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PROTECTION OF ELECTRICAL CIRCUITS AND EQUIPMENT AGAINST LIGHTNING

PRELIMINARY REPORT OF THE SECTIONAL COMMITTEE ON PROTECTION AGAINST LIGHTNING

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PROTECTION OF ELECTRICAL CIRCUITS AND EQUIPMENT AGAINST LIGHTNING

Preliminary Report of the Sectional Committee on Protection Against Lightning

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PREFACE

For some years a project has been under way under the auspices of the American Standards Association for the formulation of standards for protection against lightning. The sponsors for this project are the American Institute of Electrical Engineers and the National Bureau of Standards.

The protection of persons, buildings, oil tanks, etc., has been dealt with in a code which has received the approval of the American Standards Association and has been published as Miscellaneous Publication No. 92 of the Bureau of Standards.

It was originally intended that in addition to the three parts of the code just referred to there should be two additional parts dealing, respectively, with the protection of power and railway circuits and equipment, and communication and signaling circuits and equipment. Present practice in these fields has not, however, crystallized to the point where it was felt that definite standards could be set up as final and controlling. Nevertheless, the committee collected information as to methods of protection now in vogue and practices which have been found satisfactory in dealing with lightning disturbances. This document is a preliminary report of the committee on this subject, and it is issued not only for the purpose of making available the information contained herein, but of presenting the present results for the consideration and criticism of those who have had experience in dealing with this subject. For convenience of reference the original numbering of the paragraphs has been retained.

In this report the committee has not attempted to set down performance tests which would decide the suitability of lightning arresters for the purpose used. Neither has it attempted to set down the operating conditions which will justify the installation and use of lightning arresters. It has rather endeavored to indicate how and where lightning arresters should be installed in those cases where it has been decided that their use is justified.

In each of the parts herewith presented there is an introductory statement dealing with the subject in hand, and the report includes one appendix in which is given a general discussion of lightning, its origin, characteristics, and effects, and another containing a bibliography of the subject.

Practice in the design of lightning arresters for electrical equipment and in their application and use by power, communication, and railroad companies has varied greatly in the past. Recent investigations have increased our knowledge of the conditions involved and are leading to the application of more definite principles, but it must be realized that the most suitable practices depend upon economics as well as technical knowledge.

Further experience and the accumulating knowledge of the properties of lightning may render some of the suggestions in this report obsolete, and it is expected that at some future time this report may be revised in harmony with further progress in the art. Comments and recommended changes are invited from all who may have experience in this field.

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PROTECTION OF POWER AND RAILWAY CIRCUITS AND EQUIPMENT

INTRODUCTION

During thunderstorms the lightning in the clouds and between clouds and earth gives rise to induced potentials on electrical circuits. Experience has shown that the potentials produced in circuits in this way in certain localities are at times so high as to make it not economically practicable to insulate apparatus against them.

We can estimate the magnitude of the potentials occurring in practice from the klydonograph records which are now available. These show that transient potentials as high as 2,000,000 volts have occurred on a line 50 feet (15 m) high, causing flashover with a line insulator of 14 disks. The voltage would probably have risen higher than this had it not been limited by the flashover voltage of the insulators, which depends upon the time characteristics of the applied impulse. The usual potentials induced by lightning are, of course, much less than 2,000,000 volts, but it is usually necessary to base protection on the maximum potentials expected. For conditions approximating direct strokes a gradient of 100 kv. per foot (328 kv. per m) of line height has been assumed by some.

Although there is a considerable time lag in the breakdown of any insulation under application of overvoltage, and although the duration of these excess voltage transients is very short, it is readily seen that difficulties will be encountered in attempting to design apparatus, particularly for low-voltage systems, with insulation to withstand such potentials. Apparatus troubles are almost certain to develop unless some protective measure is adopted.

Line insulation is different in its nature from apparatus insulation in that the latter normally fails by puncture, while line insulation normally fails by flash over through the air path around it. The application of a single overpotential to a line insulator may cause a flashover with the possibility of an interruption to service. If the interruption does not occur, no harm is done because the only path affected is the air path. In the case of apparatus insulation, however, a single application of overvoltage may not cause a breakdown, but it may cause injury to the insulation which would make the path for the next application of excess voltage weaker, and by repeated application, cause failure. In other words, the solid insulation used in apparatus is subject to cumulative deterioration under the influence of these transient voltages, while line insulation is not.

A difference which further distinguishes line insulation is that it is widespread in extent. At the same time the field of influence of a lightning arrester, or the length of line which it will protect, is limited to a relatively short distance by the character of the impulses it is intended to relieve. As a consequence, it is not feasible at the present time to provide protection for line insulation, and the practice has become prevalent of designing it to withstand high induced voltages to the greatest practicable extent. Generally a large margin is provided between the flashover value and line voltage, and this margin has been fixed empirically to take care of such transient voltages as are likely to appear without too frequent flashovers. The factors which affect this margin are the height of the line above ground; the inherent time lag of the insulators; the severity of lightning conditions in the territory; shielding of the line by overhead ground wires, overbuilt higher-potential circuits, and near-by buildings; all of which tend to reduce the transient voltages. A similar effect also doubtless arises from the fact that the lower-voltage lines which are normally most subject to this kind of flashover, usually have apparatus with lightning-protective equipment connected to them at frequent intervals.

Since the practice has been adopted, as above stated, of providing lines inherently able to withstand the lightning potentials which are incident to them, protection by lightning arresters is limited to the protection of apparatus. It is evident that this must be the case, since the field of influence of an arrester is very limited. Because of the nature of the impulses, an arrester, no matter what its characteristics, will not protect any apparatus or line insulation at any great distance away from the point of connection. Apparatus insulation, however, has been shown by experience and by theoretical considerations to require under certain conditions of exposure the use of protective equipment. It is known that it is possible for transient potentials to appear on transmission lines which will be dangerous to apparatus designed for the highest voltages now in use, but whether such potentials are sufficiently frequent and sufficiently dangerous to warrant the large investment required for protective equipment for such systems has not been established.

There are other transient voltages which appear on circuits from changes in the circuit conditions, as during switching. In general, these transients are not such as to be dangerous to normally designed apparatus, and no need for protection is introduced by them. On circuits with nongrounded neutral, the phenomenon of arcing grounds can introduce dangerous voltages and cause considerable trouble with apparatus. Lightning arresters of the present day, however, are not designed to withstand such disturbances. On account of their considerable duration, if arresters are made to operate and protect against them, the arresters are quite likely to be injured or destroyed.

The major function for lightning arresters is the protection of the insulation of apparatus connected to the circuit against transient voltages which appear as a result of lightning storms.

Economical Use of Lightning Arresters and Continuity of Service.

The use of lightning arresters is, to a large degree, a problem of financial economy, the solution of which is approximate, because of the difficulty involved in evaluating the protection afforded in any given instance. It is always necessary to deal with averages taken over a period of years from a large number of arresters.

Two major factors influence the use of protective devices, viz, the prevalence of lightning in any given locality and the value placed upon continuity of service. The first is probably the least important, and is not a logical basis for the installation of arresters. The weight that should be given to it can, in some measure, be determined by consideration of the map of distribution of thunderstorms shown in Figure 7, Appendix A, but the value placed upon continuity of service is, more often than not, the deciding factor.

When determining the amount of money to be expended for protection at a given point in a system, the yearly cost of interruptions which are due to failures at that point, which would have been prevented by the use of lightning arresters, must be estimated. The operating company is probably justified in expending for protection a proportionate amount, depending upon the degree of protection afforded. The average life of the arrester and any maintenance charges must also be considered.

The cost of interruption includes the cost of locating trouble, removal of damaged equipment, installation of new apparatus, repair of damaged apparatus (or new apparatus if it can not be repaired), and also the cost of lost service. The last is the most difficult to estimate.

When estimating the cost of lost service, not only must the value of the lost revenue be considered, but the cost to the power consumer must also be included, for a shutdown of a few hours may cost the consumer many times the value of the lost revenue to the operating company. In addition, account must be taken of the loss of good will and prestige.

Some installations should be equipped with the best protection which can be obtained irrespective of considerations of economy. Such installations are those where an interruption of power supply may involve the loss of human life. The choice of lightning arresters is a matter worthy of careful thought as they, together with other protective equipment, constitute the operating company's insurance against interruptions of service. For a more detailed treatment of the economics of arrester application, reference should be made to the bibliography in Appendix B.

Correct Application of Devices.

The methods herein set forth of applying devices for the protection of circuits and equipment against the effects of lightning and other high-potential disturbances must of necessity be quite general. This means that, in the installation of devices of different manufactures which may utilize different principles of operation, details of method of installation will vary. Obviously, this report can not take account of all such details and it is therefore recommended that the user look to the manufacturer for detailed instructions regarding installation and operation of his equipment.

SEC. 40. SCOPE, ETC.

400. Scope and Purpose.

This part of the report deals with the protection against lightning of all circuits, and all apparatus connected to circuits used for general transmission, distribution, and utilization of electrical energy for power and railway purposes. Its scope is limited to the location and method of installing lightning arresters, irrespective of the method of operation.

The purpose is to set forth means and methods whereby the hazard to property, due to lightning, may be minimized.

SEC. 41. SPECIFICATIONS OF LIGHTNING ARRESTERS FOR RAILWAY AND POWER CIRCUITS

410. Voltage.

Lightning arresters shall embody on their name plates the maximum system voltage for which they are designed. The selection of arresters should be based on the maximum operating voltage which may exist for any period on the system or circuit where the arresters are to be installed. In no case should the operating voltage of the system or circuit exceed the maximum voltage rating of the arrester. The name plates shall clearly designate the manufacturer's name and the arrester classification.

411. Construction.

Arresters shall be of durable construction and preferably permit convenient inspection. Arresters for outdoor installation shall be inclosed in suitable weatherproof housings. Arresters for use on locomotives should preferably be inclosed in steel boxes.

412. Instructions.

Arresters shall be supplied with suitable instructions to enable the operator to properly install, operate, and maintain them.

SEC. 42. PURPOSE AND FUNCTION OF PROTECTIVE DEVICES

420. Lightning Arresters.

The purpose of a lightning arrester is to provide an intentional discharge path between conductor and earth for lightning and other transient overvoltages, which discharge path can be located at the terminals of apparatus or at other vulnerable points of the circuits. By virtue of the lightning arrester this discharge path is practically nonconducting at normal system voltage, but becomes automatically conducting at some voltage above normal, but below the safe insulation strength of the apparatus, and automatically restores itself to the nonconducting condition after each transient discharge.

421. Choke Coils.

Choke coils may be used with lightning arresters as a supplementary form of protection. A choke coil is an air-core coil of relatively small concentrated inductance which is inserted in series with the line conductor between the lightning-arrester connection and apparatus to be protected. The choke coil has greatest value when installed close to the lightning-arrester connection. In railway practice its use is generally warranted with arresters employing the series gap.

The function of a choke coil is to retard the travel of transient voltage waves coming toward the apparatus, and to cause complete or partial reflection of such waves at the point where the lightning arresters can most effectively discharge their energy to earth. In causing the reflection the choke coil takes the high turn-to-turn voltage stress attending reflection and thereby reduces the stress on the apparatus.

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422. Overhead Ground Wires.

The purpose of an overhead ground wire is to reduce the magnitude of the voltage induced electrostatically on exposed line wires by lightning. It acts as a partial shield or screen and thus reduces the electrostatic field between the line conductor and ground. It may also protect against a direct stroke of lightning by being itself struck. Overhead ground wires, on account of their high initial and maintenance cost, are not generally used on low-voltage circuits. Grounded conductors in overhead lines function to a marked degree as overhead ground wires in shielding other conductors of their own and adjacent circuits.

SEC. 43. RAILWAY CIRCUITS

430. Special Considerations in the Railway Protective Problem.

In general, electric railway systems should be equipped according to the best available methods of lightning protection. Several factors lead to this statement. First, one side (usually the negative for direct current) of the railway system is grounded, making possible the use of the tracks for a return circuit from any point of the system to the power house or substation. This means that lightning voltages are impressed between terminals of apparatus as well as between terminal and ground. Also, when a lightning arrester discharges, there is always the full voltage of the system applied to the arrester to impose follow current through the arrester. On the other hand, the practice of grounding railway circuits eliminates the possiblity of arcing grounds and their attendant high-frequency phenomena.

Second, the d. c. railway apparatus to be protected involves essentially rotary equipment, such as d. c. generators, rotary converters, traction motors, and the smaller air-compressor motors, all of which may be directly connected to exposed overhead circuits. It must be recognized here that while such rotary equipment meets its standards of dielectric tests, it is not possible to incorporate as large an insulation factor of safety above the standard test as can be had on stationary apparatus, such as transformers, where insulation space factor is less restricting to economy in design. Also, extra end-turn insulation, common in transformer design, can rarely be introduced in slot type of windings on rotary machines dealt with in d. c. railway practice.

Third, on the d. c. railway system, apparatus to be protected may be at any part of the system; that is, while the generating and substation apparatus is confined to definite locations on the system, the cars or locomotives may be at any point on the system.

Fourth, failure of electric railway apparatus by lightning may impose intolerable penalties in service interruptions and repair costs.

431. Methods of Protection.

Protection of railway equipment against lightning and other transient overvoltages is best accomplished by lightning arresters, which may or may not be supplemented with choke coils. Overhead grounded messenger wires will appreciably reduce the lightning voltage induced on exposed feeder or contact wires, but do not eliminate the need for lightning arresters.

432. Classification of Electric Railway Equipment.

For convenience in considering the protective practice, electric railway equipment may be divided into three classes as follows:

(*a*) Power houses and substations,

(*b*) Line conductors, such as overhead contact wires and feeders, and third or contact rails,

(*c*) Locomotives and cars.

433. Application of Lightning Protection and Installation Suggestions.

(*a*) Power Houses and Substations.—If the railway system is operating in a lightning territory and has exposed feeders or contact wires emanating from power houses or substations, lightning arresters should be installed and so located as to afford the greatest protective efficiency. This will generally include an arrester (omitting choke coil) on each station bus or bus section, and arresters with choke coils on each outgoing feeder or contact wire. The arresters and choke coils on the feeders and contact wires may be installed either indoors or outdoors, but should preferably be located at the point where the exposed conductors leave the building. Such location will insure that the arresters are on the line side of all feeder panels as well as the other station apparatus. The choke coil should be located in the line close to the point of line connection to arrester, and on the station side of the arrester connection.

The arresters on the station busses may not be necessary, depending upon the protective efficiency of the arresters on each outgoing exposed feeder and contact wire. However, bus arresters represent a second-line defense and their use may prevent damage to the generating, transforming, or converter equipment in cases of very severe lightning which might exceed the capacity of the feeder arresters.

Where feeders leave a station through underground cables, individual arresters on such feeders may be omitted, this depending largely on the length of the cable to the nearest exposed overhead line connection. Where such cable feeders do not have arresters, the use of station bus arresters becomes very essential, and the use of arresters at the junction of the cable feeder and any exposed overhead line is important in safeguarding both cable and station equipment. With arrester installations on cable feeders, choke coils should generally be omitted. Where the cables are short the feeder arresters may be installed in the station.

When arresters of the more restricted discharge capacity are used, the installation of two or more such arresters in parallel may be justified, particularly on important station busses. The size of conductor for connecting arrester to line should not be less than a No. 6 A. W. G. copper or its equivalent in conductance.

(*b*) Line Conductors, Feeders, Contact Wires, and Third or Contact Rails.—The value of line lightning arresters is rather difficult to determine. Generally, they are secondary in importance to arresters on station and car or locomotive equipment. Where railway systems are operating in regions of severe and frequent lightning, the use of arresters along the exposed feeders and contact wires will unquestionably decrease the hazard to rolling stock and station equipment. While recommendations can not be made generally for the use of line arresters, there is increased favor for them among some railway companies. In deciding the question of employing line arresters, the efficiency of the station and car arresters must be taken into account. If the protective efficiency of the station arresters and car arresters is of the highest order, line arresters may not appreciably reduce the lightning failures in station or car equipment. If, however, station and car arresters have lower protective ability, the presence of line arresters may very appreciably reduce the lightning damage to equipment and service interruptions. Line arresters in any case will unquestionably improve the protection of the system as a whole, but whether their expense is justified by reduced lightning troubles depends upon the efficiency of arresters provided for the apparatus, the severity and frequency of lightning in the region of the system, and the safety factor of the apparatus insulation.

Where line arresters are used, they should preferably be installed on the pole or bridge supporting the contact wire and as near as possible to points where feeder and contact wire are tied together (commonly called feeder taps). The number of feeder taps varies widely on different systems depending on voltage, load, size of feeder, etc., and the number of line arresters may also vary depending on the number of feeder taps and the severity of lightning in any given locality on the system. The number of line arresters to be installed per unit of length of line depends upon the value of apparatus protected, the requirements in continuity of service, the safety factor in line and apparatus insulation, and the cost of the arresters and their maintenance. This must be studied for each individual system.

Arresters for line use should be weatherproof, and require a minimum of maintenance. They should be positive in their ability to prevent follow current as any failure in this respect results in a short-circuit which might be difficult to locate among a large number of line arresters.

Where signal mechanisms or other line apparatus are located at points along the line wires, line arresters may be so distributed as to offer maximum benefits in protecting such signals. Such line equipment may justify line arresters at their terminals where line protection might otherwise be unwarranted. This depends on the type of mechanism, its susceptibility to damage by lightning and the importance of its service continuity.

The connection from line-arrester terminals to line wires or feeders should not be smaller than No. 6 A. W. G. copper or its equivalent in conductance.

The contact or third rails may experience voltage surges produced electromagnetically within the circuit by sudden interruptions in power current flow. Such cases are not often encountered in general practice, and where they do occur they should be made the subject of a special investigation.

(*c*) Locomotive and Car Equipment.—If a railway system is operating in a lightning territory and has exposed overhead feeders and contact wires, lightning arresters should be installed on each locomotive or car to protect the motors and auxiliary car equipment against damage. The arresters should be so installed and located as to afford the greatest protective efficiency to the entire car equipment. Generally a choke coil is a valuable supplement to car or locomotive arresters, but may not be justified where the protective efficiency of arresters is of the highest order. The value of the choke coil is generally greater with the series-gap type of arrester where time lag of the gap must be overcome before the discharge path of the arrester becomes conducting to transient voltages.

The effectiveness of arresters hinges appreciably on their location with respect to car wiring and equipment. In all cases advantage is had from the protective standpoint by locating the arrester close to the base of the current collector (trolley pole or pantograph) on the roof of the car. Should the car be of wooden construction, the same location of the arrester and choke coil is recommended.

434. Lightning-Arrester Grounds.

(*a*) Station Arresters.—Station and substation arresters should be grounded to the main station ground bus.

For methods of obtaining adequate ground connections for lightning arresters reference is made to sections 46 and 47.

(*b*) Line Arresters.—The grounding electrode for line arresters shall consist essentially of driven pipes or rods installed as close as possible to the base of the pole or bridge supporting the arrester. Where line arresters are installed on grounded steel bridges, towers, or poles, the arrester ground may be supplemented by an extra ground wire from the arrester to the nearest part of the grounded steel structure. For methods of obtaining adequate ground connection for lightning arresters, reference is made to sections 46 and 47.

It is usually preferable to connect the lightning-arrester ground lead to both the ground rod and the track rails. Where this is not possible the connection should be made to the ground rod only. It may be impossible to connect to the track rails in the following cases: (1) Where ground-current flow from the track to arrester ground or vice versa would promote serious electrolytic action by current flowing from the arrester ground electrodes to adjacent piping or underground conducting systems; (2) where such interconnections would seriously interfere with the system of block signaling.

(*c*) Cars and Locomotives.—The best ground connection for car and locomotive arresters is obtained by the contact of trucks to the track rails. While the track may not be actually connected to earth, the track represents a large-capacity ground for lightning or transient discharges. The arrester ground terminal may be connected directly to the steel roof or frame of the car making the arrester ground wire as short as possible. With all-steel cars or locomotives having roof, body, and frame of steel which is continuous to the trucks, it is not necessary to extend an arrester ground wire down to the truck. If a choke coil is used it should be inserted close to the collector bus in the main circuit which supplies current to the controllers and all auxiliary equipments such as lights, heating units, and compressor motors.

In the case of cars of wooden construction the grounding wire should be carried as straight and direct as possible to the motor frame of the nearest truck. Arrester line and ground leads should preferably be separated from other car wiring by 12 inches, and the paralleling of the arrester-to-ground discharge path to any other circuits should be avoided. Lightning-arrester line and ground wires should not be inclosed in iron conduit unless bonded to that conduit at each end. Wires connected to opposite terminals of a choke coil should preferably be kept separated by not less than 12 inches. The line connection of any lightning arrester shall not be less than a No. 6 A. W. G. copper wire or its equivalent in conductance.

SEC. 44. POWER CIRCUITS

440. Selection of Equipment in Relation to Flashover Voltages.

The need for protection of power circuits and apparatus against failures because of lightning potential is largely dependent on the requirements for service continuity. The possible saving in cost of apparatus repairs or replacement is appreciable, but, in general, this alone can not justify the extended use of equipment of the kinds now available. The present trend of system design toward large generating units, planned for economic generation and interconnected to effect load-factor economies, accentuates the need for protection.

Considering the problem in this light it is evident that the system of protection must include not only the protective devices employed, but also the coordination of insulation design on the line, in the station, and in the equipment.

The line is designed to give reliable service, within the limits of available equipment, by selection of proper insulators and, where necessary, by the use of overhead ground wires. Whatever the design of the line, there will almost certainly be some induced voltages high enough to cause flashover. In the present state of the art, such flashovers are unavoidable, and constitute a weakness in the protection system. They do, however, impose a limit on the potentials which reach the most vital parts of the system and thus define the design of station insulation, the selection of station equipment, from the standpoint of insulation, and the characteristics of protective equipment.

Because cloud discharges occur at random over the area covered by the system, and because the transmission and distribution circuits are of large extent as compared to the stations, most of the lightning potentials will originate in the circuits and very few in the stations. These high-potential disturbances must then, in general, travel over the circuits to the stations. If the line insulation does not flash over, the potential reaches the station reduced according to the distance traveled. The limiting case is where the point of origin is near the station. If in this case the line insulation flashes over, only the first part of the transient reaches the station and there is no reduction in its initial value. The upper limit of the potential which reaches the station is thus dependent upon the line insulation except for those rare occasions when the cloud discharge takes place directly over the station.

This upper limit is not a fixed voltage value for any particular line insulation, but varies between the crest value of 60-cycle dry-flashover voltage for transients of long wave front to several times this value for transients of steep wave fronts, as in the case where the static field gradient is such that the resultant conductor voltage would be many times the flashover value of the insulators if it were not for the fact that the flashover occurs. But the maximum value is not necessarily the most dangerous to apparatus insulation because it is of very short duration.

From these considerations it is possible to get an idea as to the voltages which may reach the station.

Unprotected station insulation, such as bus-bar supports on the line side of the arrester, must be equal in flashover value to the line insulation if flashover is to be prevented at such points. In the case where the line is on wood poles and the station structure is steel, the unprotected station insulation must be selected with the extra surge insulation value of the wood poles in mind.

In order to prevent apparatus failure and service interruption, apparatus insulation and arresters must be selected so that flashover of bushings and puncture of insulation do not occur.

The transformer should have the highest insulation, the transformer bushing the next, and the transmission line insulators in the vicinity of the station next. This is subject to modification, however, by the protective apparatus provided.

441. Protection at Stations.

Stations are often of considerable extent, and thus an appreciable problem is introduced as to the location of protective equipment. It is the common practice to place lightning-arrester protection at the point of entrance of overhead lines to the station or substation on the line side of all station equipment. Certain situations may arise where, if it is attempted to protect the bushings of the circuit-breaker at the entrance to the station by connecting the arrester on the line side of this breaker, and if there is considerable length of circuit between the arrester and the transformers, the reduced voltage transient which passes the arrester, and which in itself is harmless to the apparatus, may be doubled in value on account of reflection at the transformer. This increased voltage lasts, in the case of steep wave fronts, for the time required for the transient to travel from the transformer to the arrester and back to the transformer, and may be dangerous. If, on the other hand, an attempt is made to avoid this by placing the arrester at the transformer terminals, all the station insulation must have a transient-voltage flash-over value greater than that of the line, and apparatus bushings of higher cost may be required.

An alternative sometimes employed is the use of arresters at the point of entrance of the line to the station and at the transformers. Sometimes choke coils can be used to compensate for the circuit length within the station.

Conditions are so various that it is necessary to study the design of important stations individually and insure proper coordination of line insulation, station structure insulation, lightning arresters, apparatus insulation, and choke coils.

442. Protection on Distribution Circuits.

The foregoing applies to the protection of substations and generating stations where the circuit length is considerable and the connected apparatus is separated by several miles. The conditions are different on circuits, such as distribution and series lighting circuits, where the apparatus is connected at close intervals along the circuit.

For this condition a high degree of protection will, where required, be secured by connecting arresters to the circuit at each transformer, motor, or other important piece of equipment, but where installations are very close together, as in urban distribution systems or at industrial plants, arresters need not be spaced so closely.

Such a system of protection operates by providing paths to ground at the point on the circuit where the transient potential originates. The transient does not travel along the circuit; or does so to a very limited degree. Many arresters usually operate on each occurrence of overvoltage.

Owing to the need for many units, economic considerations have led to the use of small-size arresters for this service, even at a reduction in protective value. Because of the fact that each overvoltage occurrence is taken care of by several arrester units, these small arresters of reduced protective value have been found to give satisfactory results. Moreover, the use of arresters at frequent intervals along the circuit has a marked influence on the frequency of line-insulator flashover, and thus acts in this way to improve service continuity.

Circuits carrying voltages of the order used in house lighting and ordinarily referred to as lighting circuits do not usually require lightning protection. This comes about for two reasons. First, neutrals are grounded, small clearances are used, and they are almost always screened by buildings and other structures in such a way that the effect of lightning is not so marked. Secondly, they are for the most part rather short and low in height so that the voltage induced is correspondingly low in value.

443. Protection of Street-Lighting Circuits.

Street-lighting practice almost always involves constant-current series circuits. These circuits may be operated with either alternating or direct current. The protection of these circuits differs slightly from that of constant-potential circuits. The voltage of constant-current circuits, in general, increases with the number of lamps in service. The voltage is maximum at the time of dropping full load, due to the current-regulating devices. This maximum is generally about 25 per cent above full-load voltage.

In districts where lightning is prevalent, suitable lightning arresters should be used to protect the station equipment and at any point where an overhead circuit joins a section of underground cable. No protection is required where the circuits are entirely underground.

The type of lightning arresters required for these circuits depends upon whether the circuits are operated with direct or alternating currents. The voltage rating of the arrester should slightly exceed the maximum voltage of the circuit as defined above.

444. Line-Transformer Protection.

In former days there was a distinction between transmission lines and distribution circuits, which appeared to be fairly distinct. Transmission lines were considered to be those circuits for transmitting current at high voltage between one generating station and another generating station or substation, and to which there were made no connections for service to customers. With the developments in recent years, some companies have found it expedient to supply transformer installations connected to a transmission line at locations remote from the terminals, and such a practice is followed by some companies up to a value of 44 kv., 3 phase. Other companies consider as transmission lines certain of their lines which are operating at about 5 kv., 3 phase.

To secure the most complete protection, there should be a suitable lightning arrester connected to each wire of the 3-wire or 4-wire transmission line or distribution circuit at the point where the transformer is connected. For the neutral wire of a 4-wire 3-phase line or distribution circuit to which transformers are connected, a different type and cheaper arrester than those used on the phase wires is quite sufficient. This would mean that if there are several transformer installations connected through suitable switches or fuses to transmission lines, there should be a lightning-arrester installation at each transformer installation; in urban distribution, particularly in some of the larger cities where separate transformers are installed for lighting or power and, perhaps, for other classes of service, a study must be made to determine the proper location of arresters, to give an adequate degree of protection.

If other apparatus, such as switches, is connected to an overhead line, and if its insulation is not materially better than the insulation of line transformers, then such apparatus should be considered in exactly the same class as transformers in determining upon the lightning protection.

Where power motors are connected directly to an overhead circuit, as in the case of 2,300-volt or 6,600-volt motors for large loads, especial attention must be given to lightning protection. As has been pointed out in connection with railway-circuit protection, rotating equipment of necessity has less insulation factors of safety over the standard test and operating voltage than do transformers, and extra end-turn insulation common in transformer designs can not be readily introduced on rotary machines. For this reason the requirements for protection are more rigid in the case of motors connected directly to overhead circuits than in the case of transformers, and correspondingly greater protection is required.

The best practice in such installations is to use arresters of high quality, giving especial attention to installation, and making certain that the ground connections have low resistance. This may call for the use of several ground rods in parallel, and short grounding conductors. If the arrester is not connected directly at the terminals of the motor, it should at least be connected as close to the building entrance as possible.

445. Classes of Arresters for Protection of Apparatus on Overhead Lines and in Stations or Substations.

In arresters for the protection of a transformer installation on an overhead line, the amount of current at high voltage which can reach that transformer installation can be determined. In designing arresters for line use, the manufacturers have determined the discharge capacity by these considerations. For installation at generating stations or substations where there are a number of transmission lines, and where greater discharge capacity is required in order to secure the same degree of protection, some of the companies have designed or have produced a line of arresters called "station-type arresters" which have considerably greater discharge capacity than the arresters for installation on the line. Due consideration to the difference in the characteristics of the two types of arresters should be given in planning lightning-arrester installations.

The distribution-type arresters are designed to give adequate protection to transformers connected to circuits which, by reason of their characteristics and the presence of additional arresters on the same circuit, impose only a moderately severe duty on the arrester. Because of the large number of small transformers to be protected, usually scattered over a wide area, many arresters are required which must necessarily be relatively inexpensive.

The station-type arresters are designed to satisfactorily protect equipment located on lines where the duty of the arrester by virtue of the characteristics of the circuit, is generally very severe, both with respect to impulse voltages and currents. Usually the circuits are longer, the line insulation higher, and the importance of continuity of service even greater than found with distribution circuits. The station-type arrester is larger and more expensive than the distribution arrester, but the installations are fewer in number, and the equipment being protected more valuable. The station arrester, because of greater operating-voltage variations, requires a greater factor of safety.

SEC. 45. OVERHEAD GROUND WIRES

450. Reduction of Induced Voltages.

Calculations as well as laboratory tests (see Appendix B) show that overhead ground wires appreciably reduce the voltage that may be induced on transmission lines by lightning.

According to various investigators the reduction in induced potential which may be expected for various numbers of overhead ground wires is approximately as follows: One ground wire, 30 to 50 per cent; two ground wires, 50 to 65 per cent; and three ground wires, 60 to 75 per cent.

In arriving at these figures it has been assumed that there is positive grounding at every tower, that there is the minimum practicable spacing between ground wire and conductors, and that the ground wire itself has very low impedance.

Thus, if the possible induced voltage without ground wire were 1,000,000 volts, a 50 per cent reduction would bring this to about 500,000 volts, which would prevent flashover on a line insulated for 600,000 volts. On the other hand, the reduction from 1,000,000 to 500,000 volts would be of no avail on a line insulated for 350,000 volts. However, if the lightning stroke occurred farther away, the induced voltage would

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be less, say 600,000 volts. Then a 50 per cent reduction would bring the voltage below the flashover strength of the insulators. Because of construction, the elevation above ground, and the system of connections, these voltages are not, in general, experienced on secondary low-voltage circuits.

On account of the nature of the lightning discharge there is considerable time lag in the arc over of the insulators; that is, a much greater voltage is necessary to flash them over than at 60 cycles. For example, an insulator which flashes over at 500,000 volts, 60 cycles may require 1,000,000 volts or more if the wave is of very steep front and of sufficiently short duration. From this it follows that a reduction of 30 per cent or more in induced voltage may prevent 80 to 90 per cent of the flashovers on a line whose insulation strength is comparable to the average voltage induced by lightning and a correspondingly smaller percentage on lines whose insulation strength is less.

451. Protection to Stations.

It is generally agreed that the steep wave fronts induced by lightning are rapidly damped out by the resistance of the line conductors, so that as a rule they do not travel any great distance. Nevertheless, a certain percentage of the overvoltages are induced near stations, and those induced farther away sometimes arrive at stations with sufficient remaining voltage to endanger apparatus. Thus, any reduction caused by the ground wire assists in protecting the apparatus connected to the line.

Also, by acting as a short-circuited secondary, ground wires may aid in reducing voltage at stations, by damping out the wave of discharge; that is, ground wires not only lower the induced voltage, but also reduce that voltage further by more rapid attenuation where the surge is propagated for a considerable distance.

Ground wires assist in relieving a system by reducing the ground resistance in some cases, and by providing a positive ground return for the short-circuit current.

In determining the advisability of installing a ground wire on the lower-voltage lines, it is necessary to carefully balance the cost with the advantages of safety and service secured.

On very low-voltage systems, it can hardly be expected that ground wires would reduce the voltage below the flashover strength of the insulator.

Ground wires which have insufficient strength or which are not properly installed, may cause trouble due to breaking, swinging into transmission conductors, etc. This is not an argument against the efficiency of ground wires, but rather against the use of unsuitable or improperly installed ground wires.

452. Materials, Wire Sizes, and Method of Installation.

It is desirable that ground wires should have a low impedance, be made of rustproof material, and have approximately the same sag as the line conductors. They may be made of the same size and material as the line conductors, but, if this is not considered economically practicable, there may be used a copper-covered steel wire in which the copper and steel are intimately welded together. The conductor should be of a size to prevent corona and to give sufficient mechanical strength.

In order to prevent crystallization due to vibration of the ground wire, special methods of support have been devised which are being tried out on important lines. In general, the ground wire maintains a sufficiently good contact with the tower frame, but where this is not adequate, the use of a jumper may be desirable to insure good conductance over the ground-wire clamp to the tower.

On steel tower lines the earth footings will ordinarily serve as sufficient connection to the earth itself. Where, because of the character of the soil or foot supports, this connection is not sufficient, additional facilities, where practicable, shall be provided, such as connections from the tower structures to separate pipe grounds or connection between towers. It is believed necessary that special attention be paid to obtain good grounds, as in some cases the total short-circuit current due to accidental flashover may be concentrated at a few points instead of being distributed among a great many points. The resistance should be kept as low as possible.

In case of wooden-pole lines a conductor should be run from the ground wire to the ground at frequent intervals. Obviously the best results will be secured by grounding at each pole, except where this may incur such increased hazards to linemen or other operating difficulties due to carrying the ground potential up along the pole, that a modification may be found to be desirable.

With wood-pole construction in dry climates, pins are generally left ungrounded to take advantage of the extra insulation afforded by wood poles and cross arms, and in such cases the omission of ground wires may be justified. Wherever salt, alkali dust, etc., make uncertain the insulation afforded by the wooden structure it is generally considered advisable to ground the pins to avoid burning of cross arms, etc. Here there is nothing gained by omitting ground wire, and its installation presents the same advantage as on steel structures.

SEC. 46. LIGHTNING-ARRESTER GROUNDS

460. Impedance of Ground Connections.

(*a*) GENERAL.—The purpose of grounding lightning arresters is to secure a permanent path of low impedance between the arrester and the earth.

The problem of grounding lightning arresters is in many respects the same as the problem of grounding neutrals of power systems. Solutions to these two problems differ because of the relatively small amounts of energy and of the steep wave fronts involved with the functioning of lightning arresters.

The total impedance of a connection to earth is made up of the impedances of the following elements:

1. The grounding conductor.
2. The connection between the grounding conductor and the ground electrode.
3. The ground electrode.
4. The contact between the ground electrode and the soil.
5. The soil around the electrode.

The first two of these elements are discussed under corresponding headings and the last three under "Ground Electrode."

(*b*) GROUNDING CONDUCTOR.—Owing to the steep wave fronts of lightning-arrester discharges the potential drop in the grounding conductor is mostly inductive, and, consequently, attention should be centered on constructing this connection with a minimum of self-inductance. To attain this end, the connection should be as short and as straight as possible. Beyond a certain size, the self-inductance is not appreciably diminished by increasing the size of the conductor. In practice it is usually found that when the conductor is large enough to provide mechanical strength, any further increase does not considerably reduce its self-inductance. When a lower self-inductance is required, it can best be obtained by arranging more than one grounding conductor in parallel; for instance, one on each side of a pole.

Where exposed to mechanical injury, as near the base of a pole, a grounding wire should be protected with a covering of wood or other insulating material. A grounding wire should never be run through a metallic conduit, unless electrically bonded to both ends of the conduit. Unless this is done, the metallic conduit increases the potential drop in the conductor.

(*c*) Connection Between Grounding Conductor and Electrode.—The connection between the grounding conductor and the electrode is of the highest importance. It should have ample area of contact, should be strong mechanically, and should be kept above the ground if possible. Contact of different metals underground should be avoided so as to avoid the deterioration which would result from galvanic action. When unavoidable, such joints should be coated with tar, pitch, or paint, which will insulate the joint from any electrolytes which may be present in the soil.

In connecting the grounding conductor to a buried plate the conductor should be run along the plate and connected to it at several points. The contact should be such as to be maintained mechanically, whether to a copper plate or a galvanized iron plate or pipe, but this connection should be soldered also whenever possible.

The connection to a buried electrode should never be made by a single underground conductor, since a mechanical injury to that conductor might escape detection and render the entire system inoperative. Such underground connections should consist of several conductors run in parallel, and laid slack so as to decrease the danger of mechanical injury.

(*d*) Ground Electrode.—The total impedance between a ground electrode and the earth is made up of the following:

1. The impedance of the electrode itself: This is inappreciable compared with the total ground impedance, except in the case of grounds to extensive water-pipe systems.

2. The contact resistance between the electrode and the soil: This is relatively small in properly constructed grounds.

3. The resistance of the soil: This depends upon the size of the electrode, upon the resistivity of the soil, and upon the distribution of the current, the latter being largely a function of the general form of the electrode.

(*e*) Resistivity of the Soil.—

(1) *Character of the soil.*—The conducting properties of the soil depend almost entirely on the presence of solution of acids, salts, or alkalies. The lowest ground resistances are usually obtained in fine loam or clay. The presence of sand, gravel, or stones increases the resistance.

(2) *Effect of moisture.*—The resistivity of the soil increases very rapidly when its moisture content is decreased below about 15 per cent. It is therefore of the utmost importance that the ground electrode penetrate sufficiently the permanent moisture level. When the moisture content is increased above 15 per cent the resistivity is not materially decreased.

Ground electrodes should never be placed in bodies of relatively pure water, for instance, mountain streams or lakes, since the conductivity of such water is very low.

(3) *Effect of temperature.*—Above freezing, a change in temperature causes a change of about 2.5 per cent per ° C. in the resistivity of soil, but below it the resistivity increases more rapidly as lower temperatures are reached. Consequently, ground electrodes should always extend below the frost level.

(4) *Artificial treatment of soils.*—In order to obtain a sufficiently low ground resistance in soils of high resistivity—that is, soils containing much stone, gravel, or sand—the

resistivity of the soil around the electrodes may be reduced by treatment with a salt solution, or a high-resistance soil around the electrode may be replaced by a good conductor, such as coke.

The treatment with a salt solution consists usually in placing around the electrode some soluble salt in granular form, covering the whole with soil, and saturating it with water.

Common salt is quite satisfactory for this purpose and is most commonly used because it is quickly soluble, inexpensive, hygroscopic, and greatly reduces the resistivity of the soil. It has a corrosive effect on the ground electrode, but not to such an extent as to prohibit its use.

Other substances which have been used for the purpose are calcium chloride and sodium carbonate. These do not cause as much corrosion as common salt, but calcium chloride is comparatively expensive, and a solution of sodium carbonate has a resistivity which is high compared with that of a common-salt solution. In recent times copper sulphate has been successfully employed. Its solution has a high conductivity and it is claimed that it does not produce corrosion.

Besides corrosion, the principal disadvantage of any salt treatment is that the salt is leached into the surrounding earth and must be replaced. Grounds treated with salt, therefore, require periodic attention.

Treatment with coke consists in replacing the high-resistance soil around the electrode with coke, which has a good conductivity when well packed. Similarly to common salt, the use of coke results in corrosion of the electrode. Its chief advantage lies in its permanency and in the fact that its resistivity does not depend on its moisture content. Treatment with coke is not practicable in the case of driven grounds but is quite economical when buried-plate electrodes are used. The importance of tamping the coke well can not be overemphasized.

461. Water-Pipe Grounds.

Except under special circumstances, a water-pipe system constitutes the best ground electrode and should be used when accessible. The impedance of such a ground usually is lower than any that can be attained by means of artificial grounds, and the expense is less. The grounding of lightning arresters to water-pipe systems results in no appreciable electrolysis of the pipes because the quantities of electricity discharged are very small.

Owing to the considerable area covered by the ordinary water-pipe system, the resistance of the soil and the contact resistance between that system and the soil are negligible. The most appreciable part of the total impedance is usually that of the pipe itself and of the joints between the pipes. In certain cases this impedance may be so high as to prohibit the use of the water-pipe system as a ground electrode. Such a case may arise—

1. When the joints between the pipes are made of some high-resistance material, such as Portland cement.
2. When the only accessible water pipe extends a great distance before connecting to the main pipe system.

462. Other Underground Structures.

When a suitable water-piping system is not available, metal well casings, or other underground metal structures may be used, but structures exposed to contact with the public, such as the frameworks of buildings, metal drain pipes, fences, track rails, etc., should not be used, except that track rails may be employed for grounding railway lightning arresters. During heavy lightning discharges such structures may have high potentials to ground, and if exposed, would constitute a hazard.

Lightning arresters should never be grounded to gas pipes.

463. Artificial Grounds.

(*a*) General.—In the case of artificial grounds, the impedance of the electrode itself is usually negligible when compared with the total impedance between the electrode and the earth.

The contact resistance between the electrode and the soil is also negligible if the soil around the electrode is packed well, and if the surface of the electrode is kept free from paint, grease, or other insulating material. Iron rust on the surface of the electrode has little or no effect since it is permeable to water and has no greater resistance than the soil around it.

The principal factor in the total impedance between the electrode and the earth is the resistance of the soil around the electrode. This depends on the resistivity of the soil, which has been discussed already, and on the distribution of the current, which in soils of uniform resistivity is solely a function of the general form of the electrode, and in non-uniform soils is a function of both the nature of the soil and the form of the electrode.

The electrodes commonly used are driven pipes or rods, or buried plates. The driven form of electrode generally costs least to install, and is therefore used wherever practicable.

(*b*) Driven Pipes or Rods.—As already mentioned, of all the forms of artificial grounds, driven pipes or rods are usually the least expensive to install and should be used except when the soil is underlaid with rock or is so stony as to prevent driving, in which case buried electrodes of considerable area, such as plates or strips, should be used in order to obtain low resistance. The advantages of driven pipes or rods are:

1. Ease of construction and low cost.
2. Minimum requirements as to ground space.
3. Little or no excavation.
4. Multiple grounds can easily be provided.
5. Connection to pipe or rod is above ground and, therefore, is accessible for inspection.

There is no difference as to electrical characteristics between pipes and rods. For the same diameter, rods are more expensive, but are sometimes easier to drive because of greater mechanical strength. In certain localities the ground may be too stony to drive ordinary pipe, but may be penetrated with the stronger solid rod. Also, it is possible to obtain ground rods covered with copper which, in some cases, increases the resistance to corrosion.

There are several factors which influence the resistance of driven grounds. These factors are as follows:

(1) *Depth of driving.*—Increased depth of driving makes for lower ground resistance because of the greater cross-sectional area of the soil path of the current, the greater penetration into moist earth, and the greater penetration below the frost level. In soil of uniform resistivity little is gained by driving the pipe or rod beyond a depth of 8 feet (2.5 m). Under ordinary conditions, however, the resistivity of the soil is far from uniform, because of the freezing of the upper layers, because of their dryness, and because of nonuniformity of soil. Artificial grounds should be located where practicable below permanent moisture level, or, failing in this, at least 6 feet (1.8 m) deep. Each ground should present not less than 2 square feet (0.2 sq. m) of surface to its exterior soil.

(2) *Size of pipe or rod.*—There is not sufficient difference in the elctrical resistance with pipes from ¾ to 2 inches

(1.9 to 5 cm) internal diameter, to justify a contention that any one size is best. Mechanical consideration and permanency govern to a considerable extent. One-inch (2.5 cm) pipes will usually prove satisfactory, though 1.25 and 1.5 inch (3.2 and 3.8 cm) sizes are considered better practice. Solid rods are usually smaller.

(3) *Pipes or rods in multiple.*—The use of several pipes or rods in multiple is often necessary to secure low resistance values. Since about 90 per cent of the total potential drop takes place within 2 feet (0.6 m) of the pipe or rod, the pipes or rods should be driven at least 6 feet (1.8 m) apart whenever possible. One pipe will then be kept out of the dense current path of another, and the resistance of the ground connection will vary almost inversely as the number of electrodes.

When the pipes can not be installed at this distance, as at the base of a pole for example, two or three pipes can be driven and the ground resistance may be reduced considerably thereby, although the pipes be only 2 feet (0.6 m) apart. At 6 feet (1.8 m) apart the resistance of two pipes in parallel is approximately 55 per cent of one of them, and at 2 feet (0.6 m) apart is approximately 65 per cent. It should be remembered that a pole butt constitutes a path of high resistance, and its presence between two ground pipes increases the resistance to earth.

(*c*) Buried Electrodes.—The usual forms of buried electrode grounds are buried plates, buried strips, and patented grounding devices.

In such cases the electrodes are usually embedded in coke since the presence of coke very appreciably lowers the total ground resistance without adding much to the expense, because little additional excavation is necessary.

(1) *Plates.*—Plate electrodes should be buried from 5 to 8 feet (1.5 to 2.5 m) underground. Placing of plates deeper

than 8 feet (2.5 m) increases considerably the expense of the installation without any corresponding decrease in resistance in soils of uniform resistivity. In any case, however, the plates should be set below the permanent moisture level.

Plates may be set either flat or on edge. The latter form is preferable, although less common, as it usually requires less excavation for the same average depth of setting and results in better contact between both sides of the plate and the soil.

The shape of the plates should be long and narrow, both because the soil resistance is then lowered for a given area of plate and because excavation in the shape of trenches is usually more easily carried on than in the shape of rectangular wells, and this is of considerable importance in minimizing the cost of the work.

It has been found that there is no economy in the use of plates of more than 20 square feet (1.9 sq. m). Where two or more plates are set in parallel trenches, their separation should be from 25 to 30 feet (7.5 to 9 m).

Buried plates are usually of copper or cast iron, the latter preferably galvanized.

(2) *Strips.*—Buried strip grounds are used when bedrock is so near the surface of the ground that pipes or rods can not be driven, and plates can not be set deep enough to make an effective ground. A buried strip is the same as a very narrow plate, but with this form of electrode it is found that in soil of uniform resistivity there is little decrease in resistance below a depth of about 3 feet (0.9 m). For best economy, strips should not be more than about 20 feet (6 m) long and should be laid as straight as possible. A considerable ground area and system of buried conductors is usually required with this form of electrode.

(3) *Other forms.*—Almost any metal object of proper size can be used as a buried electrode. In selecting and installing such electrodes it should be borne in mind that the contact resistance at the surface of the electrode is usually a very small fraction of the total ground resistance, and, therefore, any increase in the contact area by means of corrugations or otherwise, has negligible effect on the total ground resistance. The soil resistance depends not on the contact area, but on the distribution of the current.

464. Separation of Grounds.

When artificial grounds are used it is advisable to connect in parallel as many of the electrodes as possible, so as to obtain a lower resistance. It is bad practice, however, to interconnect the grounds of high tension and low tension lightning arresters, or to interconnect the grounds of lightning arresters and system or equipment grounds, excepting in stations where the grounding system is extensive and all equipment frames and cases are interconnected with the metal framework of the station.

For generating stations and substations the use of a ground bus or its equivalent, grounded at more than one point, with all metallic structures included connected to this ground bus at various points, is recommended. All arrester and transformer neutrals should be connected to the same bus. This method establishes a metallic ground connection such that even if one of the individual grounding connections is lost, the resistance to earth of the ground bus does not change materially.

Where it is not desirable to ground the cases of transformers, as with distribution pole-type service, it is not economical to attempt any ground-bus scheme and, therefore, it is desirable to keep the lightning-arrester grounds separate between high and low tension sides of the transformer, and also separate from other grounds which may exist for other purposes. The chief danger here which may arise from the use of a common ground connection lies in the fact that at the time of discharge of the high-tension lightning arrester a dangerously high potential may be communicated to all metallic bodies connected to the same ground.

Where water-pipe systems are used as ground electrodes there is no objection to connecting both lightning arresters and other equipment to the same water-pipe system, because the resistance of the water-pipe system is very low and there is little danger that its potential will become dangerously high. Even in such cases, however, it is advisable to make each connection to the water-pipe system by means of a separate grounding conductor, and not to connect them by a common conductor. Otherwise, if a common conductor is broken, high potentials may be imparted to the other equipment grouped or multipled on the same grounding conductor.

The number of artificial grounds, minimum resistance, accessibility of apparatus grounded, guards, maintenance, tests, etc., is covered elsewhere in this report and in the National Electrical Safety Code. It is recommended that tests be made on a ground when installed, to ascertain whether the resistance is lower than the maximum specified.

SEC. 47. TESTING OF LIGHTNING-ARRESTER GROUNDS

470. Resistance.

The importance of low-resistance grounds for lightning arresters can not be over-emphasized. The protection against over-voltage afforded a system is dependent on the total impedance from the lines to be protected to the earth itself, and the ground resistance constitutes the major part of this impedance. Discharges of the order of hundreds of amperes being quite common, it is evident that high voltages may develop between the arrester and earth even for comparatively low ground resistances. The best arrester handicapped with a high-resistance ground will give only poor protection. Moreover, a high-resistance ground may cause high voltages to ground to appear on the grounding wires, which will introduce a possible hazard to persons or apparatus in contact with the arrester or grounding conductor.

The maximum allowable ground resistance depends on conditions, such as characteristics of the transmission line, arrester impedance, location of the ground in question on the system, and density of installation of arresters. It is difficult to lay down any general rule for ground resistance, each case requiring more or less individual treatment. The best approximation to a general statement that can be made is to say that the resistance should be low. If the number of arresters for a given length of line is high, the ground resistance may safely be higher, several grounds and arresters acting in parallel to drain the voltage from the line.

In order to be sure that the protection against lightning is the best obtainable, it is essential to measure the resistance when the ground is made or shortly thereafter, and advisable to check it periodically, besides making visual inspections Mechanical injury or corrosion may entirely destroy the protection. Yearly inspections are probably sufficient for this class of service. Periodic measurements of ground resistance are particularly important where a salt is used to improve the ground in order to ascertain whether and when the effects of the salt wear off. Tests when the ground is made may indicate the advisability of moving the connection to a different locality where better soil conditions exist.

There are several methods in use for measuring ground resistance. Four of these are described below.

471. Precautions to be Taken in Measuring Grounds.

First, it is well to mention the general precautions which must be observed in measuring the resistance of grounds. It is advisable to use alternating currents for this purpose, because direct current causes a polarizing action at the surface of the ground electrode, which introduces an error in the observed measurements. However, if a direct voltage of 100 or more is available, fairly accurate results may be obtained, the error introduced by polarization usually being not more than 4 or 5 volts. If direct current is used and temporary auxiliary grounds are required, special precautions must be observed in making these grounds, as described under 474 below.

In order to carry out the required measurements, it is necessary to establish at least one other contact with the earth. This may be an existing ground, such as a water-pipe system, a bonded-rail system, or other grounds already made. The resistance to ground of a large grounded system, such as a water supply, is usually so small that it may be neglected in comparison with the resistance of driven pipes or driven plates. It is, therefore, a good auxiliary ground to use, and, generally speaking, no correction need be applied to the measurements for the resistance of a water pipe or of a bonded-rail ground. However, in using water-pipe grounds it is nearly always necessary to connect to the system through the medium of a service pipe, which may contain high-resistance joints, although these are not met with frequently. Moreover, where they are present they usually indicate resistances which are obviously wrong. In this case the measurements may be checked by connection to another service pipe. If a bonded rail is used as an auxiliary ground, measurements should not be made while a car is drawing

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current through the rail. Of course, insulated sections of track can not be used for this purpose.

If a water or bonded-rail system is not available for use as an auxiliary ground, other existing grounds may be used, provided they are not too close to the ground to be measured. If there are no existing ground connections within reach, temporary auxiliary grounds must be made. One or two short pieces of pipe driven into the ground and soaked with water will do. The following precautions should be observed in making these auxiliary grounds. They should be sufficiently far from the ground on test and each other to avoid introduction of misleading errors. The greater the separation the better. Fifteen feet (4.5 m) as the minimum is recommended, although 6 feet (1.8 m) is permissible if the circumstances are such that much time and labor will be saved by using existing auxiliary grounds rather than new ones. If direct current is used for making the measurements, more care must be exercised in driving the auxiliary grounds than when alternating current is used. The resistance of the auxiliary grounds used for direct-current measurements should be equal to or less than the resistance measured because of the polarization effect mentioned above.

Care should be taken that no grounds exist on the circuit from which energy is being drawn, while the measurements are being made. This is one reason why a transformer is usually made use of to supply current for alternating-current measurement of ground resistance.

When measuring station grounds, the test connection to it should be made close to the ground electrode to avoid interference with protective relays in its ground wires. If the station ground resistance is high and the test current is large, some of the measuring current may go up the ground lead and out over the line to other grounds. It is always preferable to isolate the ground to be tested from the system if reliable results are desired. However, this is not always possible in the case of station grounds, so in this case prudence should be exercised in choosing the value of measuring current. This applies to ammeter-voltmeter methods only.

472. Method I (Ammeter-Voltmeter with Single Auxiliary Ground).

The simplest method is available when there is accessible as an auxiliary ground a large grounded system, such as a water pipe or bonded rail. In this case all that is necessary to obtain a reasonably accurate measurement of the resistance of the ground in question is to pass current through both in series, measure the total voltage, and calculate the resistance.

A modification of this scheme is shown in Figure 1 and may be used where the water-pipe ground has appreciable resistance. It requires an additional driven-pipe ground but eliminates the inaccuracies due to high resistance of the water-pipe ground.

473. Method II (Ammeter-Voltmeter Using Three Current Terminals).

The second method of measuring ground resistance is called the ammeter-voltmeter method using three current terminals. This is the most accurate procedure, especially if alternating current is used. Connections are shown in Figure 2. An insulating transformer is inserted so that line grounds will not be included in the circuit. Two auxiliary grounds must be used. Current is passed through each pair of grounds connected in series and the voltage measured. This will determine the resistance of the circuits R_{12}, R_{23}, R_{13}:

$$R_{12} = r_1 + r_2$$
$$R_{23} = r_2 + r_3$$
$$R_{13} = r_1 + r_3$$

Knowing the value of R_{12}, R_{23}, R_{13}, we have three simultaneous equations with three unknowns which we can solve for r_1, r_2, r_3, one of which is the ground under test.

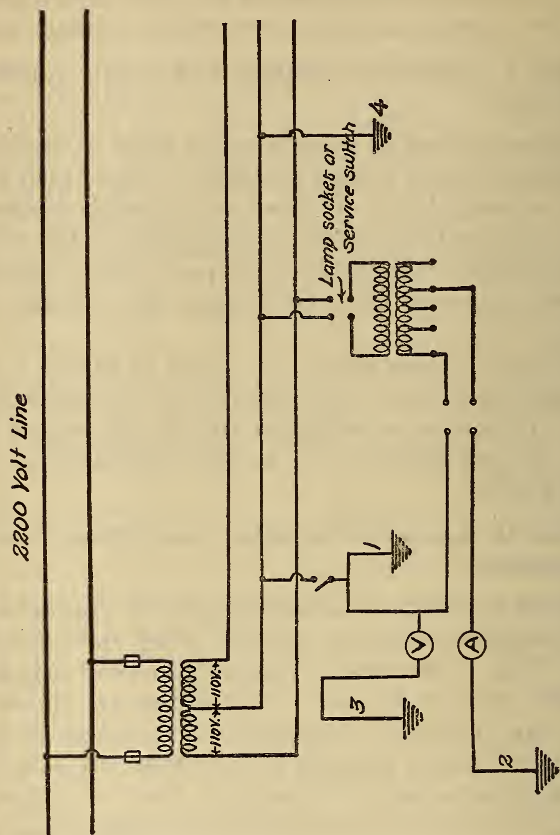

FIGURE 1.—*Ammeter-voltmeter method using two auxiliary grounds*

The resistance of *1* is determined by measuring the current through auxiliary ground *2* in series with it, and the voltage to ground through auxiliary *3*.

The precautions above should be borne in mind. If accurate results are desired, the transformer used should be capable of delivering a secondary voltage of approximately 100 volts, and should be equipped with taps for use in measuring low-resistance grounds.

If only direct current is available for the above method,

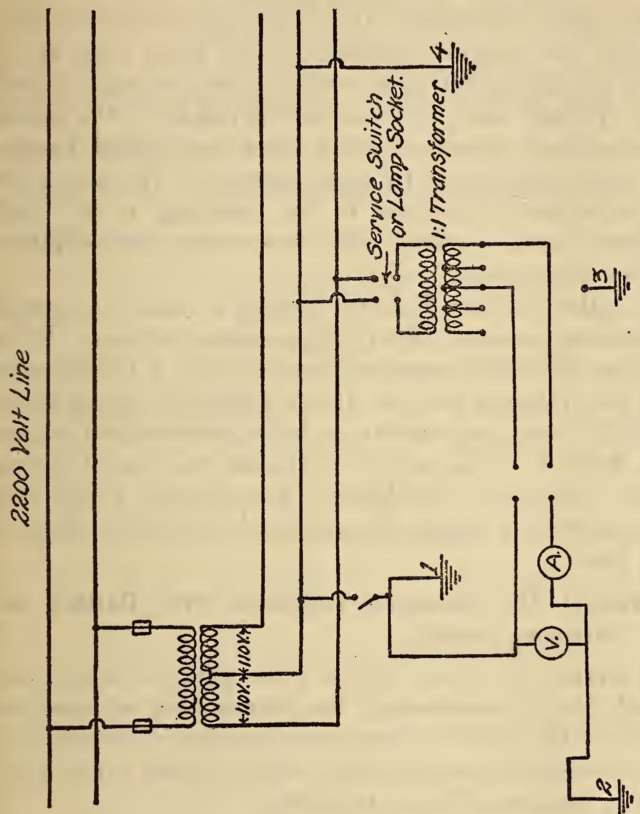

FIGURE 2.—*Ammeter-voltmeter method using three current terminals*

The resistances of *1*, *2*, and *3* are determined by measuring each pair in series. Connections are shown for measuring r_1+r_2.

good results may be obtained provided certain precautions are observed to preclude errors which are negligible if alternating current and an insulating transformer are used. As stated above, 100 volts at least should be applied to decrease the effect of polarization. However, this voltage will be shared by two grounds in series. The division of voltage may be such that the effects of polarization introduce considerable error. Therefore, it is important to exercise care in making the auxiliary grounds. Also there must be no grounds on the circuit from which energy is being drawn. If such grounds exist, and can not be removed, the direct-current method described above must be avoided because of the errors introduced by cross currents. The use of 100 volts introduces difficulties in the handling of the high measuring current which will flow when low-resistance grounds are measured.

The method indicated above requires a source of current, and necessitates connections to that source of current. When measuring lightning arrester grounds along a transmission system low voltages are not always accessible, the available source often being only the transmission line to which connection is difficult. This source of current may be of several different voltages so that different transformers would have to be available for testing, depending on which line voltage is within reach.

474. Method III (Ammeter-Voltmeter with Battery and Reversing Switch).

This method is outlined for use where great accuracy is not required, but is satisfactory for determining whether the ground is of the order of a few ohms or many. It permits the use of an entirely portable and self-contained outfit which can easily be carried in an automobile.

This is entirely similar to Method II except that a battery of about 24 volts is used as the source of current. The higher the battery voltage the more accurate will be the results.

Twenty-four volts is, in general, sufficient. The circuit is as shown in Figure 3.

Readings are taken with the switch in one position, then the polarity is reversed and the reading repeated. The mean of the two resistances thus obtained is taken as the resistance of the circuit. The ground resistances, r_1, r_2, r_3, can then be calculated as in Method II. This procedure overcomes in part the effect of polarization. It has certain limitations and

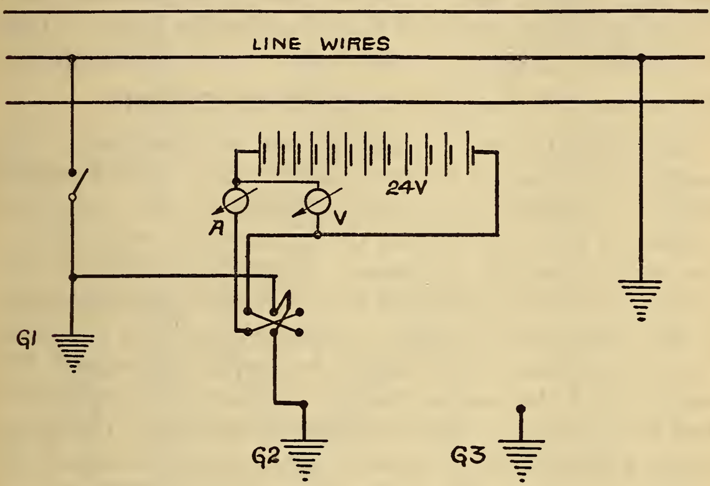

FIGURE 3.—*Use of battery and reversing switch*

too great reliance should not be placed on the results. The method requires a certain skill and technique, if even passable accuracy is desired. The readings should be taken as soon after the closing of the switch as possible and the switch then opened. Current should not be permitted to flow for any appreciable length of time before the meters are read. If this precaution is observed, it is possible to get the necessary data before polarization has gone very far. If a water-pipe or bonded-rail system is available for use as an auxiliary ground, the procedure may be simplified to a method similar to Method I.

This method should give results that are accurate within 10 or 12 per cent except in the case of very low ground resistances in the order of 1 or 2 ohms, in which case the percentage error will be greater. However, the method is generally satisfactory for determining whether a lightning arrester ground is good or bad. The fact that the apparatus is self-contained and portable and that it avoids the danger of false results due to grounds on the supply circuit recommends it.

475. Method IV (Bridge with Alternating Current).

This apparatus may be portable and self-contained. The results do not require as much calculation as in the foregoing method. The circuit is shown in Figure 4. The apparatus consists of a dry-cell feeding the primary of a small step-up transformer through a buzzer. Alternating current is thus induced in the secondary and applied to the current terminals of the bridge and grounds. A telephone receiver is used in place of a galvanometer to obtain balance of the bridge. The sensitivity of the receiver should be rather low, because it is then less responsive to disturbing stray currents. The bridge should preferably be a portable one. An outfit as used for locating faults in a line by the Murray or Varley loop tests may be used. The buzzer should preferably be of the type used in radio telegraphy. The size of the transformer is unimportant except that it should be as small as possible for the sake of portability. A ratio of 1 to 10 is preferable, but other ratios may be used. The procedure is the same as in Method III, two auxiliary grounds ordinarily being used. The resistance of each pair in series is measured and the resistance of the ground in question calculated.

If a water-pipe or bonded-rail ground is available for use as an auxiliary, the resistance may be measured in a manner similar to Method I.

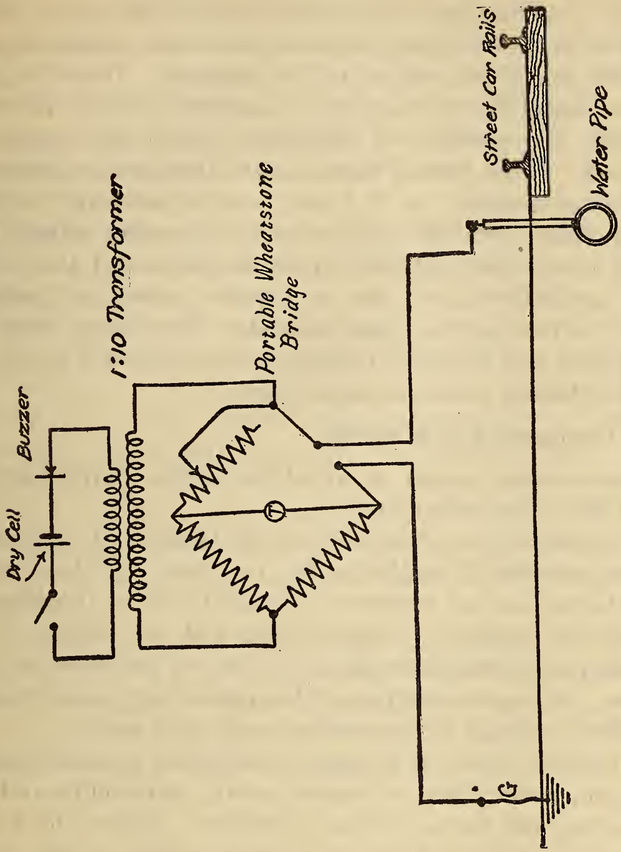

FIGURE 4.—Use of bridge to measure resistance of a pair of grounds in series

The method here described has the following advantages: The source of energy constitutes a part of the apparatus and is small. The complete outfit is low in weight, easily portable, and rugged. Where much testing is to be done, a permanent set-up can be made. The results require less calculations than ammeter-voltmeter schemes.

The disadvantages of the method should be noted. Stray currents in the earth may cause so much noise in the telephone receiver that a balance can not be obtained. If care is taken to disconnect the ground being measured from all electrical circuits, the chances of difficulties from this source are reduced. If the ground connection is attached to a circuit of considerable extent, or if a long wire is necessary to reach the auxiliary ground, inductance and capacity effects may make it extremely difficult to obtain balance of the bridge. The method requires that a certain amount of pains be taken in making the measurements. Familiarity with the apparatus and a certain technique are required if results are to be obtained in the minimum time.

476. Comparison of Methods.

The question arises as to which of the above-described methods is the preferable one.

When accurate results are desired, Method II using alternating current is undoubtedly the best. It has certain drawbacks, and on extensive systems is rather troublesome. Where the system is concentrated and low-voltage distribution is everywhere available it is to be preferred over the others. It is particularly useful in measuring station grounds in which case the set-up can be made very easily.

When the system is extensive, and many grounds must be checked, particularly at remote points, portability and ease of making the test are prime requisites. Where the desired accuracy is not too great, and results within 10 per cent of correct value are generally sufficiently reliable for the resistance of lightning-arrester grounds, Method III or IV is to be recommended.

The apparatus used in Method IV is the most portable of all, but, as indicated, it has certain limitations. It is usually inapplicable to measuring station grounds which must be left on the line, because of noise in the telephone receiver. For measuring only lightning-arrester grounds which can be isolated from the line, and when a large number of grounds are to be checked, Method IV works out satisfactorily. The apparatus is more expensive than that required for Method III unless a portable bridge is already part of the operating company's equipment.

Where all sorts of grounds must be checked, Method III is probably to be preferred, because the apparatus is portable, rugged, and easily handled after a little practice. Every operating company has meters which may be used in this set-up, so that only the outlay for the battery is required.

Several portable ground-testing instruments are available for making a comparatively rapid measurement of ground resistance. These are of the bridge or ohmmeter type. They require auxiliary reference grounds, as do the previously described methods, but possess the advantages of portability, direct indication of resistance, and safety. The instruments make use, in general, of either Method II or Method IV.

For a thorough detailed discussion of grounds, reference is made in general to section 46, and the bibliography contained in Appendix B, and specifically to Technologic Paper No. 108 of the Bureau of Standards entitled "Ground Connections for Electrical Systems," by O. S. Peters.

PROTECTION OF COMMUNICATION AND SIGNALING CIRCUITS AND EQUIPMENT

INTRODUCTION

Need of Protection.

Potentials greatly in excess of the normal working voltages may be impressed upon communication and signal circuits as a result of lightning. This is particularly true of circuits in which aerial conductors of considerable length, not in cables, are used. Conductors in metal-sheathed cables, which have no connections with aerial wire, are so well shielded that lightning effects upon them are usually negligible.

If protective devices were not employed, the presence of these abnormal potentials would be liable to result in injury to persons using or working upon the circuits, or damage to the plant through breakdown of insulation. In some cases the latter result may lead to property losses by fire.

It has, therefore, become the general practice to provide on communication circuits protective devices designed to minimize lightning effects. Such protection is, of course, provided only on circuits which include sections upon which abnormal potentials due to lightning are likely to be impressed. The protector is usually located at the junction of the exposed line with the plant to be protected.

SEC. 50. SCOPE, ETC.

500. Scope and Purpose.

This part of the report deals with the protection against lightning of all circuits, and all apparatus connected to circuits, used for general communication and signaling purposes. Its scope is limited to the location and method of installing protective equipment irrespective of the method of operation.

The purpose is to set forth means and methods whereby the hazard to life and property and the interruption of communication due to lightning may be minimized.

SEC. 51. FORM OF PROTECTORS AND METHODS OF USE

510. Form of Protectors.

Lightning protectors for communication circuits are constructed upon the principle of providing, in parallel with the portion of the plant to be protected, a path of such electrical characteristics that, under the pressure of abnormal potentials, it will carry a large proportion of the resulting current. The protectors are, of course, so constructed that under normal conditions they do not divert the operating currents from their normal paths.

The type of protector most commonly used on communication circuits is the spark gap, consisting essentially of two electrodes insulated from each other, with a space between them of such dimensions that sparks will pass from one to the other when the potential difference exceeds a given value. In the most generally used form of protector the spark passes through an air space between the electrodes, while in another class of protector the sparking occurs across a partial vacuum. The materials used for the electrodes and their shapes and dimensions vary widely in the many different forms of spark-gap protectors.

Another type of protector that has been used to a limited extent is based upon the use of a material having a critical voltage-resistance characteristic; that is, the material in question must have a very high resistance at the voltage used for the operation of the system and a much lower resistance at higher voltages.

511. Connections of Protectors.

One of the two electrodes is connected to a conductor of the circuit to be protected, and the other electrode is connected to a "ground" consisting of some metallic object or structure which is in good electrical contact with the earth.

512. Additional Features.

The protectors used on communication circuits frequently include fuses or similar devices in addition, but these additional features are not employed for the purpose of protecting against lightning. Their use is due to the fact that in well-settled communities circuits which are exposed to lightning usually are subject also to accidental contacts with electric light or power circuits carrying voltages in excess of the operating potential of the spark gaps on the communication circuits. As a result of a contact of that kind, a sufficiently heavy current might flow through the device to destroy it and, perhaps, start a fire. To avoid this possibility, it is common practice to insert in the circuit, between the exposed wire and the spark gap, a fuse which will function to open the circuit when traversed by any current large enough to create such hazard.

SEC. 52. RADIO EQUIPMENT

520. Accident Prevention.

The following rules are quoted from part 5 of the 1926 edition of the National Electrical Safety Code, A. S. A.–C 2, and apply to receiving stations and to transmitting stations of low and medium power. Requirements for making ground connections for the grounding conductor are given in sections 9 and 56 of that code, and are not repeated here.

551. The protective grounding conductor may be used also as the operating grounding conductor.

552. The protective grounding conductor for receiving stations shall not be smaller than the lead-in conductor. The operating and protective grounding conductors for transmitting stations shall have strength and conductance per unit length not less than No. 14 A. W. G. (0.064 inch) hard-drawn copper.

553. Grounding conductors shall be run in as straight a line as possible from the set or the protective device to a good permanent ground. Grounding conductors may be run either inside or outside of the building.

Recommendation.—It is recommended that the protective grounding wire for low and medium-power transmitting stations be run outside of the buildings.

Grounding conductors shall be guarded where exposed to mechanical injury. Grounding conductors may be of insulated or bare wire and need not be run on insulating supports.

571. Each lead-in conductor of a receiving station shall be provided with a lightning arrester, whether or not an antenna grounding switch is used. The lightning arrester shall be such as to operate at a potential of 500 volts or less. The arrester may be located outside the building as near as practicable to the point of entrance, or inside the building between the point of entrance and the receiving set and convenient to a ground. The arrester shall not be placed in the immediate vicinity of easily ignitible material or in a location exposed to dust, inflammable gases, or flyings of combustible materials.

572. An antenna grounding switch shall be used at low and medium-power transmitting stations to connect the lead-in conductors to the grounding conductor whenever the station is not in use. An antenna grounding switch

is not required at receiving stations, but may be used in addition to the lightning arrester. When in the grounding position, the switch shall short circuit the lightning arrester.

521. Fire Prevention.

The following rules are quoted from article 37 of the 1928 edition of the National Electrical Code. Section 3702 applies to receiving stations and section 3703 to transmitting stations.

3702 *j*. If fuses are used, they shall not be placed in the circuit from the antenna through the protective device to ground.

3703 *g*. A double-throw knife switch having a break distance of at least 4 inches and a blade not less than ⅛ by ½ inch, or a flexible grounding lead and clamp in place of this switch, shall be used to join the antenna and counterpoise lead-in to the grounding conductor. The switch or flexible grounding lead may be located inside or outside the building. The base of the switch shall be of non-absorptive insulating material. The switch or flexible grounding lead shall be so mounted that its current-carrying parts will be at least 3 inches clear of the building wall or other conductors in the case of continuous-wave sets of 1,000 watts and less, and in all other cases at least 5 inches. The conductor from grounding switch or flexible grounding lead to ground shall be securely supported.

It is recommended that the switch be located in the most direct line between the lead-in conductors and the point where grounding connection is made.

3703 *l*. When necessary to protect the supply system from high-potential surges and kick-backs there shall be installed in the supply line as near as possible to each radio transformer, rotary spark gap, motor and generator in motor-generator sets and other auxiliary apparatus one of the following:

(1) Two condensers (each of not less than 1/10 microfarad capacity and capable of withstanding 600-volt test) in series across the line with mid-point between condensers grounded; across (in parallel with) each of these condensers shall be connected a shunting fixed spark gap capable of not more than 1/32 inch separation.

(2) Two vacuum-tube-type protectors in series across the line with the mid-point grounded.

(3) Lightning arresters, such as the aluminum-cell type.

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Appendix A.—LIGHTNING; ITS ORIGIN, CHARACTERISTICS, AND EFFECTS

The term "lightning" is applied to certain types of heavy electrical discharges in the atmosphere. Within a comparatively recent period its meaning was extended to include a variety of overvoltage phenomena arising in the operation of electric circuits, but owing to the resulting confusion this use of the term is no longer considered desirable. The following discussion will be confined to atmospheric electric discharges, chief attention being given to the kind known as "streak" lightning or, to use a less scientific term, "chain" lightning, as it is this that causes damage and injury.

The necessity for protection against lightning was recognized during the earlier periods of recorded history. The devices and methods then used, however, were characteristic of the times. They consisted chiefly in exorcisms by the priesthood, the wearing of holy charms, the ringing of church bells that had been especially dedicated to the purpose, and the torture and burning of persons suspected of witchcraft. The latter were believed to be able to summon storms at will by reason of their being in league with demons and evil spirits.[1] The origin of such beliefs was in the abyss of superstition and fear which formerly engulfed almost the entire human race and from which a considerable portion has not yet emerged.

Deliverance in this particular from the thralldom of imaginary demons, witches, and angry gods came during the

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[1] J. C. Shedd, Proc. Colo. Sci. Soc., 8, p. 387; 1907.

period 1749–1752 with the invention by Benjamin Franklin of the lightning conductor, and his proof by means of his kite experiments of the identity of lightning with the electric spark. This work of Franklin marks one of the definite points of departure from a line of reasoning which ascribed all natural phenomena to capricious supernatural intervention and gave an impetus to logical inquiry into the laws of nature. Such inquiry, however, has progressed but slowly with respect to lightning flashes, only a few roughly quantitative measurements having been made, and these in very recent times. Nevertheless, the results now available enable us to estimate the magnitude of the quantities involved, and much has been gained from laboratory and field work in protection of property. It is the purpose here to summarize the existing information and attempt to distinguish between what is known and what is purely speculative.

Sources of Lightning.

The chief source of lightning is the familiar summer thunderstorm, which derives its name from the sounds resulting from its electrical discharges. Lightning has also been observed in the dust, steam, and gas clouds arising from volcanoes in eruption, in the dust clouds of deserts, and in clear skies, probably from charged bodies of air which drifted near each other or near the earth. In addition, there are silent luminous discharges within cloud layers and haze which have been observed at all times of the year, especially in regions where thunderstorms are scarce.

TYPES OF LIGHTNING

The most familiar type is streak lightning. Variations of this, but not distinct types in themselves, are ribbon, rocket, and bead lightning, and also forked and zigzag lightning.

Other types more rarely observed than streak lightning are ball or globular lightning and sheet lightning.

Streak Lightning.

Streak lightning exhibits a white or pink path of comparatively small diameter, from an inch to a foot apparently, and of a length which may be from a fraction of a mile to several miles, depending upon the conditions of the discharge. The path in many cases is sinuous and forked with extensive ramifications, while in others it appears as a single streak, the ramified forks being absent or invisible. The streak lightning of a thunderstorm may occur within a cloud, between separate clouds, between clouds and earth, or between a cloud and surrounding air. It is invariably accompanied by thunder of greater or less intensity. In the majority of cases its duration is very short, although there is a wide variation in the duration and intensity of streak-lightning flashes, which is discussed in greater detail later.

Ribbon Lightning.

Occasionally a flash of streak lightning appears as a number of more or less distinct parallel streaks, to which the name "ribbon lightning" has been given by reason of its appearance. What seems to be a satisfactory explanation is given by photographs of lightning flashes. It has been shown that most streak discharges consist of several successive discharges, which have appreciable time intervals between them. It has also been shown that in the intervals between discharges the path may be shifted by the wind through considerable distances. Thus, several successive discharges displaced in space may, on account of persistence of vision, appear as parallel streaks.

Rocket Lightning.

The term "rocket lightning" has been applied to streak discharges occasionally seen, the growth of which is so slow as to appear like a rocket. It may occur between clouds and earth, within clouds, or between clouds and surrounding air. In one case at least it has been observed between clouds and upper atmosphere.[2] It has been explained as the discharge, under certain conditions, of a positively charged cloud.[3]

Bead Lightning.

In this the path of the discharge appears as a string of luminous globes or beads, separated by darker intervals. It is rarely observed, especially in pronounced form. Several explanations of this phenomenon have been offered. One is that it is due to variations of the path of the discharge with respect to the line of sight. Another that striæ of haze obscure portions of the path. A third is that it is a combination of streak and globe lightning.[4]

Forked Lightning.

This refers to the branching of the streak discharge at its lower end in some cases, which results in its striking two or more objects at the same time. Thus two trees, or a tree and a house, some distance apart, may be damaged by the same stroke.

Zigzag Lightning.

This refers to streak discharges which assume an extremely sinuous path. In some cases, because of the relation of the line of sight to the path, it appears to describe a loop. Such discharges present altogether different appearances from different points of observation.

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[2] Nature, 68, p. 599; 1903.
[3] G. C. Simpson, Proc. Royal Soc., **111**, p. 56; 1926.
[4] Sci. Amer., **106**, p. 587; 1912. Humphreys, Physics of the Air, p. 351.

Globular Lightning.

The term "globular lightning" is applied to the second distinct type which consists of the luminous globes, or globular-shaped masses, sometimes seen during thunderstorms to move along the ground, about objects resting on the ground, or through the air, in a manner quite inexplicable to the observer. These globes seem in some cases to explode with a loud noise and cause serious damage. They are held by some to be an optical illusion arising from persistence of vision which causes one to see a ball of fire in any position toward which the eye is directed after a particularly brilliant flash of streak lightning. This explanation can hardly be accepted, however, in view of a number of observations where persistence of vision did not seem to be a factor. It is now conceded that globular lightning, or something resembling it, actually exists on rare occasions. Dr. Walther Brand, of Marburg, Germany, has assembled 600 accounts of ball lightning, of which 215 are sufficiently detailed and accurate to be worthy of study. From these he has summarized the characteristics of this singular phenomenon but does not attempt to explain it. It is thought to be a more than ordinarily brilliant brush discharge moving along a path of low dielectric strength in the storm's electric field, probably immediately preceding or following streak lightning, which would account for the apparent explosions. It is now known that the electric fields of thunderstorms are of sufficient strength to cause such discharges, especially beneath the center of greatest electrical activity.[5]

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[5] H. Norinder, Electric Thunderstorm Researches: Elect. World, 83, p. 223; 1924.

Sheet Lightning.

The proper application of this term is to the silent discharges occasionally observed in clouds and haze, which constitute a third distinct type of lightning. These discharges appear to be somewhat similar to the brush discharge of the laboratory but are of white color usually, and on a vast scale. In some cases great areas of the sky glow momentarily, and sometimes intermittently, with sufficient brightness to arrest the attention. The proper application of the term is significant, because the discharge appears to occur as a sheet, although actually it is most likely a volume effect. It is distinguished from the aurora by the fact that it takes place in the cloud layers, whereas the aurora is observed only in the rarefied upper atmosphere where clouds do not form. The phenomenon may be observed at times in winter on cloudy nights. It also occurs at other times of year, especially in regions where streak lightning is rare, and occasionally in the wake of cyclonic thunderstorms.

The term "sheet lightning," or, more popularly, "heat lightning," is erroneously applied to the illumination arising from streak lightning, the source of which is invisible on account of cloud banks, or being below the horizon, and so distant that the thunder either can not be heard or comes too late to be associated in the mind of the observer with the illumination. Sheet lightning is readily distinguished from the illumination of streak lightning by its persistence and its relatively slow variation of intensity.

Nothing beyond speculation is offered to account for glow discharges in clouds, but possible causes are these: (1) The agglomeration of charged vapor particles to form water drops by which means the potential of the drops is raised to a point where a coronal discharge occurs to the surrounding air. (2) The changing of charged vapor particles to snow crystals or ice particles which increases potential due to agglomeration and at the same time produces shapes which facilitate discharge. (3) The drifting of charged masses of vapor or ice particles from regions where the potential is high to regions where the potential is lower. The charge in the case of glow discharges is most likely negative, because, as indicated by Simpson (*l. c.*), discharges from negatively charged clouds are likely to be of this character.

St. Elmo's Fire.

This consists of silent discharges at the surface of the earth which appear as blue flamelike brushes at the tips of various pointed objects. It occurs most frequently in dry regions on the approach of storms, and also on mountain tops, especially if it is cold and dry. It is not confined to these places, however, as it occurs at sea on the masts and rigging of ships. It is not to be regarded as a type of lightning, although it may attend lightning storms.

CHARACTERISTICS AND EFFECTS

From the point of view of protective measures streak lightning is the only kind that needs consideration, since the others are rare in occurrence or harmless. Streak lightning, however, causes considerable damage and loss of life, especially in those regions where thunderstorms are frequent and severe. Its potentialities for damage are dependent upon the electrical characteristics which it has in common with electrical discharges produced in the laboratory—viz, current, voltage, and time—and their combination in power to cause explosion and energy to cause heat. Of these factors the maximum current and its duration determine its fusing or igniting effects, while the steepness of the wave front determines the extent of its secondary or induced effects. The voltage gradient very largely determines the extent of its effects on electric-power transmission and communication circuits. Of less importance from the point of view of protection, but nevertheless of considerable interest, are the following: The magnitude of the total voltage involved, whether the discharge is oscillatory or damped to such an extent as to make it a single impulse, and the cause of the noise and light. These characteristics are discussed here under the following headings: Source of static charge, voltage, energy, maximum current, wave front and duration, induced effects, thunder, illumination, character of damage, effects on persons, and thunderstorm data.

SOURCE OF STATIC CHARGE

The work of G. C. Simpson [6] at the Meteorological Office of the Government of India, Simla, gave results which form a basis for an explanation in part at least of the mechanism by which the separation of electric charges in thunderstorms is produced. Two lines of research were adopted: (1) A systematic record was obtained by means of self-registering instruments of the electricity brought down by the rain throughout one rainy season; (2) laboratory experiments were made with the object of determining the source of the electricity of thunderstorms.

The chief results of the first part of the work may be briefly summarized as follows: The aggregate amount of rain which fell during the periods of rainfall investigated was 30.04 inches (76.3 cm). The total quantity of positive electricity which fell on each square centimeter of surface was 22.3 electrostatic units, and of negative electricity 7.6 units; thus 75 per cent of the electricity brought down by the rain was positive. During 71 per cent of the time that

[6] Trans. Royal Soc., 209, p. 279; 1909.

charged rain fell the charge was positive. Considering that falling rain carrying a positive charge is equivalent to a positive current and rain carrying a negative charge to a negative current, then positive currents greater than 300×10^{-15} ampere per square centimeter were measured in six storms and negative currents of greater than 300×10^{-15} ampere per square centimeter in two storms.

In seven storms it was found that the rain carried positive charges greater than six electrostatic units per cubic centimeter of water, and in two storms negative charges greater than this amount were recorded. The heavier the rainfall the more the positively charged rain preponderated over the negatively charged rain, and all rainfall having a greater rate than a millimeter in two minutes was positively charged. Light rain was more highly charged than heavy rain. The proportion of negative electricity brought down by the rain was slightly greater in the second than in the first half of the storm. The potential gradient was more often negative [7] than positive during rain. No relationship between the sign of the potential gradient and the sign of the electricity of the rain could be detected.

The laboratory experiments showed that when a large drop of water is broken up into small drops in air the water becomes positively and the air negatively charged. In the first series of experiments drops of water having a volume of 0.24 cc fell on a vertical jet of air which broke them up into smaller drops. Under these circumstances the water of each drop, after having been broken up on the jet, carried a charge of 5.2×10^{-3} electrostatic unit of positive electricity.

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[7] Negative potential gradient in the atmosphere exists when the potential of a point decreases with increasing vertical distance from the earth, as would be the case with a negatively charged cloud and a positive charge on the earth beneath. Positive potential gradient is found under the opposite condition of a positive cloud and a corresponding negative charge on the earth.

Further, the presence of an original charge on the drops did not alter the effect. Drops originally charged positively had their charges increased, and drops charged negatively had their charges decreased.

In the second series of experiments water was introduced through two small tubes into a vertical current of air which carried the water upward. Part of that which escaped from the air current was caught in an insulated vessel and was found to be positively charged, the charge being 15×10^{-3} electrostatic units per cubic centimeter of water.

In the third series of experiments drops of water were broken up in a manner similar to that employed in the first series, but within a compartment from which the air could be drawn through an Ebert apparatus. It was shown that the breaking up of the drops caused an ionization of the air. The breaking of each drop released 3.3×10^{-3} electrostatic unit of free negative ions and 1.1×10^{-3} electrostatic unit of free positive ions. The excess of negative ions, or 2.2×10^{-3} electrostatic unit, corresponds to the positive charge retained by the water. The discrepancy between 2.2×10^{-3} and 5.2×10^{-3} as given previously is accounted for by the author by the fact that parts of the ions were discharged to the walls of the Ebert apparatus.

In 1904 Professor Lenard[8] proved that drops of water which have a diameter greater than 5.5 mm are unstable when falling through air and rapidly break up into smaller drops. He also proved that the final velocity of any drop which has a diameter less than 5.5 mm does not exceed 8 m per second when falling through still air of normal density. Thus, no water can fall through an ascending current of air of normal density which has a velocity of 8 m per second or more, for all drops less than 5.5 mm in diameter are carried

[8] Meteor. Zeit., **21**, p. 249; 1904.

upward, and all drops of larger diameter are quickly broken up into smaller drops. These facts, together with the results of the observations and experiments described above, have led to the formation of the following theory for the origin of the electrical separation of thunderstorms.

It is probable that in all thunderstorms there are upward currents of velocities greater than 8 m per second. Such currents support large amounts of water which can not fall through the ascending air. Hence, as the top of the vertical air current is approached where its upward velocity greatly decreases due to the lateral outflow, there will be an accumulation of water in the form of drops which are continually going through the process of growing from small drops into drops large enough to be broken. Each time a drop breaks a separation of electricity takes place, the water receiving a positive charge and the air a corresponding negative charge. The moving air carries away the negative ions but leaves the positively charged water behind.

A given mass of water may be broken up many times before it finally falls to the ground and, consequently, may obtain a high positive charge. When it finally reaches the ground it is recognized as positively charged rain. The ions which travel with the moving air are rapidly absorbed by the cloud particles in the upper part of the cloud, and in time this would become highly charged with negative electricity. Now, within a highly electrified cloud there may be combination of the water drops and from it considerable rain may fall at certain stages of the storm. This rain will be negatively charged, and under suitable conditions both the charges on the rain and the rate of rainfall could be large.

A rough quantitative analysis shows that the order of magnitude of the electric charges produced by the breaking of a drop of water is sufficient to account for the electrical effects observed in the most violent thunderstorms. All of the results of the observations of the electricity of rain described above are capable of explanation by the theory, which also agrees well with the actual meteorological phenomena and is quite generally accepted. It is thought by some that, while precipitation is the primary cause of the separation of electricity, the action, instead of being due to separation into parts of water drops, is similar to that of the influence machine.[9]

Electrification of clouds, however, has been observed where vertical convection and rapid condensation did not occur. According to Simpson[10] these phenomena can be accounted for by an extension of his theory. It has been shown that electrification can be produced by the separation of almost any substance. Thus, in duststorms and snowstorms separation takes place by collision and abrasion between particles in much the same way as in the breaking of water drops, which leads to electrification, with the attendant phenomena. It is rare that electrification of this type produces lightning, because separation of charges does not occur, although it may occur in the case of a snowstorm accompanied by soft hail, because the hailstones acquire a high charge in their downward course by collision with snowflakes and take their charges with them to the ground.

VOLTAGE

The voltage of lightning discharges—that is, the difference in potential between the points marking the extreme ends of the path of the discharge immediately preceding its occur-

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[9] Elster and Geitel, Wied. Ann., **25**, p. 116; 1885. Physikal Zeit., **14**, p. 1287; 1913. Geitel, Physikal. Zeit., **17**, p. 455; 1916.

[10] Nature (London), **112**, pp. 727–728; 1923.

rence—has long been a matter of conjecture. The nearest approximation so far made to the voltage of a lightning flash places it at about 100,000 volts per foot. This value was obtained by comparing the induced voltage on a model transmission line, where the total voltage was known to be 2,000,000, with induced voltages from lightning measured on an actual transmission line.[11] Other experiments indicate that at the most intense part of the electric field of a thunderstorm the electric intensity approaches the limiting value at which coronal discharges begin.[12] Hence, it appears that for a discharge a mile in length the potential difference at the beginning of the discharge is of the order of 5×10^8 volts.

A comprehensive series of measurements of the changes in potential gradient near the surface of the earth has been made by C. T. R. Wilson.[13] During the years 1914, 1915, and 1917 records were obtained during 864 discharges. The discharge was between negative cloud and positive earth in 528 of these, or at least of a kind to cause a change in potential gradient at the instrument of the same nature. This predominance of discharges with the cloud negative appears not to be in accord with the observations of Simpson, who found the cloud usually positive, but the latter drew his conclusions from photographs of flashes to earth, while in Wilson's case flashes from cloud to cloud were included.

From the magnitude of the change in potential gradient, and the distance between instrument and path of discharge, it was estimated that the average value for the quantity of electricity involved was 20 coulombs. (A change of about

[11] F. W. Peek, jr., High-Voltage Phenomena: J. Franklin Inst., **197**, p. **1**; 1924.

[12] H. Norinder, Electric Thunderstorm Field Researches: Elect. World, **83**, p. 223; 1924.

[13] Proc. Royal Soc. of London, **92**, p. 555; 1916. Phil. Trans. of Royal Soc., **221**, p. 73; 1920.

15,000 volts per meter was observed at a distance of 5 km.) If this amount of charge is distributed through a spherical mass of cloud with a radius of 250 meters it would produce an electric field of nearly 30,000 volts per cm at its surface and would have a potential of about 10^9 volts. This electric field is the limiting value at which air breaks down when the field is uniform, and it will break down at lower values where the field is nonuniform, as near surfaces having curves of short radius.

If a voltage of this value produces a discharge over a path 2 km long, the average gradient is much less than the above critical value. It does not seem necessary for the gradient to equal the critical value over the entire path for a discharge to start. Starting at the point of intense field local breakdown causes a readjustment of the field, which leads to progressive breakdown along the entire path.

In Norinder's observations gradients as large as 100,000 volts per meter were recorded at points closer to the discharge.

ENERGY

The total energy dissipated by a flash of lightning may be roughly estimated in various ways. An estimate by Peek from his measurements of lightning voltages places the energy at 1.3×10^7 watt-seconds.

Another estimate has been made by Wilson in connection with the work mentioned in the preceding section, where the quantity of electricity discharged by a lightning flash was found to be 20 coulombs and the voltages 10^9, which gives for the energy 10^{10} watt-seconds, or nearly one thousand times as much as that estimated by Peek.

The discrepancy between these two estimates may in part be attributed to the fact that most lightning flashes consist of several separate discharges along the same path, usually 1 to 10, and in one instance at least as many as 40. The estimate based on the voltage would take account only of a single discharge, and thus the 10^7 watt-seconds found in this manner should, perhaps, be multiplied by the number of separate discharges that constitute the entire flash or else a larger cloud area considered.[14]

On the other hand, the estimate based on the quantity of electricity takes account of the total change of electrical condition, but, as pointed out heretofore, 10^9 volts may be too high, in which case the energy would be less. It seems not unreasonable to take 10^8 to 10^9 watt-seconds as the order of magnitude of the energy of a lightning flash.

It is interesting to note that where lightning flashes occur at intervals of one second or less, as they may in severe cyclonic thunderstorms which cover a large area, an energy dissipation of 10^9 watt-seconds for each flash means that the power being dissipated is around 1,000,000 kilowatts. This is an impressive value, and the question may be raised as to the source of the energy. The most probable source is the vertical convection, the gravitational process so pronounced during the thunderstorm, which results in excessive condensation accompanied by electrical separation. An idea of the power involved can be gained from a consideration of the rainfall.

In a heavy storm a rainfall at a rate of 10 cm per hour is not unusual, and at this rate the power derived from the falling water, taking the height of fall as 1 km, would be 3×10^{15} ergs per second per km^2, or 1,000,000 kw for about 3 km^2. Thus, a rainfall of the foregoing amount over an area of 3 km^2 would involve sufficient power to produce a flash per second. The total power available for the produc-

[14] Trans. Roy. Soc., **221**, p. 73; 1920–21.

tion of lightning flashes may obviously greatly exceed the estimate based on the rainfall.

MAXIMUM CURRENT

What appears to be the first work on current intensities of lightning flashes was done by F. Pockels,[15] who made use in his measurements of some of the peculiar magnetic properties of basalt, and at the same time assumed that lightning discharges are unidirectional. In the course of some laboratory experiments Pockels found that for unidirectional magnetic fields the residual magnetism of prisms of nepheline basalt depended neither on the duration nor the time variation of the field, but only on its maximum value. Basalt consists of crystals of magnetite distributed through a badly conducting mineral medium, and it is upon this formation that its peculiar magnetic property depends, there being no eddy currents set up in it by a varying magnetic field which would retard the magnetization of the specimen. A magnetic field lasting only about one-millionth of a second showed the same residual and probably also the same temporary magnetization as was induced by a field kept up indefinitely at the same strength. This being the case, the residual magnetization of the basalt might be taken as a measure of the maximum magnetic field to which it had been subjected and, consequently, to the maximum value of the magnetizing current.

In order to test the method, Pockels discharged condensers of known capacities which had been charged to known differences of potential through magnetizing circuits of known resistance and self-induction, the constants of the circuit

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[15] Ann. Phys. Chem., **63**, p. 195, 1897; Ann. Phys. Chem., **65**, pt. 2, p. 458, 1898; Phys. Zeit., **2**, p. 306, 1900.

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having been chosen to give a highly damped discharge. He then calculated the maximum value of the current by means of the constants of the circuit and compared them with the values determined from the residual magnetization. The resistance of the spark gap was neglected in making these calculations, but the results agreed very well in the two cases.

The results of these experiments were made use of by Pockels in making an approximate determination of the current intensity of lightning flashes, assuming, as previously stated, that the discharge in a flash of lightning is unidirectional. The first measurements were made on specimens cut from outcroppings of basalt rock which showed irregular and local magnetization which could only be due to lightning flashes. Knowing the strength of the field necessary to produce the residual magnetism shown by the specimens, only the distance to the path of the flash was necessary to make a rough determination of the current. This distance was in some cases assumed to be the distance to the surface of the rock; in others a damaged tree was assumed to give the necessary evidence. One estimate made by assuming the distance to the flash to be the distance to the surface of the rock led to a minimum of 2,900 amperes as the current intensity; three others, on specimens obtained from the vicinity of damaged trees, gave 6,400, 6,600, and 10,000 amperes, respectively. These values are probably too small, because of the period of time which elapsed between the time of the flash and the time of making the measurements and also because of the disturbance of the basalt in cutting it out.

Other observations were made on basalt prisms exposed in the vicinity of a branch of the lightning conductor on the observation tower on Mount Cimone, in the Appenines.

One of the prisms which had been placed at a distance of 6.4 cm from the conductor and had been subjected once to the magnetizing effects of a lightning stroke gave $i=10,200$ amperes. A second prism, which had been subjected to the magnetizing effects of four strokes, gave $i=5,530$. A third prism was only slightly magnetic. There were two ground connections to the lightning conductor, so it is quite probable that the current divided symmetrically. The total currents in the two cases were, therefore, 20,000 and 11,000 amperes, respectively. These values are doubtless also too small, because the prisms were not examined until several months after having been exposed and were subjected to some vibration in the meantime.

Another method of arriving at an estimate of the current intensity of a lightning flash is to calculate it from the total quantity of electricity discharged as found by Wilson and make assumptions as to the duration and number of discharges per flash. The quantity may be taken as 20 coulombs, the number of discharges per flash about five, and the duration of each discharge about 0.000028 second. The latter value is based on experimental evidence that many lightning flashes are less than 0.000028 second in duration. The quantity for each discharge would then be 4 coulombs, and the current 4/0.000028, or 142,000 amperes. This is seven times as great as by the previous method.

A third estimate has been made from the fusing effect of a lightning flash on metal.[16] In this case the metal was in the form of a copper tube with a brazed seam which constituted part of a lightning-rod terminal. The terminal was struck and heated to a sufficient temperature to volatilize some of the solder used in brazing and make the copper plas-

[16] Crushing of a Copper Tube by Lightning. W. J. Humphreys, Monthly Weather Review, 43, p. 396; 1915.

tic enough to collapse throughout its length of 5 feet under the pinch effect of the current. The temperature rise is estimated to be about 1,025° C. The average resistance of the tube for the estimated temperature range was found to be 17 microhms per cm and the weight 2.9 g per cm. To bring 2.9 g of copper to 1,025° C. requires about 327 g-calories. The duration of the flash was assumed to be 0.01 second, much greater than in the previous paragraph, but this seems to be justified by the fact that the fusing effects were uncommonly severe. Moreover, the entire flash, perhaps consisting of as many as 40 separate discharges, is considered,[17] which would introduce a considerable factor to increase the time as compared with a single discharge.

From the preceding values for temperature, resistivity, and time it is found that

$$I = \sqrt{H/0.2389\,R\,t} = \sqrt{327/0.2389 \times 17 \times 10^{-6} \times 0.01} =$$

90,000 amperes, approximately. The pinch effect of such a current on the tube is calculated to be 400 lbs./in.^{2} (28 kg/cm^2). If the discharge were unidirectional, the quantity of electricity would be $90{,}000 \times 0.01 = 900$ coulombs, which is eighteen times the greatest observed by Wilson.

The foregoing values for the maximum current of lightning flashes differ widely, as might be expected where deductions are made from such meager data; but they are the best available at this time and, if they show anything, indicate that the maximum current ranges from thousands of amperes to tens of thousands. That such a wide variation exists is suggested by visual observation. In dry air, or in advance of a thunderstorm, lightning usually presents a thin blue appearance, while where the rainfall is heavy it

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[17] Alex. Larson, Photographing Lightning with a Moving Camera: Ann. Rept. of Smithsonian Inst., 1905.

presents a fat, white or pink appearance, which is most likely due to difference in current intensity and diameter of path, the rainfall seeming greatly to facilitate discharge.

Corroborative evidence of the magnitude of the currents of lightning flashes is found in recent laboratory experiments with artificial-lightning discharges which produce effects similar to those in nature. Here currents of 10,000 amperes at 2,000,000 volts have been attained.[18]

WAVE FRONT AND DURATION

The well-known flickering of lightning flashes, which is visible to the unaided eye, indicates that a flash of lightning does not always consist of a single discharge of electricity, but, on the contrary, consists in many cases of a number of successive discharges which follow each other with very short-time intervals between them. By standing where the light from a flash does not blind the eyes, an observer can detect the successive discharges for each complete flash of lightning, the number of which varies, for different flashes, from 2 or 3 to 10 or more. By means of swinging or rotating cameras photographs have been made which show separately the constituent parts of a flash in so far as they can be shown by taking impressions on a photographic plate moving at rather a slow speed. From these photographs have been calculated the total duration of the flash for a number of cases and also the intervals of time between the successive discharges. Moreover, by visual means using rotating disks, and other apparatus, the duration of the constituent parts of the flash have been estimated.

The first photographic evidence of the multiple character of lightning flashes was obtained by Kayser [19] and Rümcker,

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[18] F. W. Peek, jr., High-Voltage Phenomena: J. Franklin Inst., 197, p. 1, 1924.

[19] Berichte der Königl. Akad. Berlin, p. 611 : 1884.

each using a stationary camera, the path of the flash being shifted by the wind. The durations of the flashes were estimated from these photographs, but, owing to the fact that the velocity of the wind was not known accurately in either case, the results are not to be relied upon. These photographs are of importance, however, from the fact that they show the distance through which the path of a lightning flash may be shifted by the wind while the successive discharges are taking place.

A few years after Kayser's and Rümcker's photographs of lightning were taken L. Weber [20] showed that it was possible to make a time analysis of any lightning flash by moving the camera while the exposure was being made, thus spreading the image of the flash over the plate and separating it into its constituent parts. The best work on photographic time analysis of lightning flashes has probably been done by B. Walter.[21] Walter succeeded in analyzing the sparks from an induction coil by means of a moving film and at once saw that the method would be applicable to the analysis of lightning flashes. For this purpose he mounted his camera on a fixed axis around which it was made to rotate by clockwork at a uniform rate. With this apparatus Walter took a number of photographs of lightning flashes and determined the total duration of the flashes and also the intervals of time between the successive discharges.

In the case of a flash consisting of five successive discharges the total time was found to be 0.2447 second, while the successive discharges were at intervals of 0.0360, 0.0364, 0.0283, and 0.1440 second, respectively. These are fairly representative of the total duration and time intervals of the flashes of which photographs were taken. The durations and

[20] Berichte der Königl. Akad., Berlin, p. 781; 1889.
[21] Annalen der Physik, **10**, p. 393; 1903.

FIGURE 5.—*Photograph of a lightning flash taken with a moving camera by Doctor Walter*

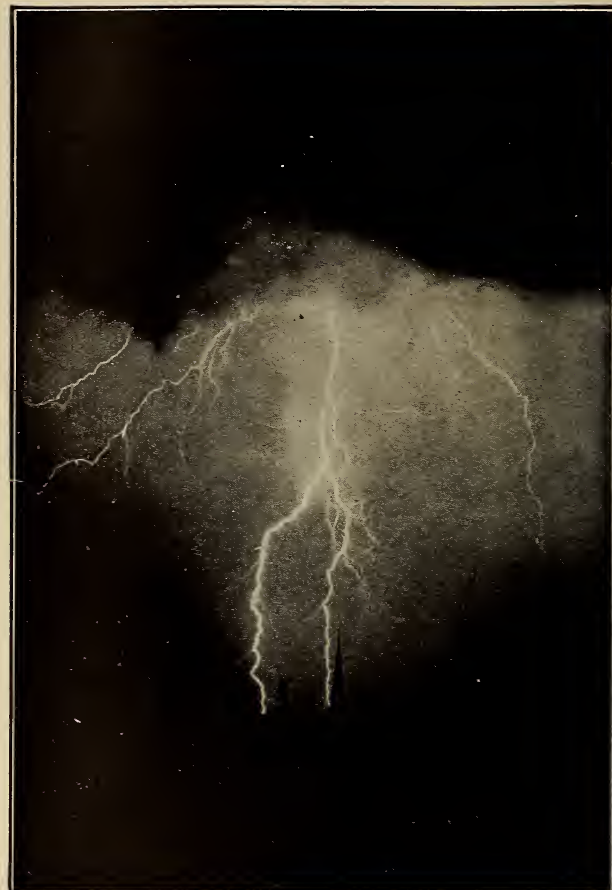

FIGURE 6.—*Same lightning flash as in Figure 5, taken with a stationary camera*

intervals are variable, however, and range for different flashes from near zero to 0.6 second or more for the duration, depending apparently on the number of successive discharges in a flash, and from near zero to 0.2 or 0.3 second for the intervals. A photograph taken by Larsen [22] with a rotating camera shows 40 distinct discharges in a single flash, the duration being 0.624 second and the average interval 0.0156 second. The intervals between the successive discharges varied from 0.0026 to 0.0520 second. This flash is exceptional because of the large number of successive discharges which occurred.

Figure 5 is a reproduction of a photograph from the collection of B. Walter, which shows in a marked way the general character of a lightning flash. Beginning at the right, the first complete discharge is shown in a nearly vertical position. The succeeding discharges branched off from the original path part way down, as may be seen by tracing the similar kinks in the different images for a short distance from the top. The remaining discharges all followed the same path, but changed markedly in character, the fourth from the right being apparently a unidirectional discharge along a thoroughly ionized path lasting a considerable time. When the cloud is exhausted by this continuous discharge a short cessation occurs, after which there is a final discharge usually much weaker than the first discharges. These phenomena are more or less clearly shown by the reproduction given in Figure 6. Many variations from this procedure may occur, but, in general, a flash of lightning is made up of the constituent discharges just described.

The characteristics of the constituent discharges of a flash of lightning are of great interest in connection with the de-

[22] Photographing Lightning with a Moving Camera: Ann. Report of Smithsonian Inst., p. 119; 1905.

sign of lightning protection. The duration of these constituent discharges has been studied by K. E. F. Schmidt[23] using a rotating disk having marked upon it a white cross which was observed by the light of lightning flashes. This work confirmed that of Walter, showing that the constituents of a lightning flash vary greatly with different flashes of lightning. The most important conclusion, however, was that for the most part the duration of the constituent discharges of a flash is 0.00003 second or less. A number were observed in which the duration was greater, but these were few. This establishes, in some degree at least, the upper limit of the duration of a lightning discharge; that is, the path must be formed and the current grow to a maximum and die out in less than 0.00003 second. This suggests also something as to the steepness of the current wave front. If the maximum current reaches 100,000 amperes, as seems possible from previous discussion, the average rate of increase is 7×10^9 amperes per second, assuming that the current reaches its maximum in one-half the duration. It is obvious that any circuit connected inductively to the path is in a way to have a considerable e. m. f. set up in it, even though the mutual inductance is very small.

The duration of lightning flashes has been studied by others[24] and somewhat similar results obtained, although in many cases longer durations were observed.

In connection with the wave front of the constituent discharges it is interesting to note that these are now considered to be unidirectional rather than alternating. From considerations of the discharge path they may be of an oscillatory character but highly overdamped, so the discharge represents the beginning of an oscillation which dies out before

[23] Elektrotech. Zeit., **26**, p. 903; 1905.
[24] De Blois, Proc. A. I. E. E., **33**, p. 563; 1914.

the first quarter wave is completed, the current dropping to zero without reversing.[25] On account of the steep wave front, however, oscillations with reversal of current may be set up in near-by metallic circuits.

In a paper by G. C. Simpson [26] a theory of the formation and extension of lightning flashes is advanced which is based upon the relative mobilities of positive ions and negative electrons. The theory is tested by laboratory experiments on a small scale and examination of a large number of photographs of lightning. The chief conclusions advanced are as follows:

1. The conducting channel of a lightning flash originates in the region of maximum electric field and develops only in the direction of the seat of negative electricity.

2. A negatively charged cloud can only be discharged by a discharge which originates in a positively charged cloud or in the induced positive charge on the earth's surface.

3. A positively charged cloud may be discharged by discharges starting in the cloud and terminating either in the surrounding atmosphere or on the earth's surface.

4. If a lightning flash is branched, the branches are always directed toward the seat of negative electricity.

5. The application of these conclusions to 442 photographs of lightning discharges reveals the fact that the preponderance of the lower clouds from which lightning discharges proceed are positively charged.

In a paper by N. Ernest Dorsey [27] a second theory is given for the formation and progress of a lightning flash which differs materially from Simpson's. It is based upon some

[25] Steinmetz, Trans. A. I. E. E., **43**, p. 126; 1924.
[26] Proc. Roy. Soc., **111**, p. 56; 1926.
[27] J. Frank. Inst., **201**, p. 485; 1926.

peculiar lightning strokes, the effects of which indicate that the direction of a stroke is not dependent upon the direction of a preexistent field due to a charged cloud but is only initiated by such a field and progresses in a manner analogous to that of a beam of cathode rays. The path of the stroke is described as being formed by an elongated dart of flying negative electrons which originates in a region of intense electrostatic stress and acquires sufficient velocity to maintain itself in weaker fields, and as an extreme case to penetrate an adverse field, until it strikes some solid object, such as a tree, with a resulting explosion as the dart is suddenly impeded. Trailing electrons combine with positive residues to form the flash, and while the path remains highly ionized the cloud may be partly discharged with a heavy flow of current.

An experiment by C. V. Boys in photographing a flash of lightning with a special camera having a pair of separated lenses revolving in a circle before a stationary plate has led him, after stereoscopic examination of the images, to the conclusion that a lightning flash originates at both positive and negative ends nearly, if not quite, simultaneously.

It should be noted that Simpson's theory of formation of a lightning flash requires that it originate at the seat of positive electricity. Dorsey's requires that it originate at the seat of negative electricity, while the photograph of Boys's indicates that it originates at both ends and meets midway. This diversity indicates the speculative character of much of the discussion of lightning beyond the results of actual measurements.

INDUCED EFFECTS

The induced effects of lightning discharges are of serious consequences in some cases and may be due to either electromagnetic induction, electrostatic induction, or both, depending upon conditions. At a distance from the flash they consist of minor electrical discharges from insulated metallic bodies to earth or to near-by objects. They may be severe enough to cause fires, damage, or injury to persons. They are observed principally upon the approach of thunderstorms when everything is dry. Rainfall usually prevents them by reducing or destroying the insulation. Such discharges, in the form of sparks ranging in length from a small fraction of an inch to more than an inch, have been noted at distances of several miles from the apparent center of activity of the storm.

The magnitude of the potentials which may be attained by insulated bodies may be inferred from the values of change in potential gradient due to lightning flashes found by Wilson. In several cases changes amounting to 15,000 volts per meter (4,600 volts per foot) were observed as a consequence of flashes as much as 3 miles away. A wire clothesline supported in such a field on dry wooden posts 2 m (6.56 feet) high would have accumulated on it a charge such that immediately following the flash its potential to ground would be around 30,000 volts. A person touching it at that instant would act as a discharge path and, if the capacity were considerable, would be severely shocked. Shocks from this cause have been received not only from insulated wire clotheslines, but also from wire fences, down spouts, and other objects. A metallic object which is grounded would, of course, show no effect other than a current discharge through the ground connection.

In the immediate vicinity of a flash the induced effects become more severe and appear as sideflashes and oscillatory disturbances in metallic circuits, the effects of which may be comparable in many cases with the effects of the main stroke. Sideflashes or branch discharges from the main path have been observed to jump gaps of several feet, especially where there are metallic objects near by. Oscillatory disturbances may be set up in electric circuits of sufficient magnitude to break down even high-voltage insulation.

Lightning may cause voltages in conductors by induction or by a direct stroke. Although most disturbances on transmission lines due to lightning are caused by induction, the highest voltages are caused by direct hits. This follows, since inductive effects may be experienced at a considerable distance from the discharging cloud, while for a direct hit it is necessary for the cloud to be nearly overhead. Induction may be electrostatic or electromagnetic. In comparison with the electrostatic effect, electromagnetic induction by lightning is generally negligible.

A charged cloud causes an electrostatic field between it and earth. Part of the field will terminate on any transmission line within the field of influence of the cloud. The line is then said to have a "bound charge." This bound charge will have a sign opposite to that of the cloud, the charge of the same sign being driven off to earth by leakage over the insulation of the line or through the station equipment or to a distant portion of the line beyond the cloud's field. If the voltage between cloud and earth or cloud and cloud becomes high enough, a lightning flash will occur. Although this flash may be a mile away from the line, the charge on the line is released and the insulated line rises from earth potential to some higher value with polarity opposite to that of the cloud. The effect is that of a voltage suddenly applied between line and ground. The field that extended between line and cloud is succeeded by one between line and ground. The voltage wave travels over the line at the velocity of light. If the line insulators are strong enough or have a high enough impulse ratio, it may travel to the powerhouse to break down apparatus or to be harmlessly discharged to ground over the arrester if it has low resistance and low impulse ratio.

The voltage that the line assumes at the instant of a very sudden discharge is that of the equipotential surface at the height at which the line is located.

The induced lightning voltage on a transmission line thus varies with the height of the line. It is approximately equal to the height of the line times the voltage gradient, where the discharge is very rapid, as is usual in the case of lightning.

Thus $V = ga\, h = Gh$, where

V = induced volts,

g = actual gradient in volts per foot where line is located,

a = a factor less than unity,

$G = ga$ = apparent gradient,

h = height of the line in feet.

The exact value of a depends upon the rate at which the clouds discharge. This is because in slowly discharging clouds the charge is dispersed over the line for a considerable distance before the cloud becomes completely discharged. The highest values are attained in the case of a direct stroke. Values of G as high as 50 kv/ft. have been measured on transmission lines in practice. The actual gradient g may be as high as 100 kv/ft., so that for rapid discharges and direct hits the induced voltage (in kilovolts) approaches the height of the line in feet multiplied by 100.[28]

As the disturbance gets well under way and half of the energy of the surge becomes electromagnetic, the voltage

[28] F. W. Peek, jr., The Effect of Transient Voltages on Transmission Lines: J. A. I. E. E., 43, p. 697; 1924.

is reduced to half. Corona and I^2R (resistance) losses draw upon the total energy as the surge travels on and the voltage is further reduced.

The induced voltage appears on the line as a direct voltage very rapidly applied or as a highly damped oscillation. There is thus usually simply a rapid rise (a steep front) to maximum voltage, then a more or less gradual tapering off or decrease in voltage (a long tail) to zero.

Due to probable variations in a, both the steepness and the magnitude of the surges occurring during any given storm will vary over a wide range, but the highest voltages (where a approaches unity) are of necessity associated with the steepest fronts. Where protection is to be obtained, it must be secured from these steepest fronts. If protection from the steep-fronted surges is secured, there will be no cause for worry over the less steep ones. On overhead transmission lines the induced voltages may reach high values, 1,000 to 1,500 kv being frequently recorded. On extremely high-voltage lines these induced voltages may not be so troublesome, since the line insulation may be strong enough to prevent spark over by most of these voltages, but on lower voltage lines they may be very troublesome. Not only will a lightning spark over be most likely to damage the insulators, but it will also generally be followed by a power arc over which may complete the destruction. At any rate the power arc requires the tripping out of the circuit to extinguish the arc, causing an interruption in the continuity of service, the maintenance of which is constantly becoming of increased importance.

When a grounded conductor or ground wire is placed near the conductors of a transmission line it has a marked effect on the voltages due to lightning that appear on the line. The ground wire reduces the voltage in two ways: First, it reduces the number of lines of force terminating on the line conductors. This reduces the magnitude of the bound charge on the conductors and the total energy later to be released in the surge. In the second place, it increases the capacitance of the line conductor to earth, so that with a given quantity in the surge the voltage to which the line conductor is charged is less, from the equation $Q=CV$. As C is increased V is decreased for a given quantity Q.

It has been found experimentally [29] that one ground wire will reduce the induced voltage to approximately 50 per cent of its original value, two ground wires to approximately 33 per cent, and three ground wires to approximately 25 per cent, etc. There is also a protection against direct hits to the line conductor, since the ground wire is generally arranged above the line conductors to take the direct hits. The experimental values given above are in general agreement with the mathematical results and apply to wires provided with good grounds made with short grounding conductors at frequent intervals. Poor grounds, or grounds infrequently made, considerably reduce the theoretical or maximum efficiency to be obtained. Troubles with the ground wire in the past have often been due to poor mechanical design. The ground wire should have a life fully as long as the line conductors. They should be strung as near as possible to the line conductors and yet far enough away to prevent flash overs at times of high wind, heavy sleet loadings, etc.

The question whether protection from induced lightning voltages is or is not to be provided is an economic one. The protection to be secured by one, two, or three ground wires is to be balanced against the cost.

The induced effects of lightning are responsible for a large majority of fires occurring in oil tanks, reservoirs, and oil farms as a result of sparks produced in or about the tanks where escaping gases can be ignited. Warehouses contain-

[29] F. W. Peek, jr., J. Frank. Inst., 199, p. 141; 1925.

ing baled hay and cotton have also been fired by induced-voltage sparks between the baling wires, which ignite the combustible material.

THUNDER

It is now thought that the sound of thunder is caused largely, if not entirely, by a sudden increase of pressure due to heating, dissociation, and ionization along the path of a lightning stroke. As stated heretofore, the energy of a stroke may amount to 10^8 or 10^9 watt-seconds, of which the greater portion is expended in heating the air. If the path is assumed to be a foot in diameter and a mile long, 10^8 watt-seconds would heat it to about 650° C., with an increase of pressure of about 2 atmospheres. The dissociation would add to this by increasing the number of gas molecules. This increase of pressure, which may in reality be much greater than 2 atmospheres, takes place very abruptly and is sufficient to account for the ear-splitting crash which accompanies a near-by flash of lightning.

The intensity of different claps of thunder is as variable as the current of lightning flashes, near-by strokes of lightning having been observed with no thunder audible to the observer. One such occasion is recorded in connection with the Washington Monument when, on April 5, 1885, during the passage of a heavy thundercloud, at least five immense sparks or bolts were seen within a period of 20 minutes to flash between the terminal and cloud, without audible sound.[30] On other occasions disruptive discharges were observed, accompanied by thunder.

One of the chief characteristics of thunder, especially at a distance, is the prolonged rumbling produced, sometimes interspersed with tremendous bumping sounds that apparently

[30] Report of engineer officer in charge of public buildings and grounds, Washington, D. C.; 1885.

carry a great deal of energy, enough to rattle windows and cause buildings to tremble. The rumbling arises chiefly from the fact that the source of the sound is long and irregular and different parts of it are at different distances from the observer, and from echoes and reflections. The crashing noise heard near at hand is smoothed out until at a distance of a few miles a rolling sound is produced. The bumping sounds just mentioned may arise from some particularly favorable condition of reflection or from direct transmission of sound from some portion of the path. A succession of bumps may arise from several successive discharges.

The distance to which thunder can be heard ordinarily does not exceed 15 miles (24 km), and usually it is less. As compared with gunfire this distance is surprisingly short, but gunfire is heard at great distances only under favorable conditions for the transmission of sound, while thunder occurs only when conditions are bad and is consequently muffled, although the total atmospheric disturbance is undoubtedly greater.

ILLUMINATION

The illumination from a lightning flash has heretofore been attributed by many to the heating of the air by the passage of the current, but this does not seem to be an adequate explanation for the reason that air heated to any practical temperature has not been shown to be more than faintly luminous. It has been found that gases, in general, which are highly transparent to visible rays of light at ordinary temperatures, as are the constituents of air, do not emit them in quantity when heated. Luminosity from gases of this sort is obtained only by ionizing them under a strong electric field, thereby producing electronic vibrations of the frequency of visible rays. Since air conducts electricity only by

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ionization, the air along the path of a lightning flash must be highly ionized, and from this it seems likely that the electric field rather than the temperature is the exciting cause of the illumination. The abrupt disappearance of the light at the conclusion of the flash also indicates the same thing. If the temperature were high enough, of course, a sufficient degree of ionization might be produced independently of the electric field to give rise to the illumination, but temperatures of this magnitude, of the order of 10^5 degrees C., do not seem likely from consideration of the probable energy and dimensions of lightning flashes. As indicated in the preceding section, the temperature is not likely to exceed those producible by laboratory means.

CHARACTER OF DAMAGE

When lightning strikes to earth the object which receives it usually suffers more or less damage, depending upon its relative conducting power. Metal, for instance, receives a lightning discharge with little damage to itself. In most cases even slender conductors, such as telegraph, telephone, and electric-light wires, will carry a discharge without fusing except where the discharge enters the metal. There 1 or 2 cc of metal may be fused to a globular mass. Occasionally fusion is more extensive, in rare instances having affected several hundred grams of metal, but such cases are exceptional. In other exceptional cases there may be electromagnetic damage to metal conductors, they being torn from their fastenings or bent out of shape as a result of the passage of the current.

When insulating or semiinsulating material receives a discharge, however, the damage is usually severe and takes on an explosive character. Trees, for instance, whether dry or green, are in frequent cases blown to splinters and in any event are split or stripped of more or less bark. The damage may also extend underground to the roots. Wood, in general, is subject to the same kind of splintering, and brick and stone work are sometimes demolished locally and pieces thrown to distances of 100 feet or more.

The extent of damage of this kind seems to depend in some degree upon whether the material is externally wet or not when struck. Prior to rainfall the damage is the most extensive; afterwards it becomes less, the discharge apparently keeping more to the outer surface. Trees struck when thoroughly wet in many cases show only a small piece of bark stripped off here and there, the remainder of the path along the trunk being barely traceable by slight superficial damage, while trees struck when dry externally are almost invariably stripped or splintered from top to bottom.

The cause of damage of this sort is generally attributed to the formation of steam at high temperatures within pores of the material, all porous materials exposed to air being known to contain more or less moisture. It is conceivable, however, that there may be more to it than formation of steam, although this would be a contributory cause. It is possible that under the high current intensity and potential gradient of a lightning discharge some of the material itself is decomposed or distilled with the formation of gaseous products, such as hydrogen, oxygen, hydrocarbons, ions, and electrons. When hydrogen, for instance, changes from the ionic, or combined state as in water, to gaseous state at atmospheric pressure the volume occupied at ordinary temperatures increases about one thousand three hundred times and becomes much greater than this at the temperatures probably developed by lightning discharges. Hence, a capillary tube in wood filled with moisture at atmospheric pressure would be subjected to an internal pressure much greater than 1,300 atmospheres if all the hydrogen contained in the moisture were suddenly released in gaseous form by lightning. This would be equivalent to an explosion of dynamite and ample to account for the explosive effects of lightning, especially where coupled with the formation of steam, oxygen, and other products arising from the decomposition of the material. There is also to be considered the electrostatic repulsion between the electrons traversing the pores, which may be very great. It has been suggested by Dorsey that this repulsion between the fibers of even a small piece of wood may be many tons.

The greatest damage to property from lightning, of course, comes from fires started by it. In some classes of property the losses are serious, especially in oil tanks, farm barns, and structures generally which house inflammable materials. Lightning fires are started chiefly by the discharge, a branch of it, or an induced spark, penetrating something easily ignited, such as explosive gases, dust, lint, hay, straw, or paper. It is seldom that fires are started in dry wood that is solid. Forest fires from lightning start usually in dry decayed wood or beds of leaves or needles.

EFFECTS ON PERSONS

When persons are subjected to direct lightning strokes the result is nearly always fatal, although instances have been recorded of extraordinary escapes from what seemed to be direct strokes. It is possible, however, that what appeared to be direct strokes actually were not. When lightning strikes, the light is so intense and the brush effects so widespread that it is difficult for an observer to be certain of what happened until the spot is examined afterwards, and even then the traces may be confusing. Moreover, the shock from a direct stroke is so great that it does not seem within reason that a person could survive it. Where the subject does survive it is highly probable that the greater portion of the stroke was expended upon some other object. The major part of lightning casualties arise from secondary phenomena, such as sideflashes and induced discharges.

The injuries inflicted by lightning consist of electric shocks of greater or less severity which may be combined with burns, and in some cases tearing of the flesh, apparently by an explosive action of the discharge. Burns by lightning frequently assume fantastic forms, and cases are reported where images of various kinds were imprinted upon the body. That such burns happen to be the image of anything is doubtless a matter of chance. Their origin is probably in surface discharges over the skin or in the layer of clothing damp with perspiration next to it. This layer, especially in thunderstorm weather, offers considerable inducement to a discharge to follow it, and the resulting heat, or burning by ultraviolet rays, might cause almost any kind of an image to be imprinted. First-aid treatment for injuries by lightning is the same as that for other electric shocks and burns. First-aid treatment, especially artificial respiration if administered in time, would doubtless prevent many deaths from lightning which otherwise result from the fact that nine-tenths of such accidents occur in isolated places where few or none are acquainted with the proper procedure.

THUNDERSTORM DATA

Such data on this subject for the United States as are available have been accumulated by the United States Weather Bureau, through its various observation stations, and have been summarized in Weather Bureau publications. Records for a period of 20 years are contained in an article by William H. Alexander.[31] Maps are shown with isocer-

[31] Monthly Weather Review, 52, p. 327; 1924.

aunics, or lines of equal thunderstorm frequency, drawn upon them for the different months of the year. Quoting the original article:

During the winter months—December, January, and February—the center of thunderstorm activity for the United States is in the vicinity of Vicksburg, Miss. In February, however, the general thunderstorm area tends to drift southeastward, with a marked secondary over Pensacola, Fla. In March the center of activity is still over the lower Mississippi Valley, with the general storm area spreading rapidly northeast over the Tennessee and Ohio Valleys. In April the center appears to be in the vicinity of Shreveport, La., with the general area spreading northeast over a large part of the Eastern States, but also north and west.

The interesting thing about the May chart is the definite appearance of the primary center over Tampa, Fla., and a strong secondary over the lower plains States. Great thunderstorm activity now prevails over the entire eastern half of the country, except in the Canadian border States, including the whole of New England. There is also an increased activity in western Montana.

During June the thunderstorm area continues to spread northward and covers the entire country east of the Rocky Mountains except possibly the extreme Northeast. The center of greatest activity is in the vicinity of Tampa. There are also definite indications of the development of a secondary center over the southern Rocky Mountain States. One of the most surprising things revealed by the July chart is the increased activity over the Rocky Mountain States, with a secondary over Santa Fe, N. Mex., almost as strong as the primary over Tampa. Marked activity also continues in southwestern Montana and in the vicinity of Yellowstone Park. The distribution in August is very much the same as in July, but with a notable decrease in intensity along the Canadian border and a marked weakening of the center over Santa Fe. The two centers, Tampa and Santa Fe, persist, though weakening, through September. In October the southeastern (Tampa) center seems to have dropped a little south and is now over Key West, while the Santa Fe center has disappeared or shifted to eastern Texas and the southern plains States, and the general storm area is rapidly diminishing. In November, as during the winter months, the active area is over the lower Mississippi Valley, and the general area is limited largely to the Mississippi and Ohio Valleys.

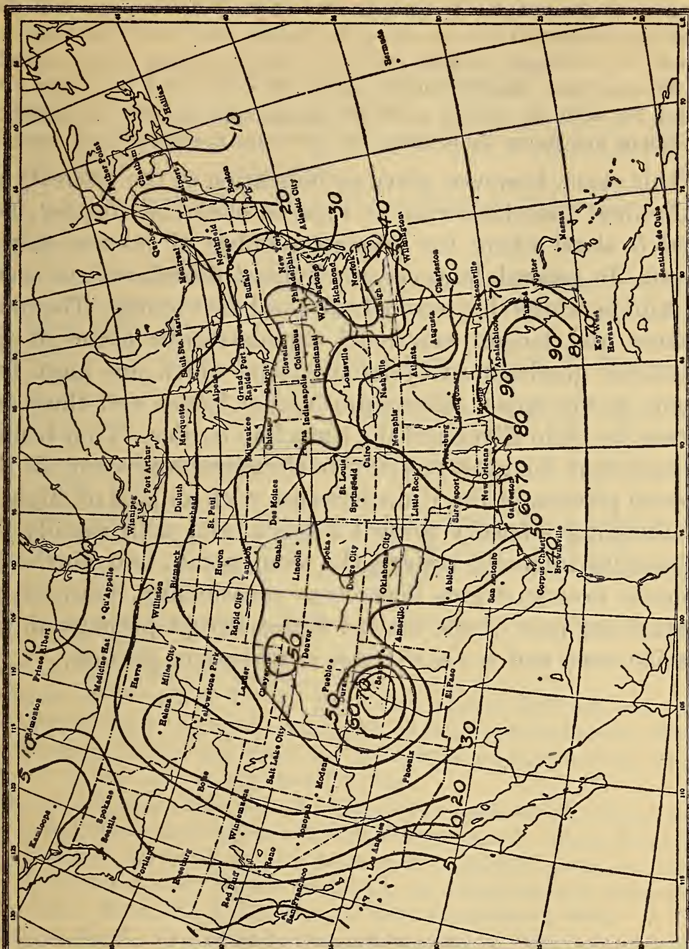

FIGURE 7.—*Average number of days per year on which thunderstorms occur*

Chart 13 (fig. 7 herewith), which shows the average annual number of days with thunderstorms during the 20-year period at a large number of stations in the United States and Canada, has a number of interesting features and is worthy of considerable study. Note that no part of the country is entirely free from thunderstorms and that they are comparatively rare along the Pacific coast; that there are two centers of maximum activity, one over Tampa, with an annual average of 94 days with thunderstorms in the 20 years, and the other over Santa Fe, with an average of 73 during the same period. The average at Tampa and Santa Fe is nearly the same for the two 10-year periods.

This chart, however, gives no indication of the intensity of individual thunderstorms as regards electrical display, nor does it show where the greatest number of intense storms occur. In general, however, the lightest thunderstorms occur in regions where they result from local convection. The most intense and longest continued thunderstorms occur in the southeast quadrant of cyclonic storms which are most frequent in the upper Mississippi Valley States and those between the Ohio River and the Canadian border. Thus it may be said that the most destructive thunderstorms occur in the central portion of the United States, with an arm of slightly diminishing intensity toward Florida, and with rapidly diminishing intensity toward the west, north, and northeast. Intense thunderstorms may occur occasionally, however, in almost any part of the United States, except perhaps on the Pacific coast and in the extreme northeastern portion.

Appendix B.—BIBLIOGRAPHY

Acheson, E. G., Lightning arresters and the photographic study of self-induction of conductors. High speed pictures of spark gaps, A. I. E. E. Trans., **6,** pp. 74–98; 1889.

Adams, P. H., Earthing power station equipment, Power, **48,** p. 451; 1918.

A. I. E. E.:

Standardization rules, definition, rating, and performance and tests of lightning arresters and protective reactors, A. I. E. E. Trans., **33,** p. 1856; 1914.

Report of committee on protective devices, A. I. E. E. Trans., **37,** p. 738; 1918.

Report of committee on protective devices, A. I. E. E. Trans., **38,** p. 893; 1919.

Report of subcommittee on lightning arresters, A. I. E. E. J., **41,** p. 896; 1922.

Present practices in protection; annual report of committee on protective devices, A. I. E. E. J., **45,** pp. 1098–1114; 1926.

Annual report of committee on power transmission and distribution, **47,** p. 676; 1928.

Protection of transmission lines from interruption by lightning, **48,** p. 210; 1929.

American Railroad Association:

Report of committee No. 4. Protection against lightning, etc., for railway signal circuits. Page 373 gives recommendations, chart showing number and kind and position of various devices, Proc. Tel. & Tel. Div., p. 85; June 11, 1919.

Report of committee No. 4. Protection against lightning, etc. Amendments and suggestions for previous report. Pages 133–136. Essential elements in telephone and telegraph plant, p. 339. Specifications for electric protection of telephone and telegraph plant. Proc. Tel. & Tel. Div., p. 127; December 3, 1919.

Andersen, R. C. Transmission-line lightning surges, Elect. Rev., **101,** p. 1071; 1927.

Allcut, C. T.:
Lightning arrester spark gaps; commercial form, A. I. E. E. Trans., **39,** pp. 939–943; 1920.
Lightning arrester spark gaps; experimental form; their relation to the problem of protecting against impulse voltages, A. I. E. E. Trans., **37,** p. 853; 1918.
Atherton, A. L.:
1922 developments in autovalve lightning arresters, A. I. E. E. Trans., **42,** p. 485; 1923.
Autovalve lightning arrester, Elec. J., **20,** p. 107; 1923.
Effect of cables in overhead circuits on operation and application of lightning arresters, Elect. Light & Power, **4,** p. 82; 1926.
Lightning arrester problems, A. I. E. E. J., **47,** p. 591; 1928.
Plans for lightning tests, Elect. World, **92,** p. 165; 1928.
220 kv. lightning arresters—A new approach to an old problem, Elect. J., **25,** p. 118; 1928.
Performance characteristics of autovalve lightning arresters, Elect. World, **81,** p. 385; 1923.
Lightning arrester application from the economic standpoint, A. I. E. E. J., **43,** pp. 813–817; 1924.
See Fortescue, Atherton, and Cox.
Bang, A., Four years operating experience on Pennsylvania Water Power Co.'s transmission line. Gives every lightning flashover, etc., A. I. E. E. Trans., **34,** pp. 1243–1274; 1915.
Beck, Edward:
Lightning arresters for supervisory control systems, Elect. J., **24,** p 388; 1927.
Study of lightning protection, Rwy. Sig., **21,** p. 216; 1928.
Bennett, C. E.:
Water resistance and gap for lightning arrester, Elect. World, **75,** pp. 365–368; 1920.
Lightning arresters, A. I. E. E. J., **43,** pp. 791–797; 1924.
Some wet and dry spark-overs obtained with compensated impulse gaps, Elect. World, **79,** p. 1065; 1922.
Draining high voltages from lines, Elect. World, **91,** p. 1297; 1928.
Berger, K., Der Kathodenstrahl-Oscillograph als Registrier-instrument speziel für raschverlaufende Vorgänge, Bull. Assoc. Suisse d. Electriciens, **19,** p. 688; 1928.
Bishop, H. M., The lightning arrester, Radio Broadcasting, **9,** pp. 241–242; 1926.

Brown-Boveri Rev., Ed., Disturbances of electrical plants due to lightning, Brown-Boveri Rev., **9,** p. 235; 1922.

Burger, E. E.:

Some fundamentals in protecting against lightning, Gen. Elect. Rev. **26,** p. 208; 1923.

Lightning arresters for transmission and distribution circuits, Gen. Elect. Rev., **28,** pp. 857–859; 1925.

Burkholder, C. I. and Marvin, R. H., Arc suppressor; operates by shunting out the arc, A. I. E. E. Trans., **30,** pp. 327–335; 1911.

Carlton, W. G., Protection of cables from arcs due to the failure of adjacent cables; general, A. I. E. E. Trans., **23,** pp. 471–474; 1904.

Chopin, M., Tests on current limiting resistances in series with lightning arresters, Revue Generale Electrique, **20,** pp. 425–428; 1913.

Clark, R. P. (*See* Creighton, Shavor, and Clark.)

Coal Age, Ed., By putting oxide film lightning arrester in case, short gap may be used, Coal Age, **20,** p. 804; 1922.

Coats, W. A., High voltage switch gear, Eng., **134,** p. 199; 1922.

Cohen, E. M. Influence of ground connections on lightning-arrester performance, Elect. Rev., Chicago, **72,** p. 959; 1918.

Collbohm, M. H., Protection of transformer neutrals from destructive transient disturbances, A. I. E. E. Proc., **36,** p. 139; 1917.

Cotton, H., Lightning arresters; ways in which overvoltages are produced; different types of arresters and their operation, Beama, **10,** p. 418; 1922.

Cox, J. H., P. H. McAuley, L. G. Huggins, Kyldonograph surge investigations, Trans. A. I. E. E., **46,** p. 315; 1927.

Cox, J. H., Lightning and its effects on transmission lines, Elect. J., **24,** p. 364; 1927.

Cox, J. H., and J. W. Legg, The klydonograph and its application to surge investigation, Trans. A. I. E. E., **44,** p. 857; 1925.

Cox, J. H., and J. Slepian, Effect of ground wire on traveling waves, Elect. World., **92,** p. 551; 1928.

Cox, J. H. (*See* Fortescue, Atherton, and Cox.)

Creighton, E. E. F.:

Means of reproducing lightning phenomena in the laboratory described; gives oscillograms and equivalent needle-gap curves, A. I. E. E. Trans., **25,** pp. 365–397; 1906.

Creighton, E. E. F.—Continued.

Description and performance of graded shunt arrester, multi-gap arrester, and electrolytic cell arresters; discussion on properties of horn gaps, low equivalent, and electrolytic lightning arresters, A. I. E. E. Trans., **26,** p. 461; 1907.

Glossary of terms used in dealing with lightning phenomena and protective apparatus; properties of lightning and characteristics of lightning arresters; methods of testing lightning arresters so as to fix their various properties; classification of various arresters giving uses and limitations; suggestions for protection of electric plants, A. I. E. E. Trans., **26,** pp. 1049–1095; 1907.

Measurements of lightning, aluminum lightning arresters, earth resistances, cement resistances, and kindred tests, A. I. E. E. Trans., **27,** pp. 669–740; 1908.

Protection of lines in general A. I. E. E. Trans., **30,** pp. 257–326; 1911.

Status of aluminum arrester; its advantages, A. I. E. E. Trans., **33,** pp. 293–309; 1914.

Questions on the economic value of the overhead grounded wire, A. I. E. E. J., **41,** pp. 21–29; 1922.

Deviations from standard lightning arrester practice, A. I. E. E. J., **41,** p. 99; 1922.

Thunderstorm researches versus no lightning arresters, Elect. World, **83,** p. 521; 1924.

Lightning protection, Elect. World, **84,** pp. 622–623; 1924.

Creighton, E. E. F., and F. R. Shavor, The compression chamber lightning arrester, A. I. E. E., Trans. **31,** pp. 811–824; 1912.

Creighton, E. E. F.; F. R. Shavor, and R. P. Clark, Protection of electric railways and methods of preventing deterioration of aluminum lightning arresters, A. I. E. E. Trans., **31,** pp. 851–886; 1912.

Creighton, E. E. F., and S. D. Sprong, Oscillograms of surges on a. c. distribution system of United Electric Power Co., N. Y. with and without aluminum lightning arresters, A. I. E. E. Trans., **28,** pp. 805–839; 1909.

Croft, Terrell, Lightning protection, methods and operation, Power Plant Eng.; December 1, 1917.

Dill, G. C., Lightning protection for special transmission lines, Elect. J., **15,** p. 203; 1918.

Dillard, E. W., Lightning investigation on New England Power Co. system, A. I. E. E. J., **47,** p. 489; 1928.

Dubois, D. (*See* Rushmore and Dubois.)
Eaton, J. R. (*See* Hemstreet and Eaton.)
Edgcumbe, K., Protective gear for "over pressure" on high-tension circuits, Elect. Rev., **75**, pp. 712–714, 744–746, 775–777, 807–809; 1914.
Electrical Review and Western Electrician, Ed., Protection of telephone equipment against lightning and high-tension sneak currents, Elec. Rev. and West. Elec., **70**, pp. 674–675; 1917.
Electrical Review, Ed:
Lightning arrester employs oxide film, Elect. Rev. **78**, p. 1029; 1920.
Operation of lead oxide lightning arrester, Elect. Rev., **78**, p. 75; 1921.
Inspection and testing of lead oxide film lightning arresters, Elect. Rev., **78**, p. 75; 1921.
Lightning protection on rural power lines, Elect. Rev., **78**, p. 669; 1921.
Electrical Review, Elec. Rwy. J., Electrical World., Ed, Symposium on lighting protection, Elec. Rwy. J., **56**, p. 1069, 1920; Elect. Rev., **77**, p. 810, 1920; Elect. World, **76**, p. 1040; 1920.
Electric Rwy. Journal, Ed:
New Westinghouse type lightning arrester, Elect. Rwy. J., **59**, p. 973; 1922.
New railway lightning arrester, Elect. Rwy. J., **62**, p. 749; 1923.
Electrical World, Ed.:
Arrangement of arresters and choke coils Elect. World, **73**, p. 1276; 1919.
Charging and maintaining lightning arresters, Elect. World, **82**, p. 483; 1923.
Devices used at Untra power station and Line Värtan, Elect. World, **76**, pp. 277–279, 377–380; 1921.
Eglin, W. C. L., Specifications for material and construction of overhead lines, rules for protection of telephone lines, A. I. E. E. Trans., **22**, p. 747; 1903.
Fallon, J., Probable shape of the overvoltages induced in overhead lines by lightning discharges, Rev. Gén. de l' Élect., **23**, p. 957; 1928.
Field, C., The oxide film lightning arrester, A. I. E. E. Trans., **37**, p. 881; 1918.
Fortescue, C. L., A. L. Atherton, and J. H. Cox. Theoretical and field investigation of lightning, A. I. E. E. J., **48**, p. 277; 1929.
Foust, C. M. (*See* Lee and Foust.)

Garrard, C. C. Horn lightning arresters; calculations of gaps and series resistance, Electrician, **72,** pp. 996–998; 1914.

Gilbert T. C., Lightning discharges, Elect. Rev., London, **99,** pp. 870–871; 1926,

Golladay, L. R., Arrester tests with the klydonograph, Elect. World, **88,** pp. 477–479; 1926.

Goodwin, V. E.:

Spheres on a horn gap to reduce time lag, G. E. Rev., **20,** pp. 658-661; 1917.

A. C. lightning arresters, G. E. Rev., **23,** p. 429; 1920.

Harrington, A. L., Installation of lightning arresters at the Crystal City Substation of the Pittsburgh Plate Glass Co., Gen. Elect. Rev., **30,** pp. 301–303; 1927.

Hayden, J. L. R.:

Notes on resistance of gas pipe grounds, A. I. E. E. Trans., **26,** pp. 1209–1214; 1907.

Hayden, J. L. R. and N. A. Lougee, Types of lightning arresters, G. E. Rev. **24,** p. 1018; 1921.

Hemstreet, J. G., and J. R. Eaton, Surge-voltage investigations on the 140-kv system of the Consumers Power Co. during 1927, A. I. E. E. J., **47,** p. 441; 1928.

Hodges, N. D. C., Discussion of lightning and proposed methods of using high-resistance conductor to dissipate the energy of the discharge, A. I. E. E. Trans., **8,** pp. 159–167; 1891.

Huggins, L. G. (*See* Cox, McAuley, and Huggins.)

Hunt, F. L.:

Lightning arresters, general, A. I. E. E. J., **40,** p. 687; 1921.

Analysis of lightning arrester operating practice, Elect. World, **79,** p. 376; 1922.

Jackson, R. P.:

Theoretical investigation tending to show the limitations of inductance of choke coils in protecting transformers and the relative value of the different arc suppressing devices, series resistors, fuses, and electrolytic cells. Tests and oscillograms, A. I. E. E. Trans., **25,** p. 881; 1906.

Potential stresses about grounded conductors and towers, A. I. E. E. Trans., **26,** pp. 873–882; 1907.

Johnson, V. E., Lightning arresters, Power Plant Eng., **25,** p. 1053; 1921.

King, H. M., Water barrel lightning arresters give satisfactory service, Elect. World, **79**, p. 586; 1922.

König. New lightning arrester, Elektrotech. Zeits., **48**, p. 301; 1927.

Lang, P., Condensers as lightning protectors; proves them good if not too large, Electrotechnik und Maschinenbau, 31, p. 725; 1913.

Lawson, J. F. (*See* Pollard and Lawson.)

Lincoln, Paul M.:

The grounded neutral with and without series resistance; advantages and disadvantages, A. I. E. E. Trans., **26**, pp. 1585–1595; 1907.

Analogy for electric surges; methods of protection, A. I. E. E. Trans., **29**, pp. 573–598; 1910.

Lougee, N. A.:

Life tests on oxide film lightning arrester, A. I. E. E. J., **39**, pp. 944–948; 1920.

Pellet type of oxide-film lightning arrester, A. I. E. E. J., **42**, p. 1019; 1923.

Life and performance tests on oxide-film lightning arresters, Gen. Elec. Rev., **23**, p. 928, 1920.

A study of the multigap lightning arrester, Gen. Elec. Rev., **25**, p. 560; 1922.

(*See* Hayden and Lougee.)

Matthias, A., Atmospheric disturbances and lightning protection, Elektrotech. Zeits., **46**, p. 873; 1925.

Influence of thunderstorms upon transmission installations, Elektrotech. Zeits., **48**, p. 1477; 1927.

McAuley, P. H. (*See* Cox, McAuley, and Huggins.)

McEachron, K. B., Effect of grounded neutral on the efficiency of lightning protection equipment, Iron and Steel Engr., **5**, p. 160; 1928.

Mershon, Ralph D., The overhead grounded wire as a protection against lightning. Calculation of shielding effect, A. I. E. E. Trans., **22**, p. 331; 1903.

Lee, Everett S., and C. M. Foust, The measurement of surge voltages on transmission lines due to lightning, A. I. E. E. J., **46**, p. 149; 1927.

Legg, J. W. (*See* Cox and Legg.)

Lewis, W. W.:

Relation between transmission line insulation and transformer insulation, A. I. E. E. J., **47**, p. 637; 1928.

Surge voltage investigation on transmission lines, A. I. E. E. J., **47**, p. 795; 1928.

Middlemass, G. H., Water-tube arrester compares favorably with others, Elect. World, **79,** p. 838; 1922.

Michener, H.:

Opinions on and experiences with lightning arrester performance on the Southern California Edison System, Elect. World, **82,** p. 803; 1923.

High-voltage switches, bushings, lightning arresters, experiences of the Southern California Edison Co., A. I. E. E. J., **42,** p. 1251; 1923.

MacLaren, M., Lightning disturbances on distribution circuits, A. I. E. E. J., **42,** p. 280; 1923.

McEachron, K. B.:

Protection of station equipment on high voltage transmission lines, G. E. Rev., **31,** p. 230, 1928.

Time, voltage, and current characteristics of lightning arresters, Gen. Elect. Rev., **29,** pp. 678–684; 1926.

National Electric Light Association: Arrester practice up to 15,000 volts, Rept. Overhead Systems Comm.; 1921.

Neall, N. J.:

Performance of lightning arresters on transmission lines, A. I. E. E. Trans., **24,** pp. 951–981; 1905.

Method of introducing artificial lightning into transmission circuits; diagrams of connections of various systems, A. I. E. E. Trans., **27,** pp. 1139–1144; 1907.

Analytical study of lightning performance tests on Taylor's Falls line. Nature of lightning. Effectiveness of rods and arresters. Present art summed up in conclusion, A. I. E. E. Trans., **27,** pp. 421–448; 1908.

Nicholson, L. C., Describes "arcing rings" for protecting insulators from lightning and power arcs. Six thousand volt plant of Ontario Power Co., A. I. E. E. Trans., **29,** pp. 573–598; 1910.

Norinder, Harald:

Experimental investigation of the shape of lightning discharges, Tekn. Tidskr., **55,** p. 139; 1925.

Some electrophysical conditions determining lightning surges, J. Frank. Inst., **205,** p. 747; 1928.

The cathode-ray oscillograph as used in the study of lightning and other surges on transmission lines, Trans. A. I. E. E., **47,** p. 446; 1928.

Osgood, Farley, Experiences with lightning arresters on 33,000 volt transmission line, A. I. E. E. Trans., **25,** pp. 349–363; 1906.

Peck, E. P., High-voltage arrester for telephone lines. Description of a high and low-voltage arrester. First with horn and cylindrical gaps, second with G. E. metal tube vacuum gaps, G. E. Rev., **18**, p. 189; 1915.

Peck, J. S., Description and nature of the ground shield. Objections to its use, A. I. E. E. Trans., **23**, pp. 553–554; 1904.

Peek, F. W., jr.:

Lightning, Bull. of Hydro. Power Comm. of Ontario, **14**, p. 92; 1927.

Protection from lightning, Elect. World, **90**, p. 351; 1927.

Progress in lightning research in the field and the laboratory, A. I. E. E. J., **48**, p. 303; 1929.

The effect of transient voltages on dielectrics, A. I. E. E. Trans., **34**, p. 1857; 1915.

Lightning. Gives data on investigation of time lags in spark gaps, G. E. Rev., **19**, p. 586; 1916.

Effect of lightning voltages on arrester gap insulators and bushings on transmission lines, A. I. E. E. Trans., **38**, pp. 1137–1178; 1919; also G. E. Rev., **22**, pp. 900–906; 1919.

Lightning, J. Frank. Inst., **199**, p. 141; 1925.

Effect of transient voltages on dielectrics, A. I. E. E. J., **42**, p. 623; 1923.

Lightning and other high-voltage phenomena, Report Smithsonian Inst., pp. 169–198; 1925.

High voltage phenomena, Frank. Inst. J., **197**, p. 1; 1924.

Lightning and other transients on transmission lines, A. I. E. E. J. **43**, pp. 697–709; 1924.

A study of the causes of lightning, Rwy. Signalling, **18**, pp. 188–189; 1925.

High-voltage transmission, Elect. World, **87**, p. 63; 1926.

Peterson, W.:

Value of the overhead ground wire, E. T. Z., **35**, p. 1; 1914.

Intermittent arcing to earth. Mostly calculations of rise in voltage on line during arcing, ETZ, **38**, pp. 553–555, 564–566; 1917.

Piloty, H., Dimensions of damping resistances for lightning arresters, Elektrotech. Zeits., **48**, p. 1865; 1927.

Pollard, N. L. and J. F. Lawson., Experience and recent development in central station protective features, A. I. E. E. Trans., **35**, p. 695; 1916.

Power, Ed.:
Lightning protection with various types of arresters, Power, **37**, p. 166; 1913.
Oxide film lightning arrester, Power, **51**, p. 596; 1920.

Power Plant Eng., Ed.:
New types of oxide film arresters, Power Plant Eng., **26**, p. 783; 1922.
Simplicity is feature of new autovalve arrester, Power Plant Eng., **27**, p. 750; 1923.

Prehm, W., Protection of transmission lines from surges. Does not like gaps or condensers. Considers it much better economy to use none at all and increase insulation at transformers, ETZ, **35**, pp. 417–420; 1914.

Ramsey, A. G., Aluminum electrolytic lightning arrester with an introduction on electrical disturbances, Inst. Elect. Engrs. J., **57**, p. 306; 1919.

Rebora, G.:
The existing protective devices for electric lines. Elettrotecnica, **8**, pp. 46–50; 1921.
Lightning protection and damage to electrical plant, Elettrotecnica, **13**, pp. 661–662; 1926.

Rhodes, Geo. I., Experience with a grounded neutral on the high-tension system of I. R. T. Co., N. Y., A. I. E. E. Trans., **26**, pp. 1605–1610; 1907.

Roberts, J. D., Fuse protection of lightning arresters, Elect. Lt. & Pr., **4**, p. 27; 1926.

Roper, D. W.:
Practical studies in lightning protection on 4,000-volt circuit during five years, A. I. E. E. Trans., **35**, pp. 655–694; 1916.
Studies in lightning protection since 1916 on a 4,000-volt circuit, A. I. E. E. J., **39**, pp. 960–975; 1920.

Rowe, Norman, Lightning rods and grounded cables as a means of protection against lightning, Guanajuato transmission line, A. I. E. E. Trans., **26**, pp. 1239–1248; 1907.

Rushmore, D. B. and D. Dubois, Collection of photographs of lightning. Description of characteristics of horn gap arrester, water jet arrester, grounded wire and choke coils. Theory of operation and description of construction of multigap and low equivalent and graded resistance lightning arrester, A. I. E. E. Trans., **26**, pp. 425–459; 1907.

Rymer-Jones, J., Lightning arrester for submarine cables, Elect, Rev., London, **90**, p. 438; 1922.

Schweitzer, E. O., A lightning arrester which uses the pressure generated by an inclosed arc to separate the electrodes, Elect. World, **72**, pp. 52–54; 1918.

Scientific American, Ed., Beating lightning at its own favorite game, Sci. Am., **127**, p. 327; 1922.

Shelton, E. K., Protection of telephone circuits used in power distribution. Describes G. E., lightning arrester and metal vacuum gap, G. E. Rev., **19**, p. 1126; 1916.

Sindeband, M. L. and P. Sporn, Lightning and other experiences with 132-kv. steel tower transmission lines, A. I. E. E. J., **45**, pp. 641–651; 1926.

Slepian, Joseph, Theory of the autovalve arrester, A. I. E. E. J., **45**, pp. 3–8; 1926.

Slepian, J. (*See* Cox and Slepian.)

Smith, Julian C., Experiences with horn gap lightning arresters, with and without series resistors, A. I. E. E. Trans., **24**, pp. 935–944; 1905.

Sporn, P. (*See* Sindeband and Sporn.)

Sporn, Philip:

1926 lightning experience on 132-kv. transmission lines, A. I. E. E. J., **47**, p. 105; 1928.

Rationalization of transmission system insulation strength, A. I. E. E. J., **47**, p. 641; 1928.

Surge-voltage investigation of the 132-kv. transmission lines of the American Gas & Electric Co., A. I. E. E. J., **47**, p. 876; 1928.

1927 lightning experience on the 132-kv. transmission lines of the A. G. & E. Co., A. I. E. E. J., **48**, p. 122; 1929.

Smeloff, N. N. Surge voltage investigation on 220-kv. system of Pennsylvania Power & Light Co., A. I. E. E. J., **47**, p. 812; 1928.

Stafford, H. E., Some symptoms of lightning arrester troubles, Ind. Eng., **82**, p. 531; 1924.

Stauffacher, Edwin R., Lightning arrester experience in California, particularly as regards the Southern California Edison Co.'s system, A. I. E. E. J., **43**, p. 660; 1924.

Stienmetz, C. P.:

Study of oscillations of very high potential in a high potential system, A. I. E. E. Trans., **18**, pp. 383–405; 1901.

Theoretical investigation of high power surge on Manhattan Railway cable distribution system, A. I. E. E. Trans., **14**, p. 297; 1905.

Stienmetz, C. P.—Continued.

Lightning phenomena in electric circuits. Kinds of lightning, causes and effects and methods of protection. General discussion, A. I. E. E. Trans., **26**, pp. 401–423; 1907.

The oxide film lightning arrester and history of protection, A. I. E. E. Trans., **37**, p. 871; 1918.

General equations of the electric circuit, lightning conductors, A. I. E. E. Proc., **38**, p. 258; 1919.

Still, A., Lightning arresters on overhead power systems, Elect. Rev., **78**, p. 733; 1921, and **79**, p. 192; 1921.

Tanzer, E. Dean, Lightning arresters, Elect. Lt. & Pr., **5**, p. 21; 1927.

Telegraph Superintendents, Association of Rwy., Report of Committee No. 5 on protection against lightning and high tension circuits. Gives list of protectors in use and methods of installation, Tel. & Tel. Age, pp. 16 and 42; 1919.

Thomas, P. H.:

Static strains in high-tension circuits and the protection of apparatus. Arresters with shunt and series resistors, gaps and choke coils, A. I. E. E. Trans., **19**, p. 213; 1902.

The function of shunt and series resistance in lightning arresters. Principles of operation of low equivalent lightning arrester, A. I. E. E. Trans., **19**, pp. 1021–1034; 1902.

Classification of lightning disturbances. Description of tests to show serviceability of lightning arresters. Tests suggested for standardization by A. I. E. E. List of institute papers on lightning phenomena. Test curves showing nonarcing power of multigap arresters and shunting power of resistors, A. I. E. E. Trans., **26**, pp. 1097–1137; 1907.

Critical study of lightning records on Taylor's Falls transmission line. Review of papers by Vaughn and Neall, A. I. E. E. Trans., **27**, pp. 755–777; 1908.

Torchio, P., Notes on Italian high-tension transmission line lightning arresters. Describes Gala arrester and Friese water resistor static discharger, A. I. E. E. Trans., **24**, pp. 945–949; 1905.

Towne, H. M.:

Lightning arrester grounds, Elect. World, **83**, pp. 131 and 183; 1924.

Lightning arrester design and research, Iron and Steel Engr., **3**, p. 474; 1926.

Vaughn, J. F., Comparative tests of lightning arresters on the Taylor's Falls transmission system, Complete log, A. I. E. E. Trans., **27**, pp. 387–410; 1908.

Wagner, R. T., Getting best results from lightning arresters, Elect. Ry. J., **62**, p. 911; 1923.

Wallau, H. L., Relative frequency of voltage surges induced by charged clouds, Elect. J., **25**, p. 374; 1928.

Weightman, R. W., Colonial telegraph and telephone lines. Describes gaps for telephone and signal line protection. Wurts gap. Lodge discharger, Inst. E. E. J., **55**, p. 119; 1917.

Whitehead, J. B.:

The electric strength of air. Describes the theories of ionization and shows theory of corona to be in accord with the theory of ionization by collision, A. I. E. E. Trans., **34**, pp. 1035–1066; 1915.

The corona as lightning arrester, A. I. E. E. J., **43**, p. 914–922; 1924.

Wirt, H. C.:

Protection of high-tension transmission lines from static discharge, A. I. E. E. Trans., **23**, pp. 550–557; 1904.

Experimental investigation of the use of resistors in lightning arresters, multigap arrestors with shunt resistor. Tests showing actual utility of reactive coil and experience had with overhead ground wire, A. I. E. E. Trans., **25**, pp. 399–426; 1906.

Wright, C. S., Lightning and electrical circuits, Elect. Engr. of Australia and New Zealand, **2**, p. 185; 1925.

Wurts, A. J.:

Discovery of nonarcing metals and design of lightning arresters, A. I. E. E. Trans., **9**, pp. 102–120; 1892.

Discriminating lightning arresters. Multigap arresters with choke coils, A. I. E. E. Trans., **11**, pp. 337–377; 1894.

Young, W. F., Tests on 22-kv. and 4-kv. lightning arresters, A. I. E. E. J., **43**, p. 1149; 1924.