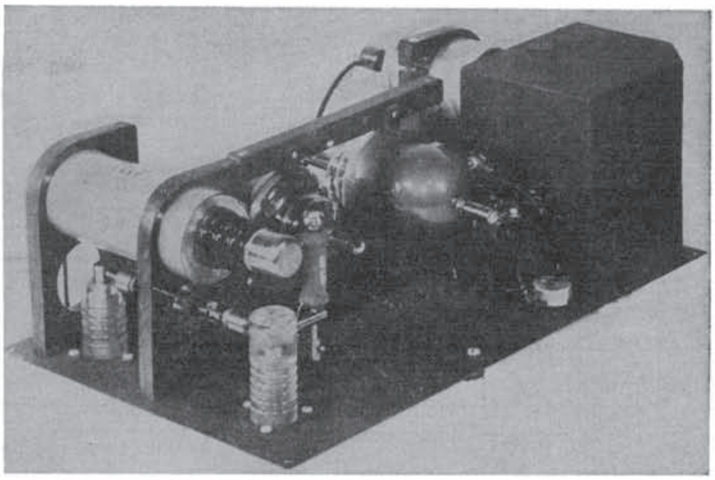


Figure 3 (left). Panel view of aircraft-ignition-cable tester

Figure 4. Interior view of tester illustrating ample clearances, rugged construction, and inherent simplicity

aids the filtering of the output voltage, and only small filter capacitances are needed for low-output ripple voltage.

The Takktron type 60.8 rectifier tube shown in Figure 1 has a maximum inverse peak-voltage rating of 21 kv. Its direct output current and voltage characteristics for various alternating input voltages are shown in Figure 2. This tube is designed for a maximum output current of two milliamperes and at this current will provide a direct voltage of five kilovolts. At "no load" the tube will deliver nine kilovolts direct current.

The tube is air-cooled and is mounted in an insulating ring support by means of three rubber *V* blocks equally spaced around the periphery of the enlarged section of the envelope. The tube terminals and the terminal connectors are designed to be free of corona at the tube potentials.

The physical dimensions of the Takktron type 60.8 tube are as follows:

(*a*). Over-all length...........6$^1/_4$ inches
(*b*). Length of envelope........4$^1/_2$ inches
(*c*). Maximum diameter of envelope...............3$^1/_4$ inches

Use in Testing Aircraft-Ignition Cable

To assist in evaluating the performance of aircraft-ignition systems, the instrument shown in Figure 3 was developed to measure the insulation resistance of cables and other ignition parts such as magnetos, distributor blocks, heads, fingers, sleeves, and plates at or above their operating voltages. The range of the instrument is 10 to 10,000 megohms measured at any voltage between 2,500 and 15,000 volts. The outside dimensions of the instrument are 10 by 11$^1/_2$ by 18$^1/_2$ inches, and it weighs 31 pounds.

An interior view shown in Figure 4 illustrates the rugged construction of the unit. A schematic diagram is shown in Figure 5. The input to the high-voltage transformer is controlled by a variable autotransformer. The secondary voltage is fed into a voltage-doubling circuit, which is filtered by a 15,000-volt 0.02-microfarad-output capacitor. An adjustable spark gap is provided to prevent overstressing of component parts as well as to limit the output voltage. In series with the gap is a 10,000-ohm resistor to reduce high current surges during flashover. The kilovoltmeter is connected across the high-voltage output of the rectifier.

In series with the grounded terminal is a current instrument with 0–100- and 0–500-microampere scales. A neon glow lamp is shunted across the current-instrument circuit in such a manner that leakage currents in excess of either current range will cause it to flash. This also will occur when current pulses in excess of 100 microamperes or 500 microamperes are of such short duration that the current-instrument pointer is not deflected because of its mechanical inertia. In addition the neon glow lamp serves to protect the sensitive current instrument against short-circuit currents encountered with faulty insulation.

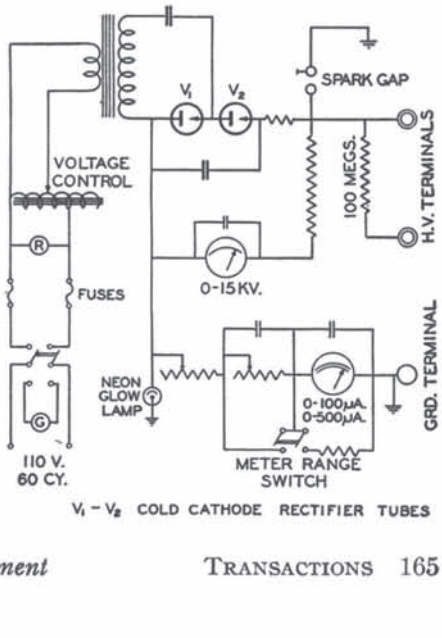
Two high-voltage output terminals are provided, one connected directly to the power supply and the other through a 100-megohm series resistor. The output voltage of the directly connected terminal is indicated by the kilovoltmeter. Figure 6 shows a typical voltage-regulation curve from no load to short-circuit current without adjustment of the voltage control. Because of the tube characteristics the instrument is not damaged when this output terminal is short-circuited at full voltage. The "off–on" switch also may be operated under short-circuit conditions without harm. This terminal is especially useful in both dielectric-absorption and dielectric-breakdown tests. Insulation resistance in megohms may be determined from the expression:

$$\frac{\text{Kilovolt reading} \times 1{,}000}{\text{microamperes}}$$

The value of the neon-lamp resistor may be neglected since it is approximately 0.5 megohm.

The other high-voltage output terminal is used where it is desirable to limit the current in the test specimen. With the internal 100-megohm resistor the voltage across the test specimen is inversely proportional to the leakage current. Figure 7 shows the voltage-regulation curve of this circuit. If the insulation is in perfect condition and therefore has low leakage current, the test voltage is approximately that indicated by the kilovoltmeter. Since aircraft-ignition harness usually is tested at voltages between 10 and 12 kv, the instrument is calibrated in megohms in this voltage

Figure 5. Circuit diagram of aircraft-ignition-cable testers



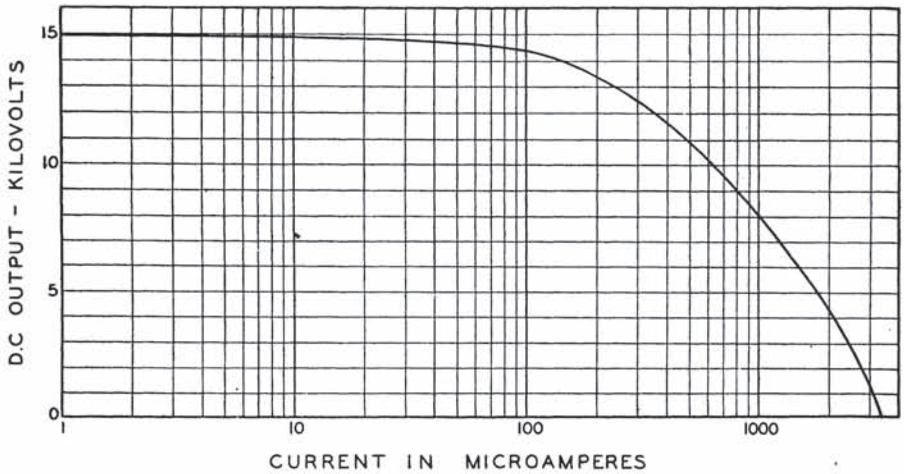


Figure 6. Voltage-regulation curve of aircraft-ignition-cable tester when series resistor is not used

Voltage adjustment unchanged

range. To determine the insulation resistance, the voltage is raised to the test value (indicated by a red dot on the voltmeter scale), the leakage current is noted, and the corresponding resistance is read on the calibration chart on the face of the instrument. Figure 8 shows a typical calibration curve. For other test voltages insulation resistance in megohms may be calculated from the expression:

$$\frac{\text{Kilovolt reading}\times 1{,}000}{\text{microamperes}} - 100$$

Since the rectifier tubes are not in the instrument circuit, it is not necessary to readjust these instruments when replacing tubes.

The series resistance increases the personal safety to the operator, and for this reason instruments with this circuit only are recommended for use by airplane mechanics or others not familiar with high-voltage testing procedures.

Where it is desired to operate the unit from a storage battery, a self-contained vibrator–inverter has been designed to supply 110 volts alternating current from a 12- or 24-volt d-c source. Since no filament power is required, the inverter and the battery drain are small.

Exploratory Work in Industrial Field

Although this instrument now is used primarily for testing aircraft-ignition cable, some exploratory work with it has been done in the industrial field to determine test requirements there. Insulation-resistance and dielectric-absorption measurements have been made on sections of a 25,000-kva 6,900-volt-class vertical water-wheel generator. The winding-to-ground capacitance of this generator is approximately 0.13 microfarad per section or 0.4 microfarad for the entire machine.

Figure 9 shows the dielectric-absorption curves at 10,000 volts for each section and for the entire machine.

Testing Cable

Insulation resistance of a 350,000-circular-mil three-conductor impregnated-paper compound-filled lead-sheath cable, rated at 15 kv, 18,385 feet long ($3^1/_2$ miles), was measured with the instrument shown in Figure 3. Test results were as shown in Table I.

Table I. Insulation Resistance of 350,000-Circular-Mil Three-Conductor Impregnated-Paper Compound-Filled Lead-Sheath Cable Rated at 15 Kv; 18,385 Feet ($3^1/_2$ Miles) Long

AT-13	Voltage, Kv	TAKK Tester (Current, Microamperes)	Resistance, Megohms
Phase *A* to ground	14.8	60	246
Phase *B* to ground	14.0	62	226
Phase *C* to ground	13.8	42	328
A to *B*	14.5	74	196
B to *C*	14.0	57	246
C to *A**	14.5	70	206

* Nothing grounded.

These and other tests indicate that for the industrial field other current–instrument ranges would be desirable. Possible ranges might include a unit for measuring insulation resistance at 2,500, 5,000, 10,000, and 15,000 volts with current ranges of 0–25 microamperes, 0–250 microamperes, and 0–2,500 microamperes. This would result in a unit with an insulation-resistance range from one-half to 30,000 megohms. Other portable testers

Figure 7. Output voltage versus leakage current when series resistor is used

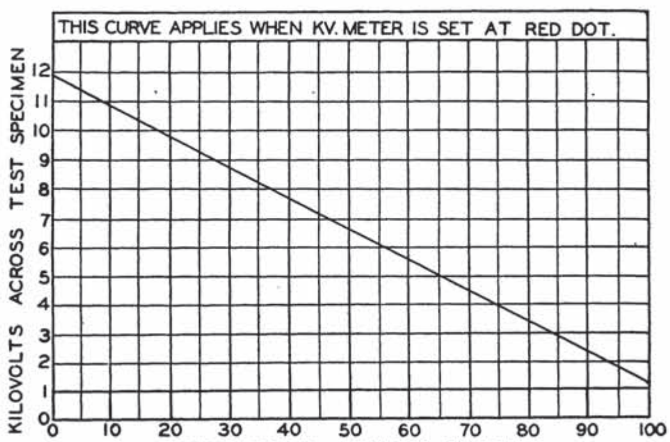
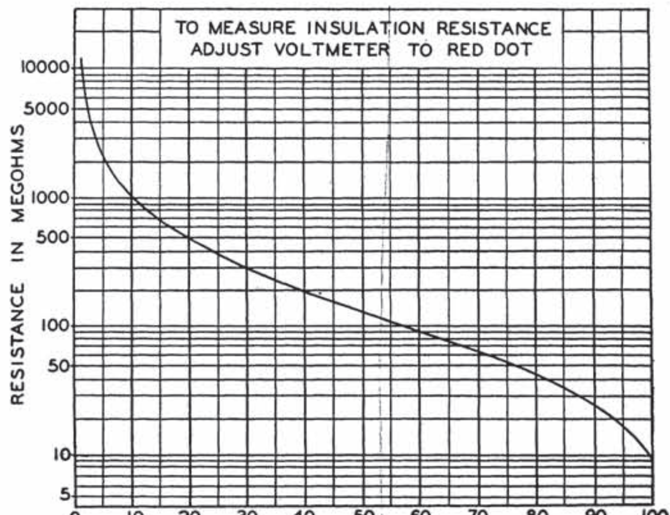


Figure 8. Typical instrument-calibration curve of aircraft-ignition-cable tester when protective resistance is used



Standards and Insulation Characteristics of Oil-Insulated Transformers

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THE STRENGTH of the insulation in transformers to resist various types of voltage stress is very important. The service and life of the transformer is partially dependent on the insulation strength, and in recognition of this fact standards for insulation strength long have been established. In the course of time improvements have taken place in design, new applications have been created, and more has been learned about the nature of stresses which arise in service. Service conditions, too, probably will change in the future, which will require changes in insulation requirements. Therefore it is natural that gradual changes in the standards, and additions to them, have taken place, with the result that sometimes they are not entirely consistent. It is desired in this paper to point out some inconsistencies and propose certain changes in the standards which might be given consideration.

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Partial History of Insulation Requirements

For the purpose of this paper, it is necessary to recall that at one time the standards required a test on the major insulation of two times the rated voltage plus 1,000 volts, and an induced test of two times the winding voltage, with minimum values specified. One of the additions to the standards arose from the electrification of railroads. Railroads use a grounded single-phase system, which led to the use of transformers with relatively little insulation on the grounded end. Without going into detail about the reasoning involved, only an induced test was used replacing both the applied test on the major insulation and the induced test on the winding insulation for this apparatus. The magnitude of the test was specified as 2.73 times the normal operating voltage to ground and was extended to any transformer with one end of the winding grounded, such as transformers for three-phase service with grounded neutral. This procedure was later abandoned and replaced by induced tests at specified levels; more nearly approaching an induced test of 3.46 times the voltage to neutral.

During the period from 1920 to 1930, the effects of lightning on transmission lines, particularly on transformers, became of special interest to utility and manufacturers' engineers. In the early 20's when transformers were damaged, the matter was dismissed on the basis that transformers were struck by lightning, an act of God, and that nothing could be done about it. The transformer designer used extra insulation between turns at the line end as dictated by experience and his own judgment. The major insulation of low-voltage transformers was in excess of that needed for the specified tests, partly because it was not difficult to obtain more insulation and partly because experience showed it necessary. At the end of the 20's, some customers were specifying levels for surge strength, requiring transformers to be stronger than specified lengths of insulator strings, gaps, bushings, and so forth. At that time, transformer designers generally did not have design information on the magnitude of service stresses nor knowledge of the strength of insulating materials to withstand them.

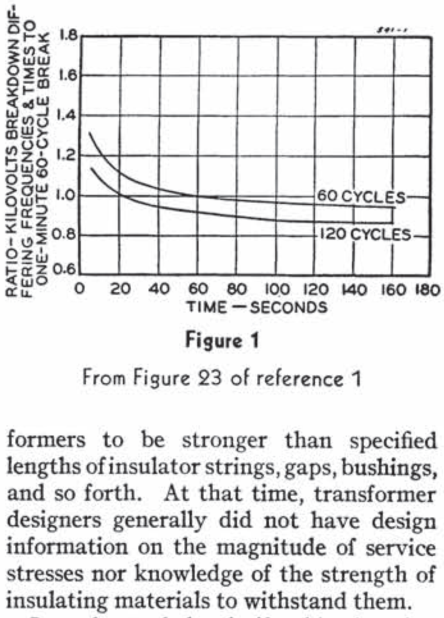

Figure 1

From Figure 23 of reference 1

In order to help clarify this situation impulse testing of transformers was started and levels were established, which were changed several times. It is of interest that these levels were lower than those specified in the late 20's, even though transformers actually were improved greatly in insulation strength in the early 30's.

In a period of such development, where levels often were based on what was expedient at the time, it is to be expected that everything would not be exactly perfect. When machines by one manufacturer are being built with certain claimed design features, it is not always possible

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have been developed for operation at 60,000 and 100,000 volts at currents up to five milliamperes.

Conclusion

The TAKK d-c high-voltage insulation tester and insulation-resistance instrument fills a need in the study of numerous types of electrical insulation. Limited experience indicates that it is useful in testing high-voltage cable, aircraft-ignition systems, and high-voltage generating apparatus. It is the belief of the authors that there are many other applications in the electrical industry where a device of this type will be found useful and economical. It is hoped that the availability of this device will encourage the collection of considerable data on insulation testing and insulation resistance which will contribute to a better understanding of the subject and further developments in the art.

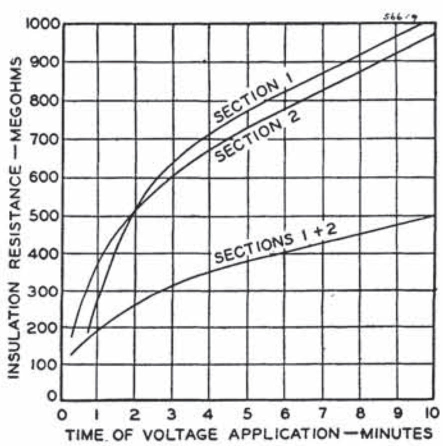

Figure 9. Dielectric-absorption curves for a 25,000-kva 6,900-volt water-wheel generator taken at 10,000 volts

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