Discussion on Lightning and Lightning Protective Apparatus.

President Wheeler: The subject of lightning and lightning protective apparatus, though of extreme importance, has unfortunately not received the attention it deserves. Most of us do not appreciate the amount of damage to property and the number of injuries and deaths caused by lightning discharges. We need more reliable information as to the nature of lightning and lightning discharges and the most effective method of protecting apparatus from these discharges. I regret that none of the papers takes up the subject of lightning striking things that are not electrical, such as buildings. I mention this because I think the public is usually misguided in the matter, many lightning rods that are worse than useless being sold to the credulous public. Engineers should at all times try to prevent the public from being imposed upon.

P. H. Thomas: Progress is being made nowadays with lightning protective apparatus. I do not believe that the behavior of lightning arresters is going to be one of our great mysteries much longer.

It is interesting to learn that European engineers are advising the use of American lightning arresters; but it is also significant that they seem to find it wise to install special additional lightning protective apparatus. This would indicate that European engineers have not full confidence in American apparatus.

There are only one or two really fundamental features in a lightning arrester; an air-gap for discharging the static charge, and some means for interrupting the arc that may be established by the discharge. However ingenious the arrangement of any arrester, these are the basic features of all—except one special type of arrester not including a spark-gap, viz., a high resistance path between line and ground, which will undoubtedly carry off slow accumulations of static charge; how serious this sort of accumulation is, I do not know, but I do not believe it very serious. It is hard to believe that a high resistance, like a water-resistance, will offer a different character of opposition to the flow of current at the 100 000 volts of a static discharge than it offers at the 50 000 volts of a step-up transformer. For ordinary discharges then, it would seem that a high water-resistance really cannot give protection.

As stated above, the basic features of all lightning arresters are air-gaps and arc-interrupting devices. The commonest form of gap is the multi-gap arrangement, which is to a great extent self-interrupting. Other interrupting devices are the extension of the arc, as in the horn arrester, by the heat generated or by magnetic force; and the interruption of the circuit by fuses. The efficacy of most of these methods is usually and must in general be increased by the use of a certain amount of resistance in series with the arrester. These are the only devices that commercial designers have to work with at the present time.

What needs to be known in regard to lightning arresters may be summarized as follows:

First, are present series resistances too great for free discharge?

Secondly, is it possible to use less resistance and still have non-arcing arresters?

Thirdly, is it possible to use less series resistance in the horn type of arrester than in the multi-gap type?

Fourthly, can any system be arranged by which it is feasible to protect lines by the use of fuses for interrupting the discharge, the difficulty being to protect the line after one discharge has occurred before replacing the fuse, and to prevent the dropping out of synchronous apparatus?

These questions are of greatest importance in the protection of commercial installations. If all our attention is concentrated upon these features, I believe the solution of this problem will be arrived at more quickly than by the effort to devise new combinations or forms of the old elements.

Taken in connection with a great deal of corroborative evidence, Mr. Neall's paper pretty nearly enables us to answer satisfactorily the first of the four questions asked above. In a majority of cases, both of lightning and static discharge—practically in all cases of static discharge—as far as the speaker's experience goes, the series resistance or the total resistance contained in the arrester, seems sufficiently small not to impede the discharge of actual accumulated electric charge without injury to the apparatus. On the other hand, there were a number of cases where Mr. Neall found discharges in the shunted gaps, showing that they perform a useful function; but as far as his evidence goes, there seems to be no reason to suppose that the series resistance in connection with the shunted gaps is not sufficient in practice in all cases where there is first-class insulation strength in the apparatus and wiring. Of course more evidence is always needed on this point.

Mr. Neall's paper does not throw much light on the second, third and fourth questions—is it possible to use less resistance? does the horn type of arrester require less? and is it feasible to use a fuse arrester?

To get the most satisfactory lightning protection, only the best types of insulated electric apparatus should be used, and the line insulation should be made as good as possible. That has not been the case until very recently. Not until recent times does the speaker believe, has the standard of insulation strength been brought sufficiently high for the best results. More attention to the insulation means, other things being equal, less trouble from lightning discharges.

Mr. Neall's efforts to obtain data from commercial operation on this important branch of engineering work should be encouraged by all operating engineers. In the first place, close attention to these details is in itself an education; it gives the operating engineers an opportunity to study the action of the protective apparatus and to judge whether it is sufficient or not. It determines, too, what are the sensitive parts of the system, where the worst discharges are to be expected, which knowledge should lead to the addition of protective apparatus; weak methods of insulation will be detected, etc. This information gathered from different parts of the country for a number of years will materially aid manufacturers in their efforts to perfect the lightning protective apparatus. A protective system like other systems should be to some extent an evolution.

Mr. Smith's paper is interesting and important, though it deals with a different kind of data. He confines his observations to one plant, while Mr. Neall gives data from plants that are operating under many different conditions of voltages and locations. Mr. Smith says that since 1903, when he installed horn arresters, he has had no difficulty from lightning so far as interruptions of circuits or damage to apparatus is concerned. If I am not mistaken, there was at that time a substantial increase in the insulation strength in the wiring and apparatus of the plant he describes, which will undoubtedly do much to help eliminate trouble and leaves us rather uncertain as to whether the horn arrester or the increase in insulation was the essential protective feature; at any rate, with the increased insulation and the adopting of the horn arrester, he has secured substantially the protection. This is a most hopeful sign, as the very high voltage plants are the ones that are the most difficult to protect. There are of course many ways in which lightning can affect the line—electromagnetic induction, electrostatic induction, the accumulation of a charge on the wire from a charged cloud, the gradual accumulation of charge from the atmosphere, and finally, the direct stroke on the line. However, all things considered, it appears that the most dangerous kind of lightning is that in which a direct stroke (usually comparatively small) actually reaches the line. In Mr. Smith's plant in all cases in which the horn arrester has acted, some poles have been damaged; in one case, 15 poles were totally destroyed. This is very significant, and the conclusion is suggested — it is supported also by much evidence from different plants—that these severe strokes do not pass very far on the line, but that in the first few hundred feet their greatest severity is overcome by the discharges that pass down the pole. Of course a certain amount of the charge passes to the nearest station where it encounters the arresters which should be able to relieve the system, as the severity of the wave is limited to the insulation strength of the line. The obvious conclusion is that it will be very helpful in high-tension plants where the lines are very long if arresters can be placed one, two, or three miles from the station. At such places the arrester gets a chance at the static wave initiated by a direct stroke or otherwise before it reaches the apparatus. The drawback to doing this sort of thing is the necessity of leaving the arrester unattended, and the likelihood that it will cause more trouble than it will prevent.

The desirability of placing the arresters on the line near the stations brings forward a discussion on the fuse type, on account of the certainty of its freeing the line after a discharge. I believe that there is a great deal to be said in favor of using fuse arresters in plants like that of the Shawinigan Water and Power Company; but if the fuse type is to be used, there is perhaps no need of making a horn of it. It should be made as simple as possible—a plain gap, a fuse of non-corrodible wires of the *smallest practicable diameter and highest resistance* enclosed in a tube, which will open the circuit quickly. Unfortunately, when one fuse is blown the plant is unprotected until another fuse is put in; but it is only occasionally that one of these very severe discharges occurs. A direct stroke on the line is not likely to occur more than once in two or three days. Another method is to provide a number of fuses connected in parallel, in which case and if a separate series gap is provided for each fuse, the chances are that any lightning discharge will pick out one fuse and leave the others. If this sort of protection be used, there can be two or three discharges without replenishing the fuses.

In the light of present experience the natural conclusion seems to be that the type of arresters found to give best service should be placed in all modern stations; if then there is any trouble in any particular locality, the arrester already installed can often be supplemented by a fuse arrester or another arrester placed on the line some distance from the station. A trial of many variations of arrangement of protective apparatus will often determine an arrangement that will protect the whole line. There may be many plants in which the horn arrester, without series resistance and without fuses, may operate without throwing out synchronous apparatus or circuit breakers, but in most cases, I think this an unlikely condition, and furthermore additions to the size of the plant may change such a condition. It will in general be necessary to have a series resistance in which case the multi-gap arrester may just as well be relied upon to protect the apparatus.

Charles F. Scott: Many of the papers that are read and much of the discussion which takes place in regard to lightning, particularly among practical station men, seem to treat lightning as if it were definite and uniform in its action. Perhaps the most characteristic features of lightning are the varied conditions under which it occurs and the equally varied phenomena arising from it. The practical question is, what lightning arrester will answer not only for a given specific condition, or for all the conditions which may arise? Some of these varying conditions are: the character of the discharges, as pointed out by Mr Thomas; the difference in the tendency of an arc to follow a discharge, *e.g.*, the dynamo current which may follow the discharge depends upon the voltage of the line and the kilowatt capacity of the station; the location of the arresters, whether at the power house or at a distant point on the line, as the line resistance between generator and arrester may be a considerable factor in determining the readiness with which the subsequent current may be extinguished. With a very high voltage the current which may follow a short circuit is less in volume; consequently, it is less apt to burn the arrester, and is in someways, therefore, less liable to damage the spark-gaps than a current at a lower voltage.

Mr. Neall's paper is valuable in that it tends to bring together many isolated cases of lightning discharges. The paper summarizes an experience of some years in the development of a system of records of lightning protective apparatus. I have visited some plants where tell-tale papers of the kind described by Mr. Neall have been in use, and found the operating engineers interested in watching the effects of lightning discharges on the tell-tale papers. The papers were classified, and after a storm, they have shown the positions at which discharges have occurred In this way some idea is reached as to the effectiveness of the protective apparatus.

No mention has been made this evening of the practice of grounding the neutral point of the system. As is well known, those who use a grounded neutral are usually of the opinion that it is the only safe way to operate a plant; on the other hand, there are others who regard the insulated system as the only safe way to operate. The practice of the Shawinigan Water and Power Company is, I believe, to ground the neutral; at the Missouri River Power Company plant the practice is to keep the system entirely insulated. The latter plant has run continuously for service 24 hours a day and seven days a week, carrying a fairly uniform load all the time. As motors are used in connection with mining operations and smelters, the interruption of the power would be a very serious matter. During the past year they have had only three or four disturbances on the high-tension system; one of these was in the station and was simply a discharge across a new terminal that had recently been put in and was not properly insulated. The arc following the discharge went out of its own accord without interrupting the circuit. Out on the line there had been several discharges resulting in short-circuits; these short-circuits were interrupted by opening the switches at the power station, and as these switches were closed immediately the only inconvenience was that of starting such motors as had stopped. I have been told that the Missouri River Power Company has had more interruption from lightning on 2 000-volt distribution lines than on the 55 000-volt transmission line. The service of this line has been so satisfactory that an extension to the plant is being made, and the whole system will operate at 70 000 volts. This is higher, I believe, than is employed anywhere at present.

The operating engineers at this plant say that by listening at the telephone, at times a slight crackling noise may be heard every little while, due probably to a discharge on the line. The phenomena of lightning on the line manifests itself in different ways. When a storm—such as a winter wind storm with a light driving snow—first strikes the line, there is a slight clicking in the telephone; when the storm is leaving the line the telephone clicks in a different way.

The matter of protecting the poles on the line seems to me to be one of the most serious questions in lightning protection. Mr. Smith reports that great disturbances occur on the line, such as the splintering of poles, with no concurrent disturbances to the generating and transforming apparatus within the station. I believe that no transformer in service has been damaged by lightning during the several years that his plant has been in operation. It is rather remarkable that in a country where storms splinter so many poles, the apparatus in the station has been so well protected.

W. S. Franklin: The problems that confront us at present in connection with lightning-arresters can, probably, be solved only by experiments on long-distance high-voltage transmission lines. It seems to me that the important thing to know about a lightning arrester is not that it operates successfully a great many times, but the number of times it fails to operate, the number of failures that result in damage to the apparatus in the station or to the pole lines. Mr. Neall's paper, though interesting, seems to me to be faulty in this respect.

The series lightning arrester described by Mr. Torchio—Gola's series arrester—is, I think, a very fanciful arrangement. It is well known that iron is not magnetic at the excessively high frequencies which correspond to the frequency of lightning discharges; therefore, the iron diaphragm is no longer iron so far as the lightning discharge is concerned. The only thing that constitutes a sufficient change in the condition of the line effectually to reflect a pulse of discharge is change in capacity or in inductance. Changes in resistance are extremely ineffective in producing reflection unless the resistance is suddenly made very large indeed over a considerable length of line.

The kind of resistance that is needed not only for line discharges but also for use in series with a spark-gap, is that which offers a comparatively low resistance to quick discharges and a comparatively high resistance to slow discharges—in short, a skin resistance. The use of resistances in series with spark-gaps has been by no means pushed to the extent it should be in the development of lightning arresters. My idea is to use a series of three-foot terra-cotta pipes painted before the final firing with about two cents' worth of platinum chlorid spread out on a surface about six feet broad. This arrangement presents an enormously high resistance to a slow discharge, corresponding to low frequency machines, and at the same time a resistance nearly as low as a solid conductor to the extremely rapid discharge induced by lightning. In the protection of pole lines something similar should be done to prevent a flow of current down a pole when the pole acts as a lightning arrester; that is, to prevent it from flowing through the fairly high resistance material of the wood, for a high resistance substance conducts not only on the surface but through the material. If the pole were made of copper, it would conduct only on the surface; being of wood, even the extremely quick pulses of current which constitute lightning discharges are able to penetrate into the very heart of the pole. Perhaps the problem could be solved by applying to the pole some kind of conducting paint offering a comparatively high resistance, but not so high resistance as that of the pole itself.

In regard to the freedom of spark discharge, as affected by resistance in series with gaps, I think the question of the influence of a series resistance cannot be answered by the character of the spark in the gap. An ordinary thread two or three feet long connected in series with a Leyden jar will discharge across the spark-gap, and instead of giving a large brilliant spark will give the weakest kind of a pale-violet spark. In this case the noise produced by the spark is a snap, as clearly defined as the snap of the brilliant spark produced when there is no resistance in series. The sharpness of this snap is the real indication of freedom of discharge, and to judge of the freedom of discharge by the brilliancy of the spark or by the amount of the visible puncture produced in the bit of paper placed in the spark-gap, would be misleading. I think that the retardation of discharge by series resistance, provided that the resistance is of the right kind, has been greatly overestimated.

The practical way to judge of the influence of series resistance upon the freedom of the discharge is, it seems to me, to have an auxiliary spark-gap in parallel with the lightning-arrester, and then to have that auxiliary spark-gap protected by a small amount of inductance and then to see, when the rush of current comes in over the line whether the time that elapses during the building up of sufficient voltage to break through the lightning-arrester is enough to allow the current to force its way through the choke-coil and to jump across the auxiliary gap. In judging of the freedom of discharge in the lightning-arrester, this time element is very important.

The enumeration of the important features of lightning protective apparatus by Mr. Thomas is very interesting. I think that a vitally important feature is the provision for the dissipation of the energy of the discharge (*e.g.*, in a series resistance) so as to prevent oscillation and thus greatly lessen the time during which the spark-gap remains a fairly good conductor and thereby reduce to a minimum the likelihood of the formation of an arc

Mr. Scott expresses the opinion that the most important problem facing us at the present time in the matter of lightning protection, is to protect against these extremely violent lightning discharges. It is precisely in these cases where it is necessary to provide for the dissipation of the energy. Ordinary "static discharges" so called, represent but little energy, and special means for dissipating this energy is unnecessary.

J. H. Hallberg: I wish to relate an experience with a modern well-known lightning arrester. It was installed on a

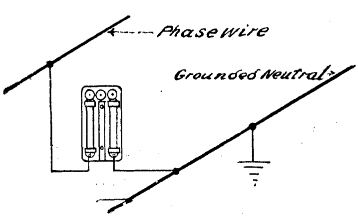

Fig 1.

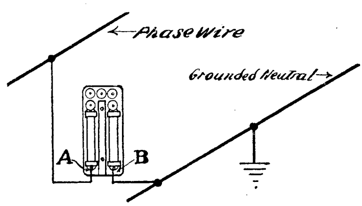

Fig 2.

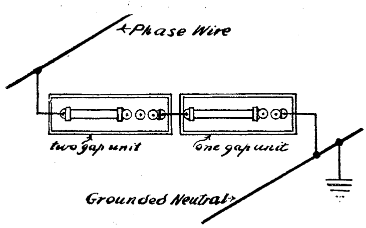

Fig 3.

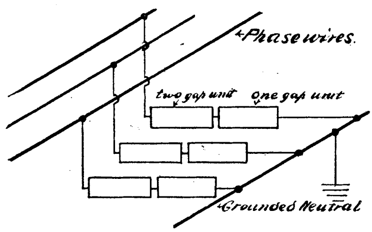

Fig 4.

three-phase four-wire 4 000-volt system, with a grounded neutral. There were about 2 400 volts between the neutral and each phase-wire, and about 4 000 volts between the phase-wires.

Fig. 1 shows a standard 2 400-volt lightning arrester which would be entirely destroyed during a lightning discharge, due to the main current following the discharge. Fig. 2 shows a 3 600-volt arrester, which in several cases permitted the lightning discharge to jump and the current to follow from *A* to *B*. instead of over the air-gaps as it normally should. Fig. 3 shows the same type of lightning arrester differently assembled; this was installed later on and successfully overcame all troubles under the most severe conditions. Fig. 4 shows the lightning arrester equipment which was finally adopted as a standard for the system referred to.

I have experimented considerably with several arresters, and find that, in the form of arrester here referred to, if the resistance is maintained it produces a straight path, and effectually prevents the main current from following the lightning discharge.

It would be interesting to know if the graphite resistance used in the General Electric lightning arrester deteriorates to any appreciable extent with repeated discharges.

H. C. Wirt: I believe there will be no appreciable increase of resistance in any of the General Electric arresters made within the last three years where the resistance amounts to 450 ohms with a six-inch stick. That resistance is now made almost wholly of carborundum, whereas in the first form of arresters graphite resistances were used. The carborundum is much more satisfactory than the graphite.

My experience is that all types of lightning arresters give more or less trouble. There is real need for reliable data on the operation of lightning protective apparatus, and I think it unwise to attempt to draw conclusions from investigations extending over a short period of time. Though the puncturing of paper may occur frequently, still it may not be a true representation of the operation of the arrester. Before any reasonable conclusion can be drawn from them, these punctures should be carefully examined by one who has had considerable experience with lightning protective apparatus. An experience of this kind is remarkably uncommon.

What is wanted is improvement in all makes of lightning arresters. I have reports on all makes of arresters in operation except some of recent construction, and experience prompts me to say that these arresters, too, will give more or less trouble. For the last year and a half, I have been observing carefully the operation of lightning arresters in a modern power house; up to two months ago, I felt safe in predicting the successful operation of a particular form of arrester; now I am tempted to qualify such predictions because within the last month three transformers have burned out during storms.

Personal observation leads me to believe that more can be learned from high-tension than from low-tension plants. There are disturbances going on in such systems which are not shown on any instruments now in use. I think we should not be hasty in forming an opinion regarding the possibilities of an arrester without any resistance. Very little has been written regarding the form, size, and number of gaps, size of cylinders, static capacity of these cylinders, though all these things have been under investigation. There is also considerable difference in respect to non-arcing metals. I think it is possible to reduce the number of gaps by using better non-arcing metals.

The lightning arrester on the line may not be under observation at the critical moment, and an entire season might pass without a discharge that would cause an injury to the apparatus. I think it may be possible—it seems so from recent tests—to get a condition at the factory that approximates the conditions on the outside. The article by Dr. Steinmetz on the Manhattan trouble is worth careful study. I think it is possible for arresters to take care of many of the conditions that cause surging.

H. A. Pikler: It seems to me that in most of the cases where the rising potential is due, not to the direct effect of the stroke of lightning, but to magnetic or static induction, surges, and short-circuit, that the protective apparatus does protect the line. In cases where the lightning strikes the line directly, the insulators are broken down and the poles damaged. I believe that in cases like this, the resulting damage is due to the enormous skin effect on the line. Short portions of line offer so good a resistance tc the very high oscillatory discharge of the lightning that it naturally seeks a path of lower resistance; this breaks down the insulation and goes to ground through the pole. A remedy for this would be to install lightning-arresters at such distances and on such portions of the line that the resistance from the arrester to the ground is lower than that of the insulator. If this were done perhaps the discharges would go along the lightning-arrester and not through the insulator to the pole.

H. G. Stott: Lightning phenomena may be divided into two classes; the first corresponding in degree to the surges which are the result of switching in and switching out cables, short-circuits on the lines, mistakes in synchronizing, etc., which may amount to a net rise of three or four hundred per cent. This class of phenomena can undoubtedly be taken care of in several ways with the apparatus at present in use. The second class, however, corresponds to the effect produced by the explosion of a ton of dynamite, and at present there is apparently absolutely no way of safeguarding apparatus from a direct lightning stroke of this kind. In the case of the first class the present type of lightning arrester is probably an element of safety to the insulation of the entire system and will safeguard against any ordinary surge, or induced lightning discharge. When purchasing apparatus, a small additional investment will frequently be sufficient to give an insurance of safety to the insulation of four or five times the working voltage, and would seem to be the best kind of an investment in lightning protection. In the second class of lightning discharge we are brought face to face with two absolutely contradictory conditions: the first condition is that in order to take care of the lightning discharge the best possible path to earth must be provided; the second condition is that the worst possible path to earth ought to be provided in order to prevent the line current from following the discharge to earth. These two conditions it seems practically impossible to harmonize; for whatever is done to improve the one must at the same time work against the other, so that any apparatus designed to meet both requirements must necessarily be a compromise and, therefore, inefficient under both extreme conditions.

A plan I should like to see tried would be to put in a single air-gap in series with an oil-switch in the connection to the ground. A current transformer would operate the oil-switch through a relay, in case of a severe discharge to ground followed by the line current, after a predetermined interval. This oil-switch after tripping out would then automatically close itself again after an interval of, let us say, three or four seconds, and so be ready for the next discharge. The generator relay being set, of course, for a longer time than the time-interval, would not operate.

Philip Torchio: A word further in regard to the protective devices I have seen in Italy. The opinion abroad is that the present lightning arresters safeguard the ordinary operation of a station; for even if a generator is struck by lightning it would be disconnected from the bus-bars before causing a shutdown. But the real troubles are short-circuits along the line caused by a flashing between the wires; these short-circuits cannot be stopped without opening the line, resulting, of course, in an interruption to the service.

The Milan Edison Company has put in double insulators of the type described by Mr. Semenza in a paper presented before the INSTITUTE a short time ago.* Since then—it was three years ago—no trouble has been caused by the breaking down of insulators, though there have been a great many storms.

It seems to me that at present the question of lightning protection of the station apparatus is not so important as the protection of the line itself. What really needs to be known is how to protect the whole line, say, at 20 miles from the station, as well as just outside the station.

The water-resistance dischargers used abroad are in a way similar to the arresters mentioned by Professor Franklin. They expose large surfaces to lightning discharges. Mr. Thomas has said that these discharges—on account of their high resistance—would not act to discharge the line potential more than any other type of resistance under ordinary operating conditions. But will not these oscillatory discharges, involving a relatively small amount of energy, be made harmless in a short time by even a high resistance discharger acting as a safety valve?

N. J. Neall: I think, considering all the difficulties in getting the performance of lightning-arresters during storms, that the method described in the paper is the most effective yet proposed for getting the needed information from operating en-

*TRANSACTIONS, A. I. E. E., 1904, Vol. 23, p. 147.

gineers. I should be very glad to hear of any other method that can be used to get the same information. One year of trial is certainly not sufficient to establish a case; three or five years would be better, because that is the only way in which to get a record of all the storms which might affect a given line.

As far as the bad performance of arresters is concerned, the tests now placed before you are complete; had there been any bad performances they should have been included in this record. As a matter of fact I do not know of any cases of serious failure of the low-equivalent arrester in and of itself. In some instances extraordinary conditions affected the operation of the arresters, and for this reason I have not endeavored to give the impression that the arresters are capable of taking care of very high discharges.

The value of the standard protective apparatus as manufactured to-day is not for extraordinary disturbances but for every-day conditions. A few years ago nothing was heard about line protection; but now that lines are operated from 60 to 200 miles in length the protection of the line itself has become an important matter.

The remaining point is, that the papers placed in the discharge-path of the condenser were in the path of a 30 000-volt condenser. The character of that discharge is different from the discharges obtained by Mr. Wurts from a static machine and Leyden jars. The energy of the discharge is different. There is no novelty as far as the skin effect is concerned, in the tests made by us; we have however gone a little further and used larger quantities than have been previously employed.

Charles P. Steinmetz: The successful operation of long distance transmission systems depends to a large extent upon their protection from lightning. Unfortunately, the same absolute confidence can not yet be placed upon the proper performance of that part of the electric circuit constituting the lightning protective apparatus that is had in respect to almost every other part of the system, notwithstanding all that enthusiastic engineers and designers of lightning arresters may assert. The reason is obvious: Under the term "lightning" are included a large number of phenomena, not all of which are fully understood or have been investigated.

In its broad definition, "lightning" in electric circuits comprises all the effects of voltages different from and usually higher than the normal operating voltage of a system. Such abnormal voltages may enter a system from the outside, as in overhead lines, or originate in a system. Hence the terms "external" and "internal" lightning may be used. The nature of both types of disturbance is the same, but they frequently differ quantitively, as in frequency, amplitude and duration.

Common causes of internal disturbances are: spark discharges over faults in the insulation, sudden changes of circuit conditions, etc. Some of these disturbances have already been discussed before the INSTITUTE. Other disturbances such as high-frequency oscillation resulting from a ground on a high-voltage three-phase system; the interesting effects observed at the junction of overhead lines with underground cables; and the complex set of phenomena resulting in a three-phase system from the coincidence of the 3d, 9th, 15th, etc., harmonic, may well form the subject of a paper. As is well known, the 3d, 9th and 15th harmonics in a three-phase system are in phase, and therefore rise and fall simultaneously; which may result in cross-currents flowing between the different parts of the system through the ground, and occasionally high-frequency oscillations or low-frequency high-power surges of the whole system against ground—in the latter case, mainly of triple frequency.

The discussion on the paper deals only with those high-voltage disturbances that enter the system from the outside, that is, from the atmosphere. The designing of lightning protective apparatus is seriously limited by the fact that such apparatus must not only promptly and effectually discharge atmospheric disturbances entering the line, but must do so without producing internal surges. The charge and discharge of electric transmission systems by atmospheric disturbances is sudden and liable to be oscillatory. It is, therefore, a sudden change of ci cuit conditions; and it is changes of this character that produce internal surges. If lightning were a very high-frequency oscillation, like the discharge from a Leyden jar, the system could be protected by interposing reactive coils between the station and line, and shunting the discharge through multiple spark-gaps to ground; if it were a steady gradual charge of the line, it could be discharged to ground by a high-resistance shunt, with or without a spark-gap; again, if it were a low-frequency high-power surge, an effort could be made to take care of it.

But lightning is not limited to any one of these phenomena; it may include two or all of them at the same time, as for instance, a gradual static charge of the line, followed, as soon as the voltage has risen sufficiently high, by a discharge in the form of a high-frequency oscillation, which in short-circuiting the line, gives rise to a low-frequency high-power surge. And even still other, and practically unknown forms of lightning may exist; for instance, globular lightning has occasionally been observed, so that no question can be raised regarding the fact of its existence; practically nothing is known about it however, excepting that it is extremely destructive; it seems to be rather a discharge centre than a simple discharge. Obviously, then, since our knowledge of lightning is incomplete, the results of efforts to construct lightning protective apparatus cannot yet be perfect.

In the interior of a body of perfect conductivity, no electrical disturbances can be produced by external causes. Hence if a transmission system is enclosed by a grounded conducting shell—put underground—atmospheric disturbances cannot enter it. Since a transmission line cannot be put underground, the best available protection is to put the ground above the transmission line. That is, a grounded system of wires above the transmission line is the most perfect protection from lightning, and the more perfect the nearer it approaches the character of a grounded enclosing shell of perfect conductivity. A single grounded wire over the transmission line offers considerable protection from atmospheric disturbances; but two such wires are better than one; and, naturally, the greater the number of wires the more perfect is the protection afforded.

To protect a transmission line by overhead ground wires, however, it is essential that the line be within the protective zone of the wires, that is, within the space enclosed by an angle of 45 degrees, or preferably 60 degrees from the ground wires downward.

Barbed wire, by reason of its more rapid action, is more effective than ordinary wire against some kinds of atmospheric disturbances; for example, electrostatic charges picked up from drifting rain or fog; while with other disturbances it offers no superiority over plain wire.

The conductivity of the ground wire is of considerable importance. For the purpose of bringing ground, or zero, potential up to a point above the transmission line, and thereby lowering the electrostatic potential of the space in which the transmission line is located, the size of the ground wire obviously is immaterial; but high conductivity of the ground wire is of importance in protecting the transmission line from the inductive effects (electromagnetic or electrostatic) of oscillating, or sudden, atmospheric discharges, such as lightning flashes; and also in protecting the stations in case a direct stroke of lightning reaches the line, by its damping effect as a grounded secondary conductor.

Inasmuch, however, as a system of overhead ground wires cannot be a complete enclosing shell of perfect conductivity, its protective effect, however great, cannot be quite complete; therefore protective devices have to be installed at the stations as safeguards against the entrance of lightning from the line.

The elements available for the construction of station protective apparatus are mainly spark-gaps, resistances, and reactive-coils. The purpose of the spark-gap is to isolate the line from the ground when normal voltage prevails, and to connect it to ground in case of abnormal voltages, but to connect it in such a manner that the connection is disrupted again when the voltage returns to normal; that is, the gap must let a spark pass at abnormal voltage, but must not hold an arc at normal voltage. *n* sparks in series require about the same voltage as (in some cases very much less voltage than) one spark *n* times the length; *n* arcs in series, however, require nearly *n* times the voltage of a single arc of *n* times the length. Hence the greater the number of the spark-gaps, and the shorter, therefore, their length, the more favorable is the relation of arc voltage to spark voltage. This relation of spark to arc has led to the almost universal introduction of the multiple-gap arrester.

In addition to spark-gaps, arc-interrupting devices, as for instance shunted resistances, are used; which, due to the particular character of the arc, are caused, by the increase of arc voltage with decrease of current, to make the arc unstable and so extinguish it.

The purpose of the series resistance is to make the discharge non-oscillatory. A discharge from line to ground or from line to line will be oscillatory if no series resistance or other oscillation-preventing device is in circuit, and may cause a low-frequency surge in the system, which may be more destructive than the lightning itself.

In its effect upon the discharging capacity of the arrester, the series resistance is unqualifiedly bad; the greater the series resistance interposed, the less discharge ability the arrester has. Considered solely from the standpoint of the discharge of lightning, the best lightning-arrester is therefore the one that has no series resistance. If an arrester could be made without series resistance and depended upon to discharge non-oscillatory it would be the preferable type.

The reactive-coil protects the station against a high-frequency oscillation, but offers no protection whatsoever against static charges of low-frequency surges, because the amount of reactance which can be introduced is limited: The reactance employed must be less than would be appreciable at the normal frequency of the system; and therefore less than would exert an appreciable effect on low-frequency surges. Its purpose is to obstruct a high-frequency oscillation, like that of a Leyden jar discharge, but it is not a general protective device any more than is the series resistance.

The important feature of very high-power discharges is their extreme suddenness, which causes destruction at the point of entrance, usually in the middle of the transmission line, without transmitting sufficient energy to the terminal stations to be very serious at those points. Very high-power discharges destroy transmission-line poles, but do not menace a station unless the discharge occurs very close to the station.

J. B. Taylor (by letter): Professor Franklin referred to the suddenness and sharpness of the sounds caused by atmospheric disturbances on telephone lines indicating rapidity with which charges may collect on a conductor under different atmospheric conditions. Tests on telephone lines have led me to the conclusion that these sharp crackling sounds are due to the sudden discharge of a line to ground, on account of its potential having gradually increased to a breaking-down point. On several occasions I have observed discharges of this nature in the middle of winter during snow storms. A line approximately 40 miles long would charge and discharge with such rapidity that the disturbance in the telephone line was, on several occasions, mistaken for a cross with a telegraph line.

The action in this case was apparently as follows: each flake of snow carries a charge, and sufficient of these strike the wires to charge the whole line. On account of the protectors used—carbon blocks separated by thin sheets of mica—as soon as the line reached a potential of about 400 or 500 volts one of the discharge gaps would be bridged, and the line discharged with the accompanying sharp click, these discharges occurring so rapidly that the result was the same as though the line had become crossed with a telegraph circuit. A Weston voltmeter connected between telephone line and ground would give a steady deflection, in one case the deflection corresponding to a current of, roughly, 3 to 4 milliamperes. These disturbances would sometimes continue without interruption for several hours, and the service was seriously interfered with. The obvious remedy was to ground the neutral, thus causing the charge to be dissipated as fast as it accumulated. This neutral point was readily obtained from a tap taken from the middle point of an impedance coil bridged across the line. The line to which I have referred was at Burlington, Vermont, and the observations made some years ago, when I had no facilities for getting more complete data as to the polarity and potential of the snow-flakes. Snow-storms causing this trouble would occur perhaps on an average of three or four times in a year.

After devising the grounded neutral for removing the trouble, I learned that in Montreal this same charging of lines during snow-storms was of more frequent occurrence, and the same remedy—the grounded neutral—used to remove such disturbances.

W. S. Franklin (by letter): The practically important thing nowadays in making up one's mind what to try in the way of improved lightning protection is *elimination.* Let us not entertain the distracting idea that everything ever imagined is to be considered in this important practical problem; in fact I think that many aspects of the lightning discharge may be legitimately and definitely set aside.

First as to globular lightning. There is no doubt in my mind that this is a wholly subjective phenomenon. A fixed impression on the retina of a particularly vivid end-on lightning flash follows the eye when, at the crash of thunder, the attention of the observer is upset and at the same time the eyes jump and the slowly-moving globe of fire seems to have vanished in a crash of simultaneous thunder.

Secondly, as to sudden versus sluggish lightning discharges. I believe that the sudden variety is the only variety that need be considered. Even the slow accumulation of charge on a line which engineers call the "static charge" is a series of spits, if one can trust the evidence of the telephone. A very sluggish lightning discharge of moderate intensity can be taken care of by the grounding of a point in the system; for example, the neutral point in a three-phase system, and a very sluggish discharge of high intensity would on the other hand represent an immense amount of energy and it would have to be taken care of by the same means that are used to guard against short-circuits in the system; that is, by fuses and circuit breakers.

Thirdly, as to the use of a guard wire. A complete metal shell would be absolutely effective as a screen for purely static effects, and at the time of discharge a complete metal shell would allow a disturbance to pass through it too small to be of any consequence. The incomplete metal shell, the guard wire, approximates in its degree of shielding to a complete metal shell. For purely static and very sluggish dynamic effects this degree of approximation is fairly great. For extremely abrupt dynamic effects, however, the guard wire becomes more and more nearly ineffective. Sunlight, for example, is an extremely abrupt type of electrodynamic disturbance, and of course in this case the guard wire screens only its shadow.

I am inclined to think that the value of the guard wire lies mostly in its affording what one might call a spark-guard to prevent a spark from above from actually reaching the transmission wires. Of course when analyzed this spark-guard effect partakes in part of the nature of the ideal screening effect of which Dr. Steinmetz speaks, but it is by no means simply that. The behavior of a system at the instant of a breakdown cannot be described in terms which apply to the system in a quiescent or steadily varying state; the ideas of static screening and of the reflection of an orderly electromagnetic wave by the guard wire cannot be applied to what takes place at the instant of a terrific collapse or breakdown of the dielectric (the air) near the line.

Fourthly, it may be of importance so to design a transmission line as to realize the condition of the "distortionless" circuit; for example, by providing high-resistance leakage paths to earth from the line, so that any wave starting out from the place of a lightning discharge would retain its abruptness unimpaired, and thus be of a character to be arrested by a choke-coil and deflected to earth through a spark-gap.