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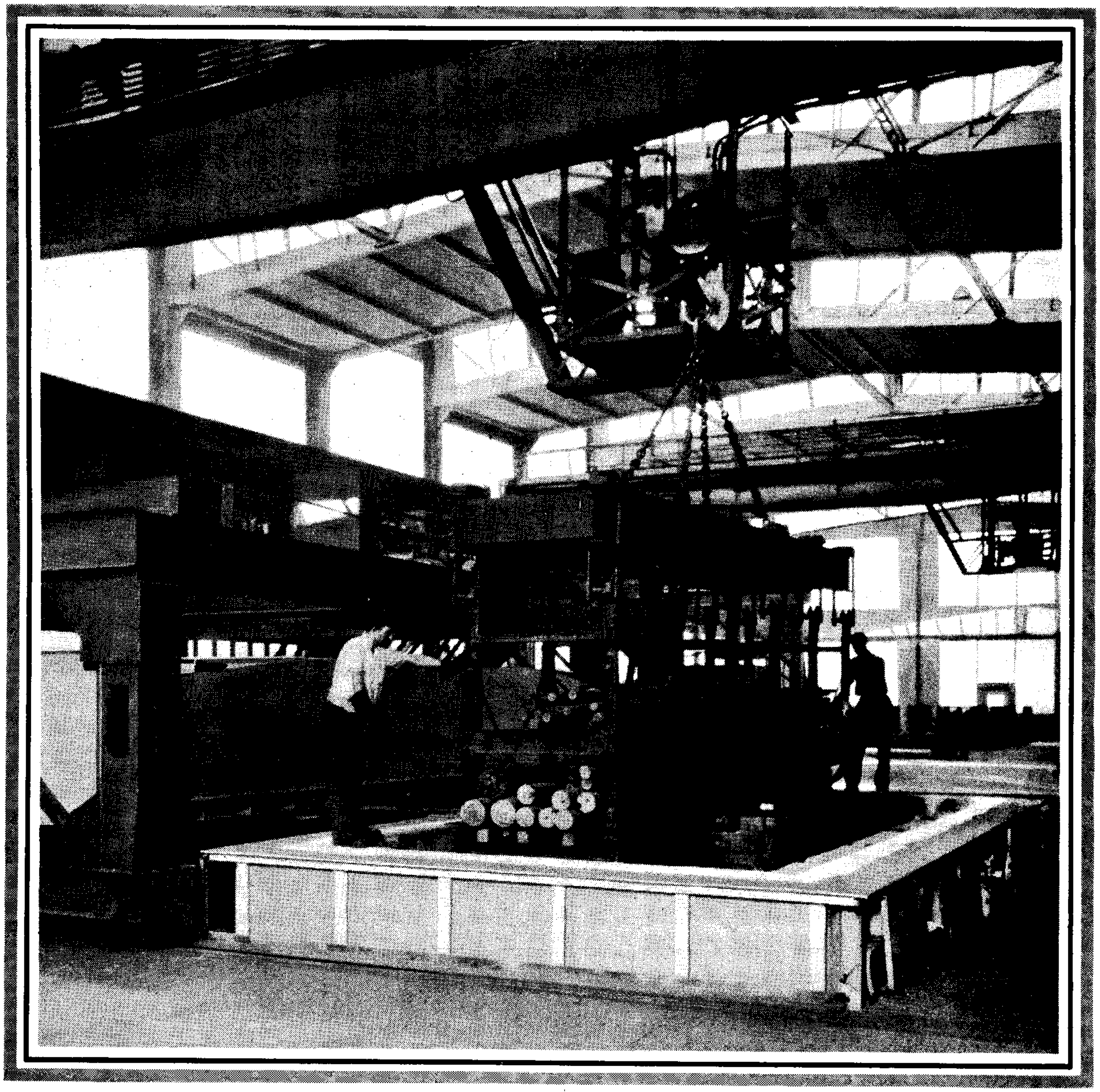
GENERAL ELECTRIC REVIEW

VOL. 34, NO. 4 APRIL, 1931



ELECTRIC HEAT

In its program of modernization, Industry is availing itself not only of the latest advances in electric power and light but also in that newer branch of electric service—electric heat. The rapid growth in the utilization of electric heat is indicated by a consumption of 6,000,000,000 kw-hr. for this purpose in 1929, which is more than double that of 1925. In the above photograph are shown two 50-ton 1100-kw. pit-type furnaces for annealing bar stock 25 ft. long

Instruments for Lightning Measurements

Latest Developments and Applications of Surge-voltage Recorders—Cathode-ray Oscillographs—Lightning-stroke Recorders—Surge Indicators—Lightning-severity Meter

By C. M. FOUST
General Engineering Laboratory, General Electric Company

CONSTANTLY increasing demands for uninterrupted service on transmission lines has focussed attention upon the most disturbing factor—lightning. The problem simply stated is: "How may transmission lines and protective equipment be arranged to avoid tripouts and loss of power due to lightning flashover of the line insulation?" Progress toward the solution of this problem has until recent years been greatly hindered through lack of suitable measuring instruments. For a long time, sphere gaps and needle gaps were the only measuring devices of practical importance for such purposes and these devices have obvious limitations which narrowed their usefulness on actual power lines. Within the past few years, however, intensified effort has resulted in the design and application of various surge-measuring instruments, through the use of which a great amount of engineering information concerning lightning surges has been gathered. Present progress justifies the belief that the continued use of these devices will result in a solution to the lightning problem.

Classification of Instruments

Surge-measuring instruments suitable for lightning surges must record within microseconds (millionths of a second) and must be of such nature that automatic registration is obtained. The uncertainty of the time of occurrence of electrical storms and lightning strokes necessitates instruments that are ever in readiness for operation. The short time elements involved militate against the use of movable parts in the instruments; and the devices described in this article will therefore depend for their operation upon rather unusual electrical principles.

For the purpose of presenting a summary of the present available instruments, Table I has been arranged.

Surge-voltage Recorder

The surge-voltage recorder is built in both the moving-film and stationary-film type of instrument. Both types utilize the Lichtenberg figure method of registration of crest surge voltage and their voltage-figure size calibrations are the same. The instruments are single phase and are equipped with direct and reversed-polarity electrodes connected in parallel. This arrangement permits the registration of each surge voltage regardless of polarity with both a positive and negative Lichtenberg figure.

The measuring range of the instrument is 3 to 30 kv., giving a ten-to-one ratio between the highest point on the calibration scale and the initial registration

TABLE I

Name of Instrument	Quantity Measured	Method of Connection	Method of Registration	Direct Instrument Range (Kilovolts)	Time Scale
Surge-voltage recorder (moving-film type)	Crest voltage	Capacitance coupling	Lichtenberg figures on photographic film	3–30*	½ in. per hr.
Surge-voltage recorder (stationary-film type)	Crest voltage	Capacitance coupling	Lichtenberg figures on photographic film	3–30*	None
Cathode-ray oscillograph	Wave shape and amplitude	Capacitance coupling	Cathode-ray on photographic film	0–1*	Microseconds (millionths of a second) per cm.
Lightning-stroke recorder	Indicates direct stroke to tower	Shunted across tower or ground wire	Lichtenberg figures on photographic film	9–23	None
Surge indicator	Indicates insulator flashover	Shunted across tower or ground wire	Disruptive link trips target	2 and above	None
Lightning-severity meter	Integrates field intensities at time of lightning strokes	Small antenna	Glow tube illumination on photographic film	——	None

* By the use of a suitable voltage divider, the measurement range of these instruments can of course be extended upward for a transmission line of any voltage. Three million volts have been measured.

voltage. The use of the double-registration feature has great advantages for the following reasons:

(1). Because negative surge voltages up to approximately 2.5 times normal give negative Lichtenberg figures upon a directly connected recorder and on such a recorder are entirely obscured by the normal line voltage band.

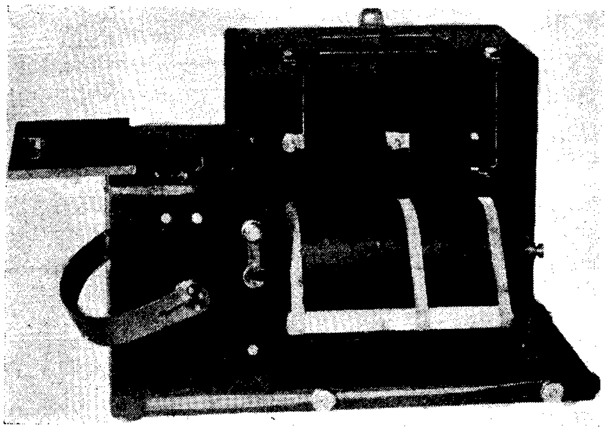


Fig. 1. Surge-voltage Recorder of the Moving-film Type, Shown with the Film and Clock Compartments Open

(2). Because negative Lichtenberg figure sizes are dependent upon the rate of voltage rise to a much greater degree than the positive figures.

(3). Because the availability of both figures for all high-voltage surges permits more accurate determination of the nature of the surge producing the figures.

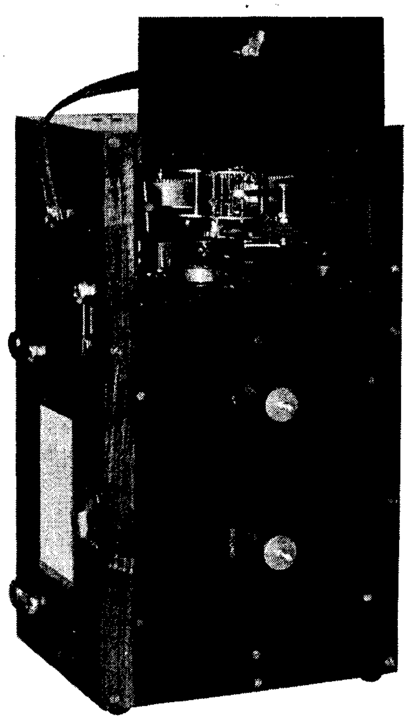


Fig. 2. Moving-film Type of Surge-voltage Recorder, Shown with the Clock Compartment Open and the Film Compartment Closed

Surge-voltage Recorder (Moving-film Type)

The moving-film type of surge-voltage recorder is shown in Figs. 1 and 2. An earlier design has been previously described. [1] The present instrument has been improved in two respects, first in the design of the enclosing box and second in the method of time registration. The insulating box has been rearranged to provide a fixed compartment for the clock mechanism and a hinged cover for the photographic-film compartment. The advantages obtained are protection to the clock and definite alignment of the hinged cover.

The voltage-figure size calibration is shown in Fig. 3. This calibration holds for both the moving-film and stationary-film types of surge-voltage recorder.

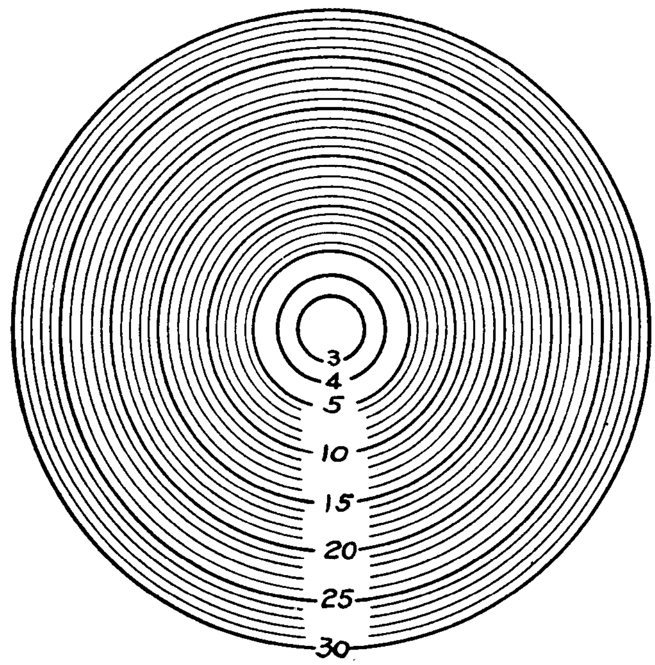


Fig. 3. Voltage Calibration of Surge-voltage Recorder, Showing Relation of Positive Lichtenberg Figure Size to Crest Value of Surge Voltage

A specimen field record from the moving-film type of instrument is shown in Fig. 4. It will be noted that the time markings are very clearly printed on the center of the film and that the serial number of the instrument appears above the hour of 12 midnight. This time marking is accomplished through engraved numbers filled with radioactive material on the driving drum and has been found to be very satisfactory. Edge-light fog which frequently occurs due to loosely rolled films will not cover the time scale. Fig. 4 shows about ten inches of the seven-foot record obtained for each weekly exposure. The clock drives the film ½ in. per hour or 1 ft. per day and will drive it satisfactorily for eight days.

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(1) "Measurement of Surge Voltages on Transmission Lines Due to Lightning," by E. S. Lee and C. M. Foust, GENERAL ELECTRIC REVIEW, March, 1927, pp. 135-145.

Field Installations and Records

Referring again to the typical surge-voltage record in Fig. 4, the black parallel lines below and above the timing marks are normal voltage lines on the directly connected and reversed recorder respectively and are obtained from the normal excitation of the circuit. The Lichtenberg figures at about 2:15 a.m. indicate a surge voltage of negative and unidirectional polarity, and about ten times normal line voltage. The smaller figure to the right indicates a surge voltage of two times normal voltage. Fig. 5 shows a typical installation of the moving-film type of surge-voltage recorder with the instrument sheltered in the standard metal housing and mounted in the tower structure; and Fig. 6 shows an installation with the instrument on a ground pole.

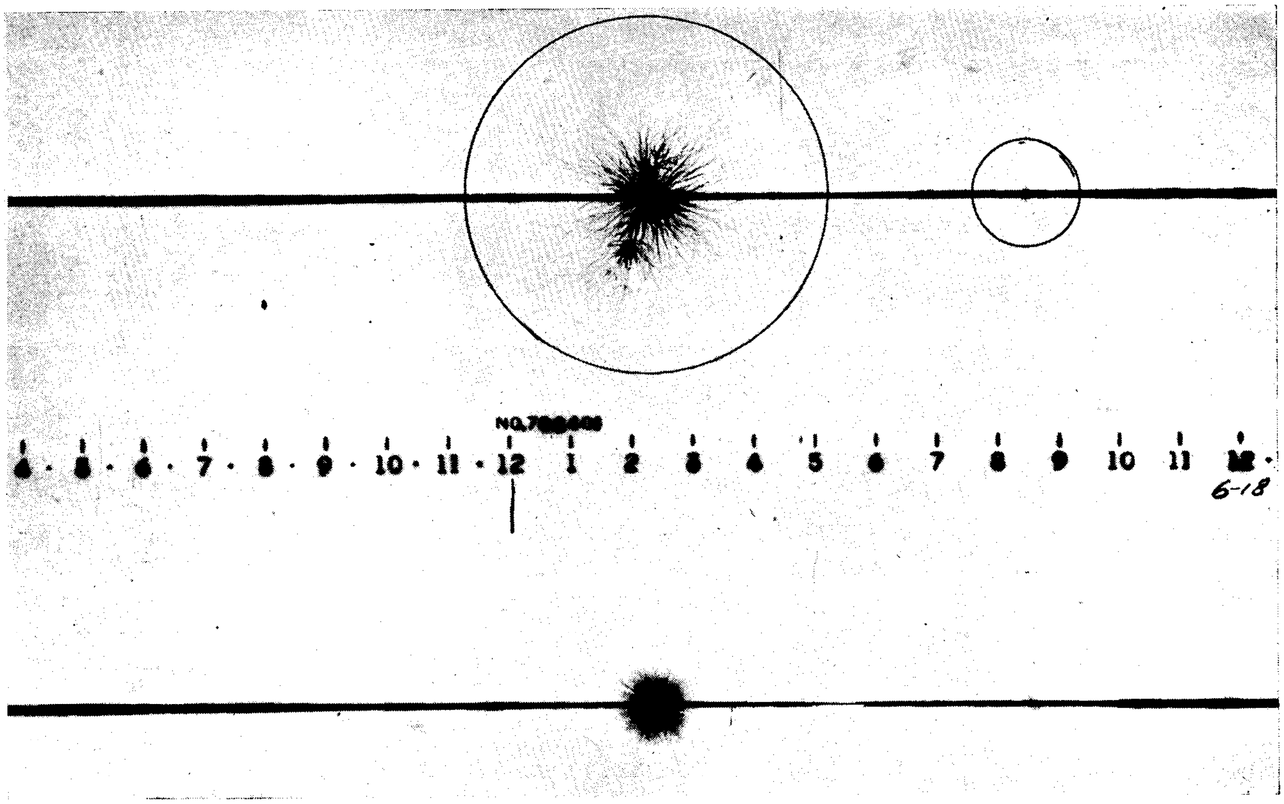

Fig. 4. Transmission-line Lightning-surge Record Made by a Surge-voltage Recorder of the Moving-film Type

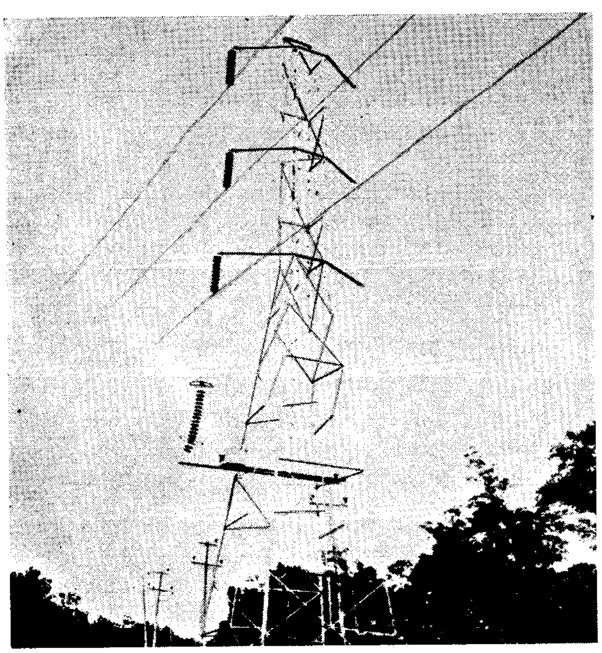

Fig. 5. Typical Installation of Moving-film Type of Surge-voltage Recorder on a Transmission-line Tower

The connection of the surge-voltage recorder to the transmission line is made through a very low capacitance by means of an insulator-string voltage divider with grading shields as shown in Fig. 7. If all the dimensions are adhered to within reasonable limits, the arrangement can be used on lines of various voltage ratings by selecting a suitable number of insulator units. Table II gives values for various line voltages.

TABLE II

Rating of Line (Kilovolts, Phase Voltage)	Number of Insulator Units (Fig. 7)	Voltage Divider Ratio
33	3	15
44	5	20
66	7	26
88	10	36
110	12	45
132	14	60

This type of voltage divider has been given a thorough trial over several years' operation and has been productive of satisfactory results.

A thorough study of surge voltages on a transmission line necessitates the installation of a number of recorders spaced along the line at intervals of a few miles between each. Such an installation will furnish a voltage profile such as that shown in Fig. 8. From this profile may be calculated an attenuation curve for the surge as it travels from the point of disturbance.

A great amount of valuable information has been gathered with this technique on various systems. The analysis of these data has resulted in the development of an empirical formula (2) as follows:

$$e=\frac{E_0}{KsE_0+1}$$

in which

e = voltage in kilovolts at distance s from origin
E_0 = crest voltage at origin of surge
K = a factor depending on the particular line and ranging from 0.0004 to 0.00006
s = distance in miles from origin of surge.

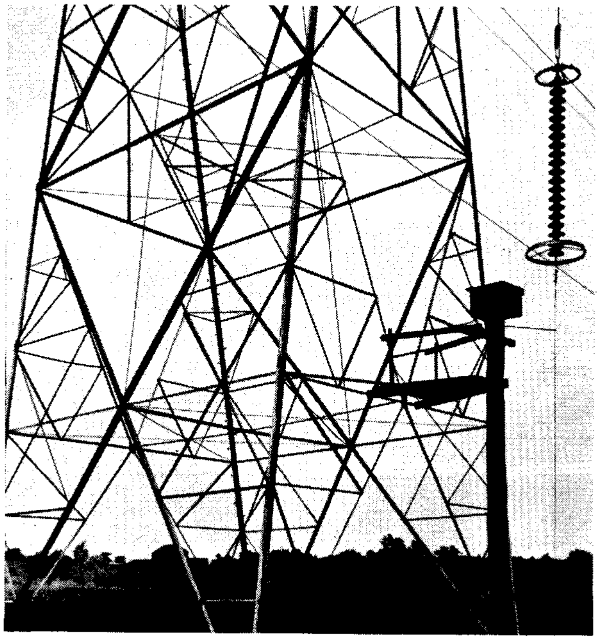

Fig. 6. Typical Installation of a Surge-voltage Recorder of the Moving-film Type on a Ground Pole Beside a Transmission-line Tower

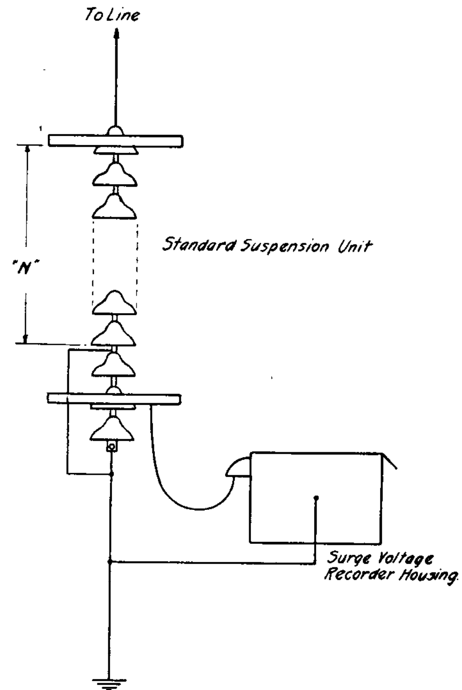

Fig. 7. Installation Arrangement of a Moving-film Type of Surge-voltage Recorder and Insulator-string Voltage Divider, and the Connections to a Transmission Line and Ground

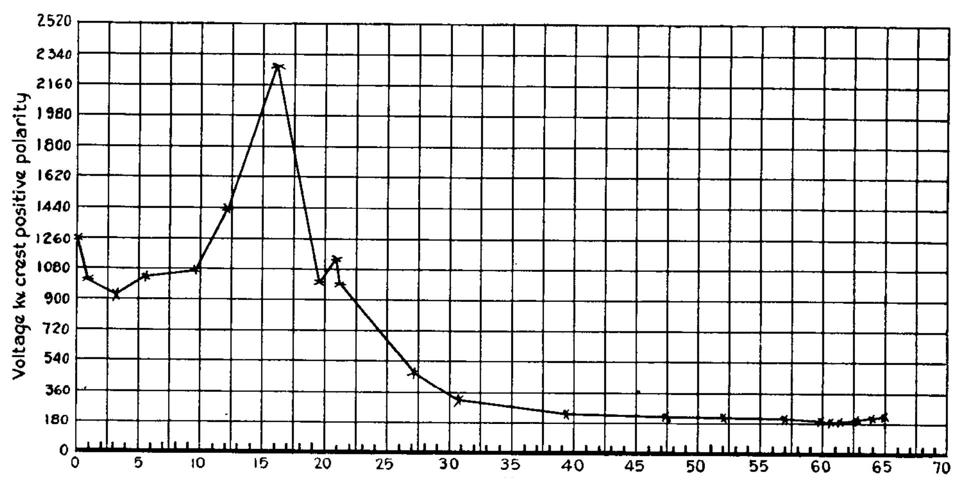

Fig. 8. Profile of the Crest Surge Voltage as a Lightning Surge Travels Along a Transmission-line Conductor. This profile is plotted from the records of surge-voltage recorders installed along the line

This formula has been checked by applying surges from an artificial-lightning generator and the agreement is within the limits of accuracy of the testing equipment.

In addition to attenuation data, valuable information on amplitude of surge voltages and frequency of occurrence of surges has also been obtained. (2) Surge voltages of 14 times normal crest voltage to ground (2400 kv. on 220-kv. line) have been measured but these are few in number. At the lower voltage

(2) "Lightning Investigations on Transmission Lines," by W. W. Lewis and C. M. Foust, General Electric Review, March, 1930, pp. 185-198.

amplitudes, the number of surges increases rapidly. At two or three times normal voltage, surges are usually as frequent as 100 per lightning season. It must be kept in mind, however, that at low amplitudes it is difficult to differentiate between switching and lightning surges.

Surge-voltage Recorder (Stationary-film Type)

Progress in lightning measurements soon demonstrated that a smaller and lower-cost instrument designed for use in the same field as the moving-film type surge voltage recorder was very desirable. Such an instrument is particularly applicable on distribution systems where it is necessary to obtain a number of measurements on the same pole or tower and where the available space is limited. Figs. 9 and 10 show a stationary-film type of surge-voltage recorder designed for use in this field.

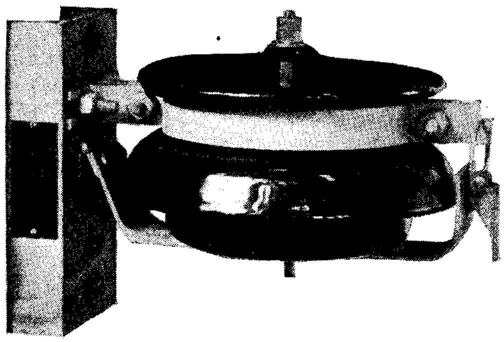

Fig. 9. Surge-voltage Recorder of the Stationary-film Type

Fig. 10. Stationary-film Type of Surge-voltage Recorder with the Porcelain Housing and Film Container Open

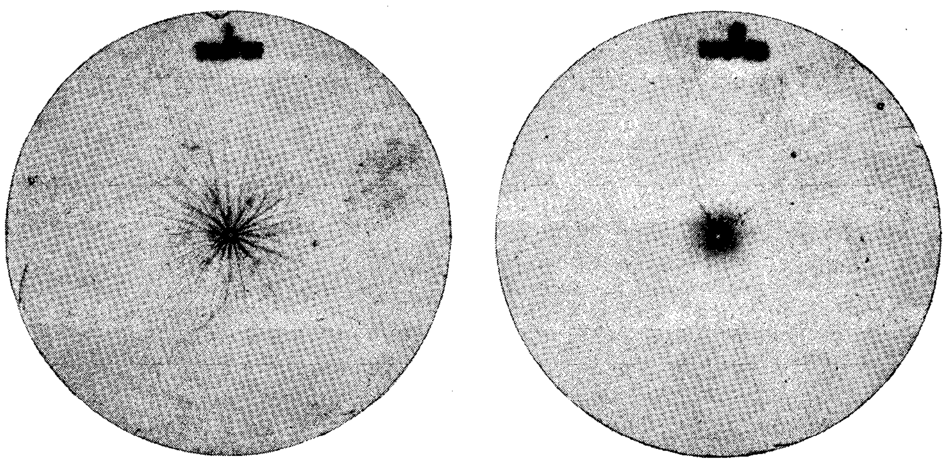

Fig. 11. Highly Damped Oscillatory Surge as Recorded by the Stationary-film Type of Surge-voltage Recorder

This instrument has the same calibration characteristics as the moving-film type previously described. Two circular films four inches in diameter are placed one in each side of the insulating film box shown. The top film is in contact with the directly connected electrode and the bottom in contact with the reversed polarity electrode. As in the moving-film-type recorder, positive and negative Lichtenberg figures are obtained with each surge voltage applied. The film box is entirely enclosed in a porcelain housing which makes a thoroughly weatherproof instrument. The supporting brackets may be readily bolted to the cross arm of a tower and the lower portion of the porcelain housing when unlatched swings downward to permit withdrawal of the film box containing the exposed film and the insertion of another film box containing an unexposed film.

Each film box has a serial number engraved and filled with radio-active material so that the number is marked on every film exposed in that recorder. Specimen records of films from this surge-voltage recorder are shown in Fig. 11.

For surge-voltage measurements above the range of the instrument, a capacitance voltage divider is desirable. Fig. 12 shows an arrangement of voltage divider and surge-voltage recorder which has a measuring range up to 200 kv. The voltage divider consists of two standard line-insulator units mounted on the surge-voltage recorder, the entire equipment being supported on the recorder bracket arm. A porcelain protecting cap is provided for the top insulator unit. This cap insulates the hardware connected to the line and therefore makes the entire outfit proof against injury to the attendant.

A number of these instruments have been used during the past lightning season on distribution systems, and while a great amount of data has not as yet been collected the performance of the instrument has been satisfactory.

Cathode-ray Oscillograph

Laboratory experience with lightning generators early demonstrated that the time element or wave shape of the surge had an important bearing on insulation failure. Therefore, in addition to the measurement of the surge-voltage amplitudes of lightning surges on transmission lines, the determination of wave shapes became necessary. The cathode-ray oscillograph offered the only solution because the time elements involved are of the order of microseconds and recording instruments with mechanically moving parts are too slow to trace such wave shapes.

The fact that the electrons in the cathode-ray stream can be deflected by voltage applied to small deflection plates simplified the application of the cathode-ray oscillograph to a marked degree. A connection to the transmission conductor through a low capacitance obtains ample energy for full-scale deflections; and by using insulators, similar to those of the normal line insulation, to serve as this capacitance a thoroughly safe arrangement was obtained without adding hazard to the line service.

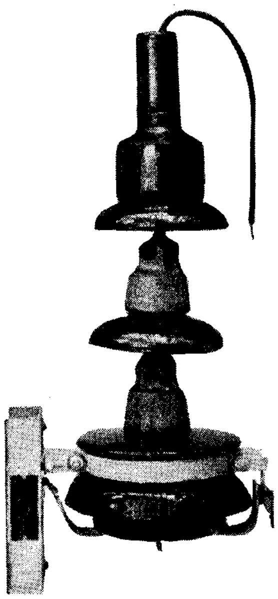

Fig. 12. Stationary-film Type of Surge-voltage Recorder with Capacitance Voltage Divider for Measurements up to 200 kv.

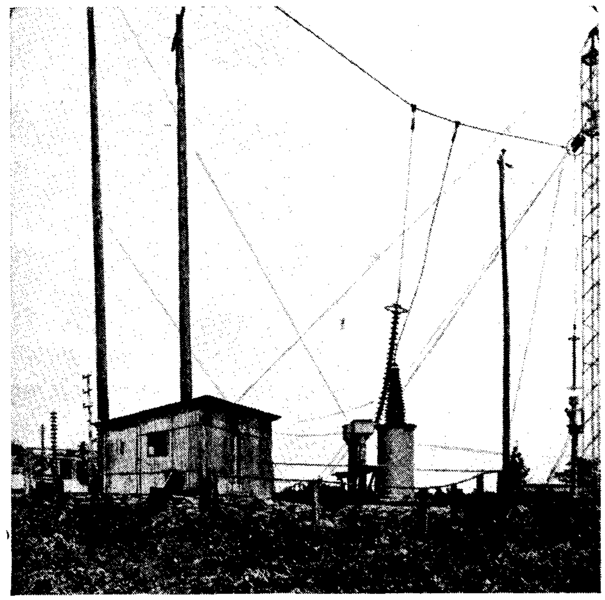

Fig. 13. The 1928 Cathode-ray Oscillograph Transmission-line Lightning Laboratory

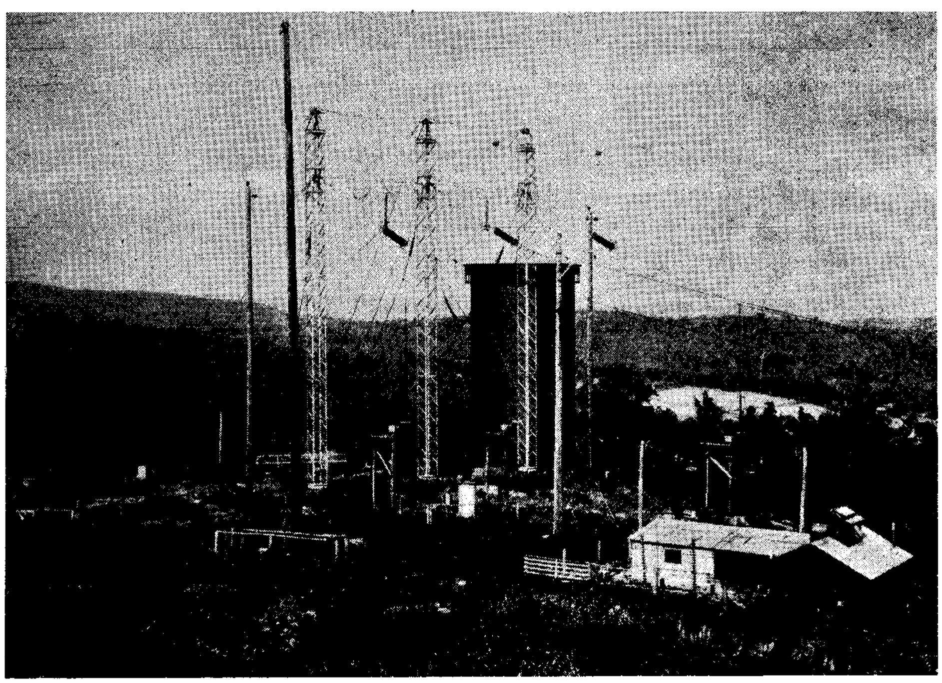

Fig. 14. The 1929 Cathode-ray Oscillograph Transmission-line Lightning Laboratory

Figs. 13, 14, and 15 show cathode-ray oscillograph field laboratories for 1928, 1929, and 1930. In 1928 one instrument was used as shown in Fig. 16, and in 1929 (Fig. 17) and 1930 (Fig. 18) two instruments were used. The 1930 arrangement includes all progress in equipment and technique resulting from the previous years' experience. For this reason, space will not be taken here to describe the 1928 or 1929 arrangements.

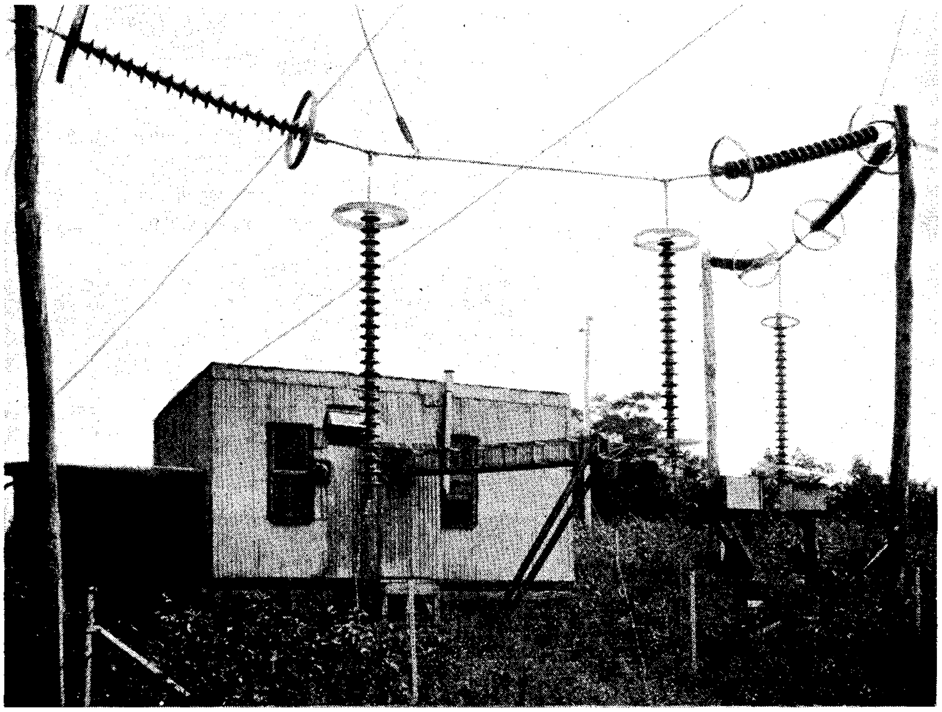

Fig. 15. The 1930 Cathode-ray Oscillograph Transmission-line Lightning Laboratory

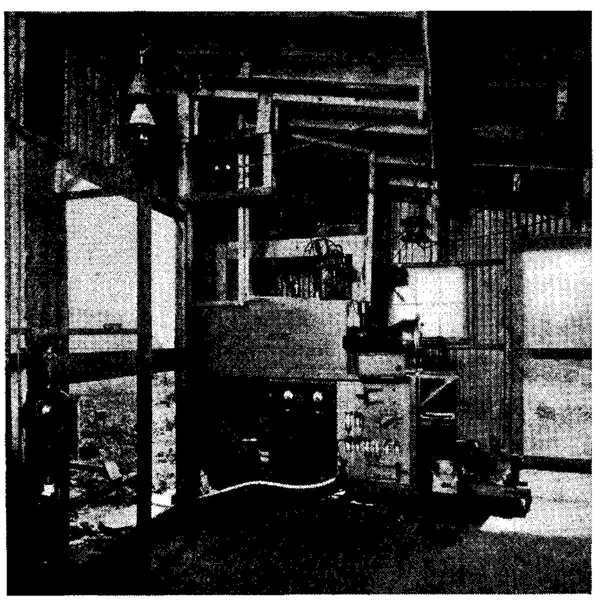

Fig. 16. The Single Cathode-ray Oscillograph in the Lightning Laboratory of 1928. (*See Fig. 13*)

The two oscillographs used in a 1930 lightning laboratory, and arranged as in Fig. 18, were connected in accordance with the diagram shown in Fig. 19. There are several particular operational features of this arrangement which merit attention. Through the sensitive tripping gaps and circuits provided, the first oscillograph begins to trace the wave shape automatically within ¼ to ½ microsecond after the incoming wave arrives on the transmission line conductor. This oscillograph then proceeds to record the lightning surge on a very fast time axis (50 microseconds full film width). The second oscillograph begins to trace the surge within 1 to 2 microseconds after the first instrument is in operation and records the remaining portion of the lightning surge and later the reflections as the surge returns from the various points of transition along the conductor. Figs. 20 and 21 are typical examples of lightning surges obtained by the two-oscillograph method.

Continuous records of all lightning surges throughout a storm period are of course desirable. To make available sufficient films for a great number of surges coming in rapid succession, a special film holder was designed. This holder is shown in Fig. 22. The film holding compartment has been enlarged to permit the insertion of five 12-exposure roll films thus making possible 60 independent exposures.

Several hundred oscillograms have been obtained throughout the period of operation of the equipment. Specimens of oscillograms which have added materially to the knowledge of wave shapes of lightning surges on transmission lines are shown in Figs. 23(a) to 23(e), inclusive.

Lightning-stroke Recorder

Soon after the first measurements of voltage amplitude and wave shape of lightning surges were made, it became apparent that an instrument which would differentiate between the direct strokes to a transmission tower, ground wire, or conductor, and the induced surges on a conductor would be of marked value.

This realization resulted in the design of the lightning-stroke recorder, which is an adaptation of the Lichtenberg figures for this purpose. This instrument is shown in Fig. 24. It consists of a porcelain base which is securely fastened to a tower leg by a steel clamp, a weatherproof metallic cover, and a light-proof film packet. The porcelain base carries an electrode which is connected electrically to the supporting clamp and the metallic cover holds an electrode which is connected at a point on the tower leg some 15 to 30 ft. above the instrument location. The film packet is placed between the electrodes. In Fig. 6 a lightning-stroke recorder is shown mounted on and connected to the near leg of the tower.

A high-current surge (50,000 amp. or above), such as is associated with a direct stroke, gives ample voltage across the 15 to 30-ft. sections of tower leg bridged by the instrument lead to result in a Lichtenberg figure on the photographic films in the packet. The currents associated with induced surge voltages are not of sufficient magnitude to result in registrations on the instrument. In this way the lightning-stroke recorder when installed on each tower will indicate the locations of direct strokes and will give an approximate value of surge current associated with each.

The Lichtenberg figures obtained on the films in the sealed light-proof packet do not have the same characteristics as those obtained by surge-voltage recorders where the electrodes are in direct contact with the photographic emulsion. However, laboratory tests have shown that close study of the lightning-stroke recorder films will permit the polarity of the recorded surges to be determined. The current-figure size calibration for this instrument is shown in Fig. 25, and a typical transmission-line direct-stroke record is shown in Fig. 26.

Fig. 17. The Two Cathode-ray Oscillographs in the Lightning Laboratory of 1929. (*See Fig. 14*)

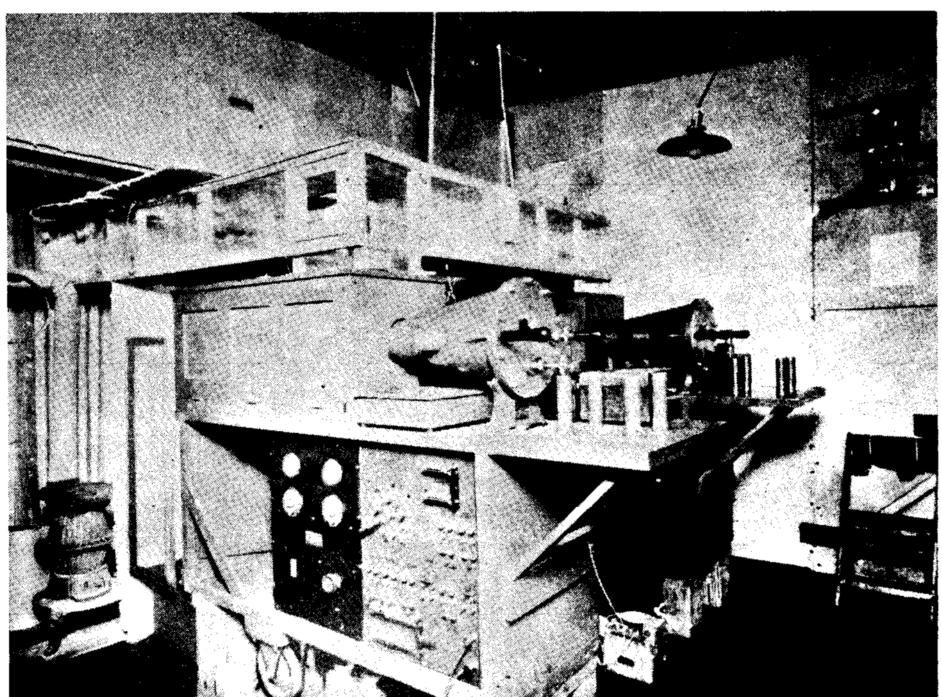

Fig. 18. The Two Cathode-ray Oscillographs in the Lightning Laboratory of 1930. (*See Fig. 15*)

Surge Indicator

Transmission lightning studies have emphasized the need for a device which would give an immediate indication visible from the ground when an insulator assembly flashed over. Uncertain ground patrols and costly tower climbing examinations have not resulted in accurate information concerning the location and number of insulator assemblies that have been flashed over.

To remedy this situation, a program of study and test of several types of suggested devices was carried out. As a result of this work, a surge indicator suitable for use as an indicator of flashovers on a

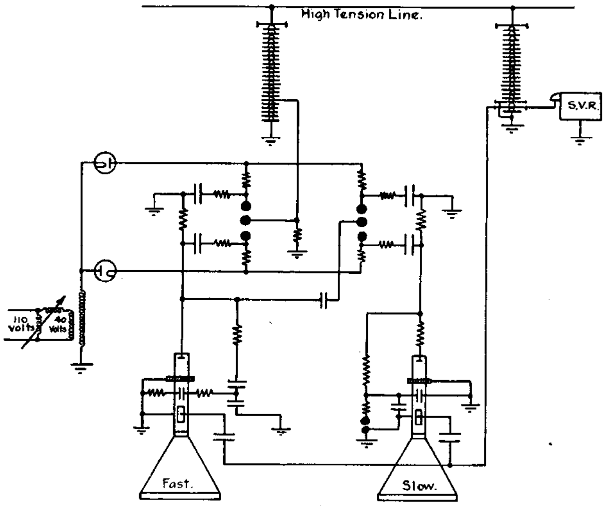

Fig. 19. Connection Diagram for the Automatic Operation of the Two Cathode-ray Oscillographs in the Transmission-line Lightning Laboratory

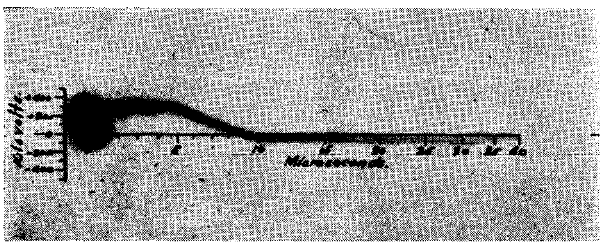

Fig. 20. Cathode-ray Oscillogram of the Voltage Variations During the First 50 Microseconds of a Lightning Surge on a High-voltage Transmission Line

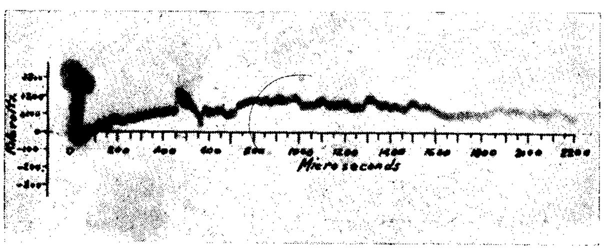

Fig. 21. Oscillogram of the Voltage Variations During a 2200-Microsecond Period of a Lightning Surge on a High-voltage Transmission Line

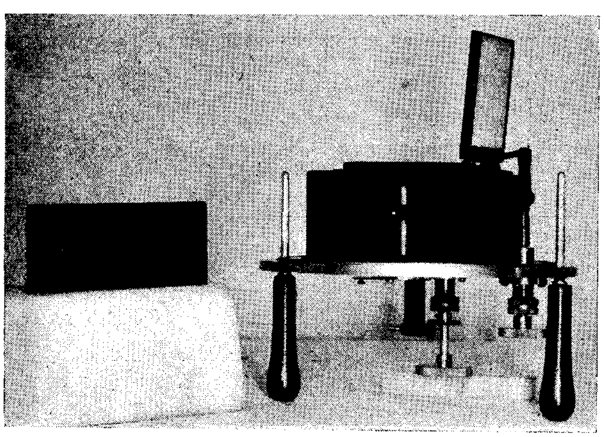

Fig. 22. Special 60-exposure Film Holder for Cathode-ray Oscillograph

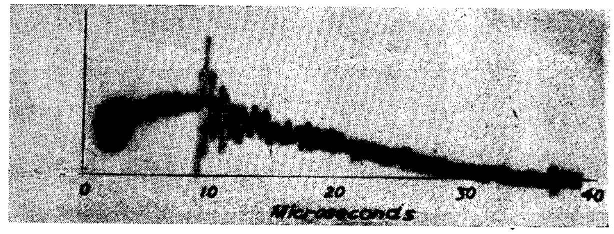

Fig. 23(a). First Cathode-ray Oscillogram of Lightning Surge on a Transmission Line. Taken at Wallenpaupack, July 27, 1928, on phase Y. The superimposed oscillations are due to flashover on an adjacent phase

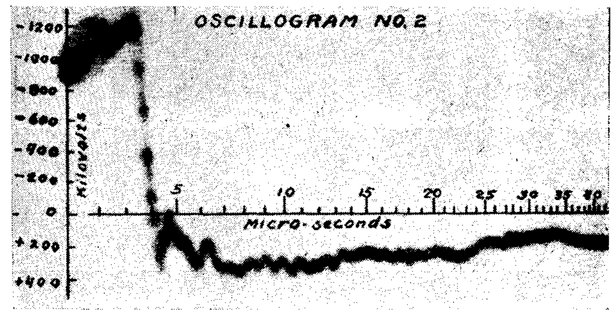

Fig. 23(b). Cathode-ray Oscillogram Obtained on May 29, 1929. Dead-end protective gaps at this point flashed over on all three phases. This flashover caused a sharp change in voltage from 1260 kv. negative to 310 kv. positive in one microsecond. Flashover took place on the front of the wave

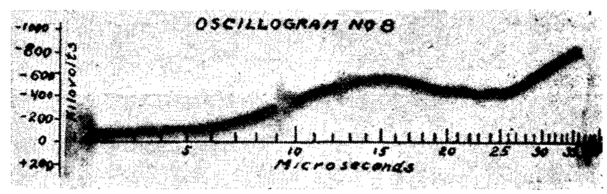

Fig. 23(c). Cathode-ray Oscillogram Taken on June 19, 1929. Record obtained while line was not energized. Voltage was still rising at the end of 36 microseconds and was then suddenly reduced to zero. Subsequent examination of line insulation indicated a flashover 23 miles away, which appeared to correlate with this oscillogram

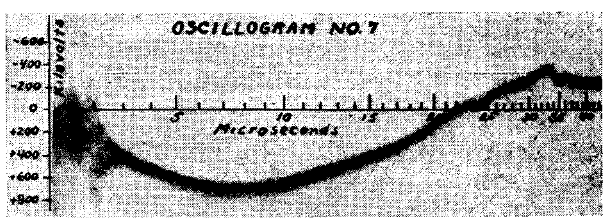

Fig. 23(d). Cathode-ray Oscillogram Taken on July 19, 1929. This is a wave which has a slightly oscillatory nature and is typical of a large group of waves. A cloud-to-ground stroke was seen at the instant this oscillogram was obtained. This stroke was at least 10 miles distant from the laboratory and some distance from the line

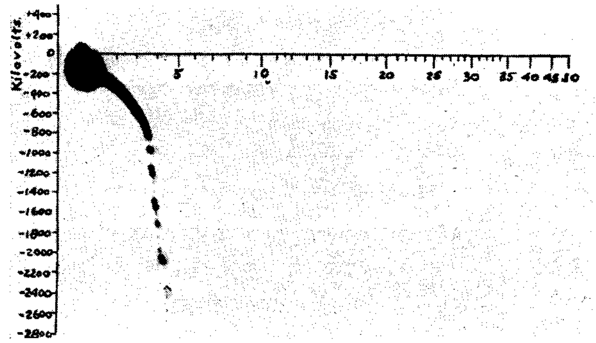

Fig. 23(e). Cathode-ray Oscillogram Taken on July 24, 1930. The lightning stroke was within one tower span from the lightning laboratory

Fig. 23. Notable Cathode-ray Oscillograms

transmission-line insulator assembly was conceived and designed. This instrument is shown in Figs. 27 and 28. It consists of a weatherproof metal housing 8 in. in diameter and 2½ in. thick, an indicating target, a frangible trip link, and a lead-in insulator. Fig. 27 shows the instrument with link installed and the indicating target concealed. Fig. 28 shows the target indicating that a surge has passed (line-insulator units flashed over).

The surge indicator will operate satisfactorily when connected across a portion of the tower structure (usually the tower arm) which carries the flashover current from a particular insulator assembly. Fig. 29 shows the location of the instrument and connecting lead for a transmission line of horizontal configuration and Fig. 30 for one of vertical configuration of conductors. It will be noted that in each case the location of the instrument is such that it is readily accessible to the attendant near the main or upright structure of the tower. The tap lead extends along the tower arm and is connected to the iron of the tower at a point near the support for the insulator assembly. This

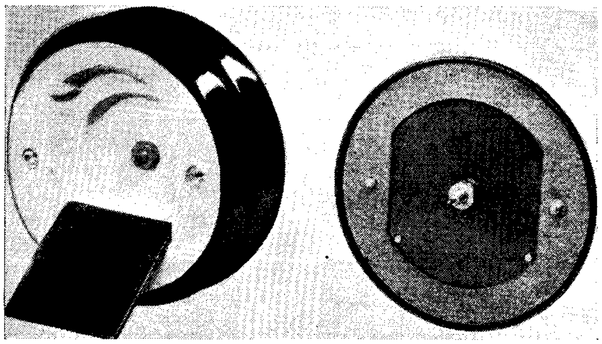

Fig. 24. Lightning-stroke Recorder Open to Show the Film Packet

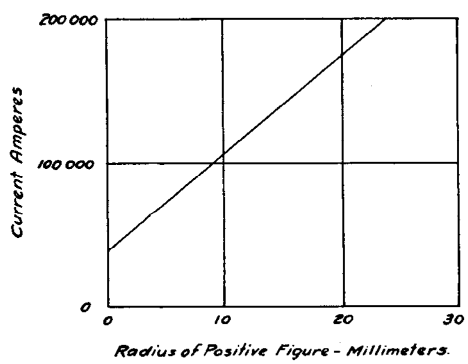

Fig. 25. Calibration Curve of the Lichtenberg Figure Size and Tower Surge Current for the Lightning-stroke Recorder

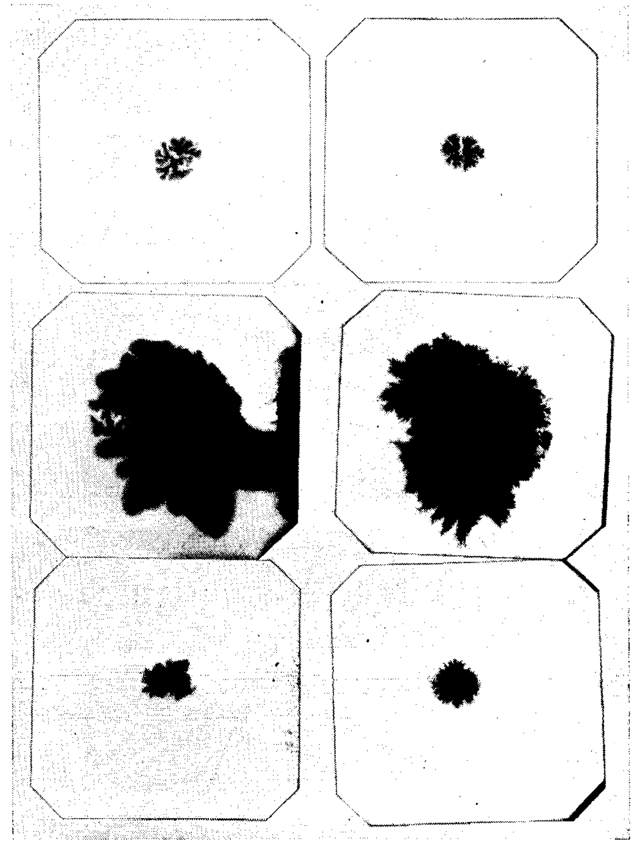

Fig. 26. Typical Direct-stroke Records Made by the Lightning-stroke Recorder

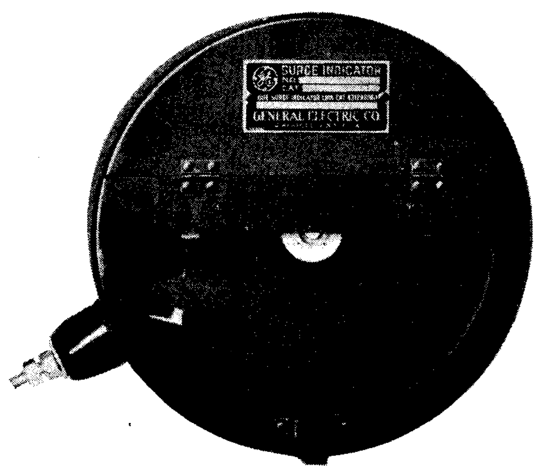

Fig. 27. Surge Indicator with Frangible Link in Place and the Instrument Set in Readiness for Service

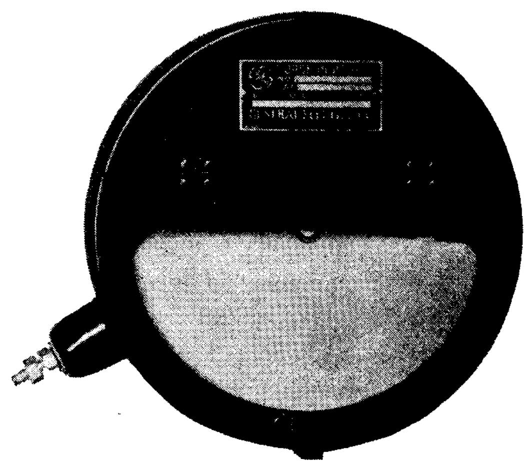

Fig. 28. Surge Indicator with Target Showing, Thus Indicating That a Surge has Taken Place

connecting lead is securely fastened to the tower at each end and supported with sufficient insulators along its length to prevent the lead from falling on a live conductor and causing a line interruption.

Briefly, the instrument operates according to the following procedure: When the insulator assembly flashes over the rush of discharge current through the tower arm gives sufficient voltage across the instrument and the necessary follow-up current to disrupt the frangible link and allow the spring pressure to force the indicating target into the visible position. Power current from the line is not necessary for instrument operation. The insertion of a new trip link, which is accomplished very readily, resets the instrument in readiness for another surge indication.

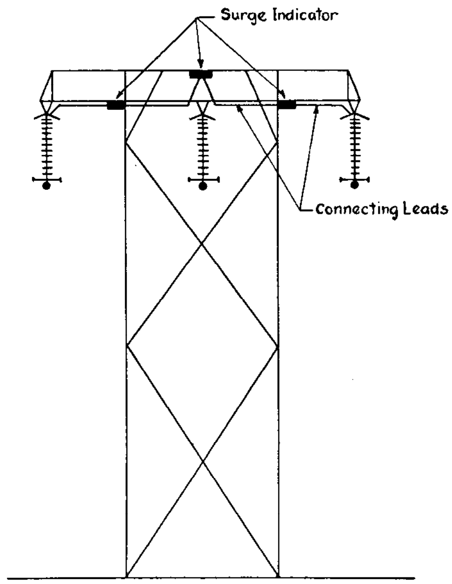

Fig. 29. Schematic Diagram for Mounting Surge Indicators and Connecting Them to a Tower Having Horizontally Arranged Conductors

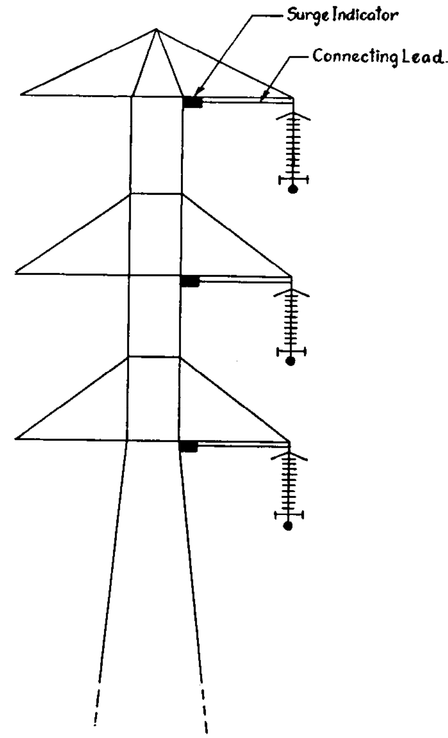

Fig. 30. Schematic Diagram for Mounting Surge Indicators and Connecting Them to a Tower Having Vertically Arranged Conductors

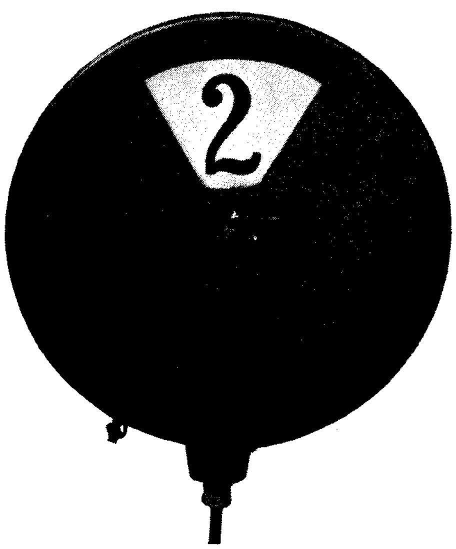

Fig. 31. Surge Indicator for Multiple-surge Indication, in Position That Indicates Two Surges

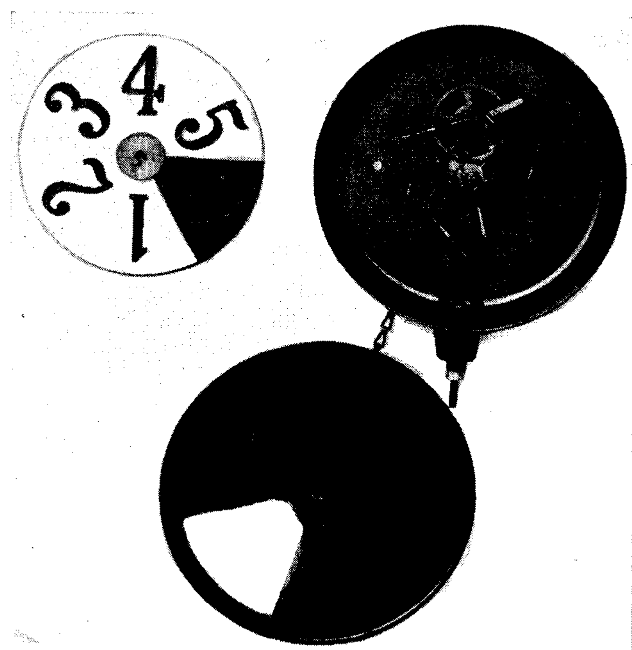

Fig. 32. Interior of the Surge Indicator Shown in Fig. 31

Some 1500 of these instruments have already been installed on transmission lines and very gratifying results have been obtained. A positive record of flashover is obtained and the cost of tower climbing patrols is materially reduced.

The surge indicator has been designed in another form for multiple-surge operation as shown in Figs. 31 and 32. This arrangement permits the insertion of five trip links and the indication of five surges without reloading.

Lightning-severity Meter

The instruments already described have all been designed for connection to the transmission line or tower and serve to obtain measurements or indications of surge conditions on the structure only. It is very desirable that some device be available which will serve to record the intensity of storm conditions to which the transmission line is subjected.

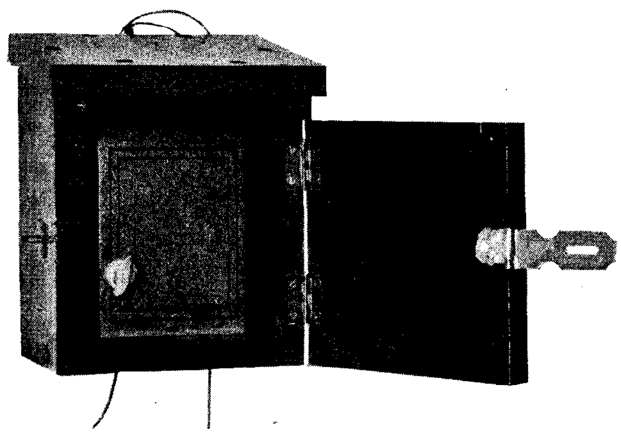

Fig. 33. Lightning-severity Meter

To serve this purpose, the lightning-severity meter was produced. This instrument consists of a camera containing a photographic film, a glow lamp, and an antenna. Fig. 33 shows the instrument and Fig. 34 shows a field installation. Fig. 35 shows the type of record obtained.

When the antenna is within the cloud field, it obtains a charge proportional to the strength of that field. When the stroke takes place, the field around the wire collapses and the antenna charge passes through the glow tube thereby producing a porportional illumination which is recorded on the photographic film. The depth of light exposure on the film is a measure of the integrated field intensity over the period of exposure. The depth of exposure can be readily measured by photometric methods and an arbitrary but definite rating for storm severity obtained.

Several field installations of this device have been operated through the 1930 lightning season and the results obtained suggest that valuable information will be obtained through the future operation of this instrument.

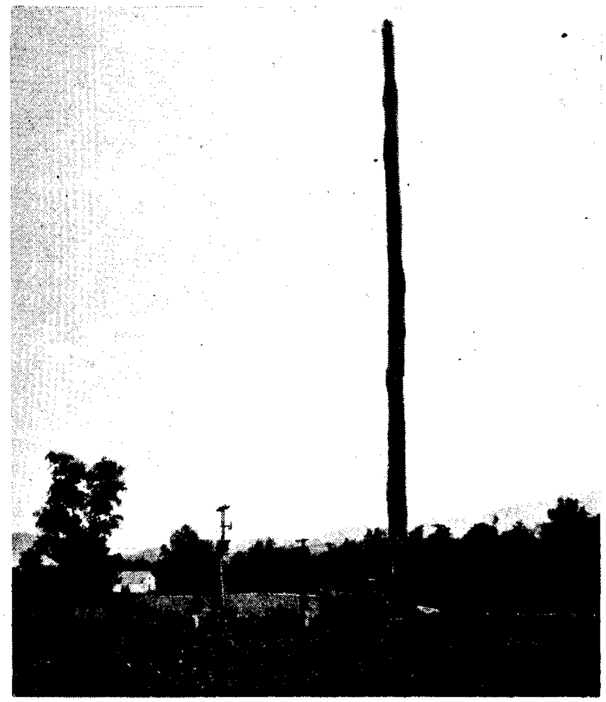

Fig. 34. Installation of Lightning-severity Meter and Antenna for Field Measurements

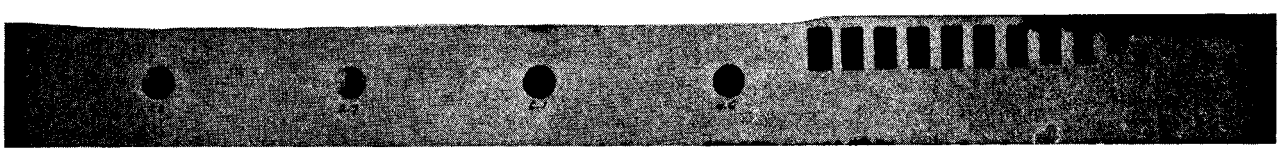

Fig. 35. Type of Record Made by the Lightning-severity Meter

Conclusion

The number of instruments recently designed and now available for lightning-surge measurements has already resulted in a marked improvement in the engineering understanding of lightning phenomena. Through the continued use of these instruments, additional valuable data can be obtained and a final solution of the lightning problem reached.

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