

## DISCUSSION ON "RECENT INVESTIGATION OF LIGHTNING PROTECTIVE APPARATUS" AT NEW YORK, DECEMBER 28, 1906.

**Ralph D. Mershon:** There is probably no other natural force amongst those with which modern engineering has to deal of which so little is intimately known as of lightning. In most engineering problems it is possible to control and reproduce at will the conditions actually existing in practice, and thus study the phenomena resulting therefrom; or, if this is not possible, there is a natural repetition of the phenomena of sufficient regularity so that they can be studied and traced back to the elements on which they depend. With lightning this is not so. The conditions existing in practice cannot be controlled, and the elements involved are so enormous, numerous, and variable that it is impossible to reproduce them. The natural repetition of phenomena is at such irregular intervals, and the phenomena, when they do occur, are apparently so erratic, due to the number and variability of the elements on which they depend, that no satisfactory searching study has been made of them.

As a result, we have no intimate knowledge of lightning and the conditions governing it and its effects. Theorizing in regard to it is, in the lack of definite experimental data, of little value. Theory cannot be much more than guessing, and, within certain limits of probability, one guess is just about as good as another. There is about as much use in trying to forecast the weather for a certain day next year as to tell what lightning will do.

In view of the above, I am always more or less skeptical of any theories advanced in regard to lightning or lightning protection; at any rate, unless actual practice has shown that there may be some foundation for the theory. Even though practice should uphold the theory, as it has in a few instances, I should be skeptical, for, as has been the case more than once, the next installation may upset both practice and theory.

We are, I think, at times too much inclined to theorize without a sufficiency of data; to attempt to reason from a few facts pieced out with such fundamental data as we have at hand, instead of first experimentally obtaining at least a fair amount, if not all, the information possible, directly applicable to the subject in hand, and then endeavoring to formulate a theory. The paper under consideration this evening is, it seems to me, somewhat open to criticism in this regard.

By means of the data of Figs. 4 and 5 obtained on one transformer, having a certain internal electrostatic capacity and subjected to a frequency or steepness of wave-front, which may or may not approximate that in the case of lightning, the endeavor is made to specify, within certain limits, the inductance which will form an effective protection. I think that if it were worth while, it could be shown that with other transformers and other frequencies of discharge, the criteria by means of which the writer of the paper has fixed the limits of effective inductance would be very materially modified. In my opinion

the author would have done much better to have turned to his Figs. 6 and 7 and said: "Here are curves showing what in practice we can stand in the way of reactance. Guided by them, let us use all the reactance permissible." Even then, I should not be inclined to agree with him as to the advisability of choke-coils. A choke-coil of any considerable size is an awkward and an expensive thing. It is expensive not only in itself, but in the space it takes up, and, besides, it usually adds complication to the station wiring, the high-voltage wiring which it is especially desirable to keep simple.

If we must have choke-coils, let us put them in the same case as the transformers, and so save the complication in station wiring. Better still, let us do away with them altogether, and put such amount of insulation as may be necessary on the end-turns of the transformers, such amount of insulation as will take care of a considerable strain between the end-turns. Then, if we use a low-resistance arrester or its equivalent, we shall, I think, have ample protection.

As between a high inductance choke-coil in connection with a high-resistance arrester, and no choke-coil in connection with a low-resistance arrester, I much prefer the latter. And it is possible to have the low-resistance arrester equipment, as I will show later on, even though the electrolytic arrester described by the author should not prove to be all that it promises, but which I hope it will realize.

I have known of many cases where choke-coils of considerable reactance in connection with arresters of considerable resistance have failed to protect under severe conditions, but I have never known a case where very low-resistance arresters or fused arrester-gaps have failed to protect. I have known of a number of cases where apparatus has been damaged not only in spite of the choke-coils installed with it, but apparently because of them, due to disturbances on the circuit other than lightning, and a piling up of potential of the transformer terminals, probably because the choke-coil kept the transformer from freely ridding itself of a charge set free in its windings. Such happenings as this would seem to indicate that if a choke-coil were used, an arrester should be installed on each side of it.

Transformers will undoubtedly be more expensive with heavily insulated end-turns, but I think that in most cases the extra expense will be little, if any, greater than that of the separate choke-coils and the space they take up. This will certainly be the case for such extra insulation as will be necessary with a low-resistance arrester. The demand for a number of voltage taps need not interfere with the end-turn insulation, if the desired variation in the length of the transformer winding be obtained at the middle of the winding; that is, at the junction of the two halves of the winding instead of at the ends. Multiple series connections of high-voltage windings ought not to be often required, and I believe that as time goes on they will

be required less and less; but even where they are required, I believe that the same heavily insulated end-coils might be used as end-coils for both series and multiple connection, and meet most of the requirements in practice.

I am inclined to doubt the correctness of the opinion that the author seems to hold relatively to the resistance of lightning-arresters. I have reason to believe that under some conditions even a high-resistance arrester will be of benefit; and I do not think the author himself is prepared to state that the high-resistance arresters now installed afford no measure of protection. I do, however, agree that a low-resistance arrester is desirable at all times, and absolutely necessary for proper protection under some conditions.

It is possible to have a system of lightning protection which will automatically adjust the resistance of the path to ground to that value necessary to take care of the discharge. Suppose we assume that the magical 400 ohms worked out by the author is the resistance which must not be exceeded under extreme conditions. Suppose that with a given voltage and generating capacity, a horn, or other suitable arrester, will operate satisfactorily, if it has, say, 2000 ohms in series with it. Suppose we have five such arresters connected to each line wire, each arrester having 2000 ohms in series with it. Set one of the arresters on each wire for low-striking electromotive force; another arrester on each wire for a higher striking electromotive force; another for a higher, and so on to the fifth arrester, set for the highest striking electromotive force which the apparatus to be protected can, for a short period of time, safely withstand. Now suppose there is a rise of voltage on the line under such conditions that one 2000-ohm path to earth will properly discharge it. The lowest gap will flash over, and discharge take place through the 2000 ohms in series with it, this discharge keeping the electromotive force of the disturbance down below that necessary to strike across the next higher gap. If a disturbance occurs requiring a 1000-ohm path, the lowest gap will strike, also the next lowest, giving two 2000-ohm paths in multiple for the discharge. Similarly, with other disturbances more severe, more and more of the gaps will flash over until, in the extreme case, all five gaps will be active and the resistance of the combined path to earth will be 400 ohms—that specified by the author. If desirable, there might be one or more gaps having fuses in series with them, so that when they acted, the discharge would have a path to earth of practically zero resistance.

The above scheme of lightning protection might be carried out to any extent, and any desired number of gaps be used, the result being that under any given condition the path to earth would have a resistance as low as necessary to take care of the disturbance upon the line and that the disturbance to the transmission system, due to the dynamic current which would

follow the lightning discharge, would be proportionate to the necessities of the case. In an extreme case the disturbance to the system due to the dynamic current over all the gaps might be such as to cause a shutdown, but the apparatus would be protected. A shutdown without any damage to the apparatus is preferable to a shutdown resulting in apparatus which has to be patched up; fortunately, such extreme disturbances are rare.

Such a system of protection as that described would apply not only to disturbances requiring a path to earth, but also to discharges passing from a conductor to conductor. It is to be noted that in such a system the operation of successive gaps not only reduces the resistance, but also the inductance of the path.

I have for some time past made use of the scheme of lightning protection outlined above, except that only three sets of gaps are used on each line wire, and the highest gap has a fuse in series with it. My experience so far, extending over one lightning season, has been very satisfactory. A previous experience, extending over several seasons and with a system of protection similar to, but much less elaborate than that with the three gaps just described, was also satisfactory. I have come to believe that such a system is about as near to being an absolute protection for station apparatus as could be expected. This assumes, however, that the apparatus has that margin in insulation strength which good apparatus should have, enabling it for a short period of time to withstand considerably more than its normal voltage.

The electrolytic arrester described by the author is a very interesting and promising piece of apparatus. I have seen it in experimental operation, and, so far as experiments go, it seems as if it might be effective. It remains, however, to be seen how it will behave in practice; what difficulties may arise due to the evaporation or freezing of the electrolyte, or to the sudden formation of vapor, in the case of a lightning discharge of extreme severity. Any or all of these troubles may be met with, but no doubt they can be overcome, the latter possibly by using a number of these arresters in multiple, either in series with gaps of the same size or set for different striking electromotive forces. It looks as if we may at last have the ideal lightning-arrester and I sincerely hope that this is the case.

In my opinion a very desirable requirement of a lightning-arrester is that it should be capable of being installed outdoors. I believe that as time goes on more and more high-voltage apparatus will be installed outdoors, instead of in a building. I think the time will come when not only lightning-arresters, but bus-bars, transformers, and even automatic circuit-breakers, where such are used, will regularly be installed outdoors. It seems rather illogical, and, from some standpoints, almost ridiculous, to instal high-tension bus-bars in a building with

barriers and all sorts of other complications, when the lines led off the bus-bars go immediately out of doors, unprotected, and often installed upon very questionable line structures.

I understood Mr. Jackson to say that in obtaining Fig. 4, the middle point of the transformer was grounded, so that the discharge went through half of the transformer winding only. I would like to ask if he took any observations similar to those of Fig. 4 on the other half of the transformer winding? It would be interesting to know what voltages could be obtained on the other half of the winding? It would have considerable bearing on his statement indicating that the iron renders ineffective the space occupied by it, so far as the inductance of the coil is concerned.

**Chas. P. Steinmetz:** This paper deals again with those four elements which, since the earliest days of electrical engineering have constituted the parts of lightning protective apparatus; namely, the resistance, the inductance, the spark-gap, and the circuit-opening devices.

In regard to the reactance or choke-coil, I also fully believe in the effectiveness of the reactive-coil. It is obvious that the reactive-coil cannot be considered as a protection against all of the manifold manifestations of atmospheric electricity or internal surges; anybody can see that against a slow accumulation of electrostatic charge on the system by induction from the clouds, etc., whereby the total system rises as a whole in potential above ground, a reactive-coil cannot protect; also, it cannot protect appreciably against a very low-frequency surge where the oscillation is of enormous magnitude and of a frequency not much above the normal line frequency. Then any amount of reactance which it is permissible to put in circuit, will not offer a sufficient protection. Hence, the reactive-coil is not a universal protective. However, it can be shown experimentally that at least against high-frequency oscillations, against travelling waves of steep wave-front, the reactive-coil offers a very marked and satisfactory protection.

I cannot agree, however, with the paper regarding the numerical values of the minimum effective reactance. I believe the numerical values given are not correct general conclusions, but merely incidental to the particular conditions of the experiment from which they were derived. The spark-gap was connected across the 200 end-turns of the transformer, and it was found that the electrostatic stress across these 200 turns of the transformer, without reactive-coil, or with very small reactive-coil, had an equivalent spark-gap of one inch; that is, about 20,000 volts. The spark-gap was reduced to one-half by an inductance of about 7 millihenrys. If the writer of the paper had connected the spark-gap, not across 200, but across 20 end-turns only, he would have obtained a curve similar to that given in Fig. 5, but with an entirely different set of abscissas, and would have found as minimum effective inductance sufficient

to reduce the spark-gap to one half, about one-tenth of the value given in the paper. If he had connected the spark-gap across the two end-turns, probably the minimum effective reactance would not have been 7 millihenrys, but something like 0.07, or about one hundredth part of the value recommended, so that the effective reactance depends on the number of turns across which the electrostatic stress is observed. The error made by the writer is one of those into which I believe all of us who have done experimental investigating and drawn conclusions from it have fallen at one time or another; that is, to draw general conclusions, especially regarding the magnitude of a phenomenon, and then afterward find that these conclusions are not general, but special results of the particular conditions under which we experimented.

Let us see what happens if a voltage is suddenly impressed upon a transformer, as here the voltage of the Leyden jar or the condenser, of about 50,000 volts, or by an atmospheric oscillation or travelling wave, etc., or the line voltage when connecting a transformer into the circuit. Before closing the circuit the transformer windings are at zero potential; in the moment of closing the circuit 25,000 volts are put on one terminal; that is, on the beginning of the end-turn, but the ends of this turn and the second turn are still at zero potential; and so at this instant the full potential of 25,000 volts exists across a single end-turn. An instant—a fifty-millionth of a second or so later—the current has passed along the first end-turn, and voltage exists at the beginning of the second turn, while the third turn is still at zero potential. In this instant the full potential of 25,000 volts is across two end-turns; that is, each gets about half of the voltage. Again, in another fifty-millionth of a second, the potential distributes across three turns, then across four turns, five turns, etc. You see the maximum potential difference which can exist without any reactive-coil across the first turn is the full voltage of 25,000 volts. The maximum potential difference across the second turn is half, half being across one turn and half across the other; across the tenth turn it is one-tenth, and across the 200th turn it is  $\frac{1}{200}$  of the full voltage.

Suppose we take out the first nine turns and put them outside the transformer as a reactive-coil. The first transformer turn, then, is what was before the tenth turn; and at the same discharge, the same impressed voltage, the maximum potential at the first transformer turn is the maximum potential which was formerly got at the tenth turn; that is, it is one-tenth of the impressed voltage. That is, by putting nine transformer turns outside of the transformer and in series therewith, as a reactive-coil equal to only nine transformer turns, very much less than the minimum referred to by the speaker, the maximum electrostatic stress which can exist anywhere in the transformer is reduced to one-tenth of the previous value. But the maximum electrostatic stress across the 200th turn is reduced only from  $\frac{1}{200}$  down to

$\frac{1}{200}$  of the full voltage, because it is now the 209th turn, and the sum of all the electrostatic stresses across the first 200 turns is not appreciably reduced at all. Hence if we use a reactive-coil equivalent to nine transformer turns, and measure the electrostatic stress across the first 200 turns, we find no appreciable effect, while actually we have reduced the maximum electrostatic stress on the most exposed part of the winding, the first transformer turn, to one-tenth of the previous value; that is, we have secured a very high protection.

After all, if a transformer breaks down internally by a sudden discharge, it is not the 200th turn which breaks down, or the 100th turn; it is one of the very first turns, where the electrostatic stress is the maximum, and where, therefore, there is a maximum potential difference many times greater than given by the data in the paper, which data give, not the maximum stress anywhere in the transformer, but the value integrated over a very large part of the transformer; that is, an average which bears no direct relation to the maximum, against which we have to guard.

I do not need to go into this matter further because this phenomenon of distribution of potential in the transformer windings at a sudden application of voltage has been very fully discussed, in the classical paper read before the American Institute of Electrical Engineers four years ago by Mr. Percy H. Thomas.\* There this phenomenon is very fully explained.

I think it fortunate that such high reactance is not necessary, but that a very great reduction of the maximum electrostatic stress results from very moderate reactance; that is, by a reactive-coil which does not occupy as much space as the whole transformer. Obviously, the more reactance is put in the circuit, the more the stress on the transformer is reduced, but very soon it becomes a question whether it is more economical to build a larger reactive-coil, or to increase the insulation of the transformer end-turns. To insulate between the end-turns against full voltage is difficult, and an additional reactance is therefore desirable; but as we have seen, a reactive-coil of very few turns only, already reduces the maximum stress at the end-turns to a very few per cent. of the maximum possible stress, and so to a value against which sufficient insulation of the end-turns can easily be provided for, without appreciable increase of size and cost of the transformer. A moderate size reactive coil and additional insulation of the transformer end-turns is preferable, because it does not make it necessary to have such a very large reactance, which spoils the regulation of the system by two per cent. or becomes impracticable altogether on a large-current low-voltage system.

This feature is also important in considering the question whether the reactive-coil is a reactive-coil at all. It might also be stated as a conundrum for high-frequency phenomena:

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\* TRANSACTIONS of A.I.E.E., 1902, Vol. XIX, p. 213.

when is a reactive-coil not a reactive-coil? In speaking of reactive-coils as guarding against high-frequency oscillations we always assume that such a coil contains inductance and a very small resistance; but we usually forget that it also contains distributed capacity, that there is a capacity from turn to turn which may be relatively small where circular conductors are used. There is, too, a considerable distance between turns; this

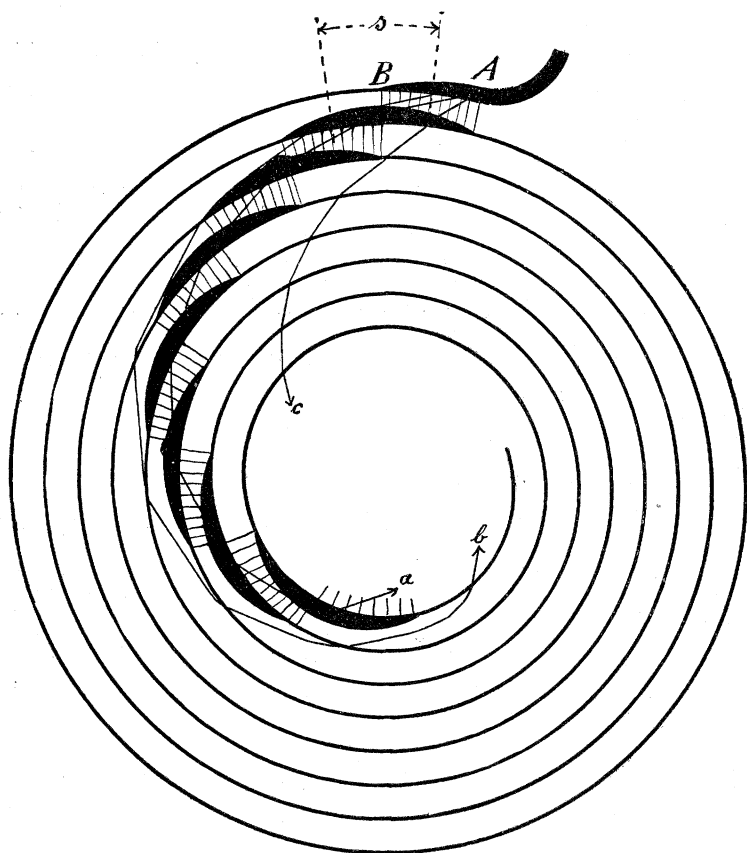


FIG. 1.

becomes very much larger where flat conductors wound in a flat coil are used, very much larger where we submerge the reactive-coil in oil, due to the higher specific inductive capacity of the oil, the specific capacity of the oil being two or more times that of air, and due to the shorter distance between the turns, permitted by the higher disruptive strength of the oil. At such very high frequencies as are produced by spitting from the line, by brush and spark discharges, by an arcing ground on one side of

an isolated three-phase system, and many other such phenomena, the electrostatic capacity of the reactive-coil begins to be appreciable.

What happens I can sketch only roughly. Let the reactive-coil be shown diagrammatically in Fig. 1, as a spiral, with the turns inside of each other. If a discharge enters at the lead *A*, if the frequency is high enough the current does not go around the complete spiral, but the current passes from one conductor to the next conductor through the capacity between the turns as a condenser. The current, starting at full value at *A*, gradually tapers down in the first turn, to nothing at *B*, within a limited distance; in the second spiral, the current is zero at *A* and gradually rises to a maximum at *B*. In the same way the current passes from the second to the third turn, etc. The current thus transfers across from turn to turn by the electrostatic capacity between the turns, gradually rising in each turn, by transfer from the preceding turn, and fading out again by transfer to the next turn. Thus the current flows a short distance only in each turn, but does not go around if the frequency is high enough.

Assume that:

$L$  = inductance per unit length of conductor,

$C$  = capacity per unit length of conductor,

$N$  = frequency of the oscillating current, or frequency representing the steepness of the travelling wave.

$s$  = length from condenser center to condenser center, then

$Cs$  = capacity of each of these condensers formed by successive turns.

$Ls$  = inductance of the short path of the current from condenser-center to condenser-center.

The current has an infinite number of paths,  $a, b, c$ , etc.

There is one path, on which the capacity reactance:  $k = \frac{1}{4NCs}$

equals the inductive reactance:  $x = 4NLs$  and the total impedance thus is a minimum, equal only to the ohmic resistance; that is, this path is non-inductive, and the current flows across the reactive-coil on this path.

In this case:

$$k = x$$

it follows:

$$s = \frac{1}{4N\sqrt{LC}}$$

or:

$$N = \frac{1}{4s\sqrt{LC}}$$

That is, if:

$L$  is the inductance,  $C$  the capacity per unit length of the conductor, if the frequency of discharge is high enough, the current

does not follow the turns of the reactive-coil, but passes in a spiral, non-inductive path across the coil, and the reactive-coil is not a reactive-coil. The frequency where  $s$  equals the length of one turn, gives the limiting frequency at which this phenomenon is completed, at which the last inductance has disappeared. This limiting frequency is very high, somewhere in the range between 10,000,000 and 100,000,000 cycles, but it is a frequency which does occur in discharges from a line, not a discharge which comes from a long distance, but a frequency which occurs where a steep wave approaches a station, and then meeting any obstruction spits over to other conductors near by, or into space. This phenomenon has to be considered when dealing with reactive-coils at very high frequency, and may be one of the causes why reactive-coils occasionally do not protect, but let extremely high frequency pass, just as well as low frequency, and act only in the case of intermediate frequencies.

The phenomena resulting from distributed capacity in the reactive-coil at extremely high frequency are obviously more complex than those illustrated above. For instance, during the decrease of current by transfer to the next turn, across the intervening capacity, a transfer back to the preceding turn takes place also, and so a second parallel path of current, of lesser intensity, appears ahead of the main path  $a$ , as shown by  $b$  in Fig. 2, a third path at  $b'$ , etc., and in similar manner, back of the main path, secondary paths  $c, c', c''$  etc., appear. These secondary paths, overlapping at the opposite side of the coil, result in various interference phenomena. Thus if all the turns of the coil are of the same effective length, at those frequencies at which the length of turn is a multiple of  $s$ , resonance effects intensify these standing waves; while at an intermediate frequency the standing waves passing around the coil in opposite direction, meet in opposition and thus neutralize. Again, with a coil in which the diameter of the turns tapers, resonance appears in some, opposition in other turns, and radially distributed nodes appear at all frequencies, shifting with a change of frequency.

Coming to the next element of the lightning-arrester, the series resistance, I fully agree with the sentiment—which can be read between the lines of the paper—that the best series resistance is the one of lowest value, and the lowest value is zero. There are, however, two points of view; one point is that of the designer of the lightning-arrester, and the other that of the operator of the transmission system. For the protection and safety of the lightning-arrester, the higher the series resistance the better; and it is extremely difficult to produce a lightning-arrester without series resistance, which is really safe against self-destruction. But from the point of view of effective protection of the system, any series resistance is objectionable. Here also the writer of the paper has calculated numerical value for one particular condition, and concluded therefrom that 400 ohms

series resistance is permissible. This conclusion is justified only for the particular condition where an electrostatic charge of 100,000 volts appears somewhere on the line and approaches the station along the line. There may be other disturbances in which this series resistance is not permissible. It may happen that in a station a short circuit takes place, and instantly ruptures. For instance, by some overload the circuit opens, but the switches fail, as should not happen, but still occasionally

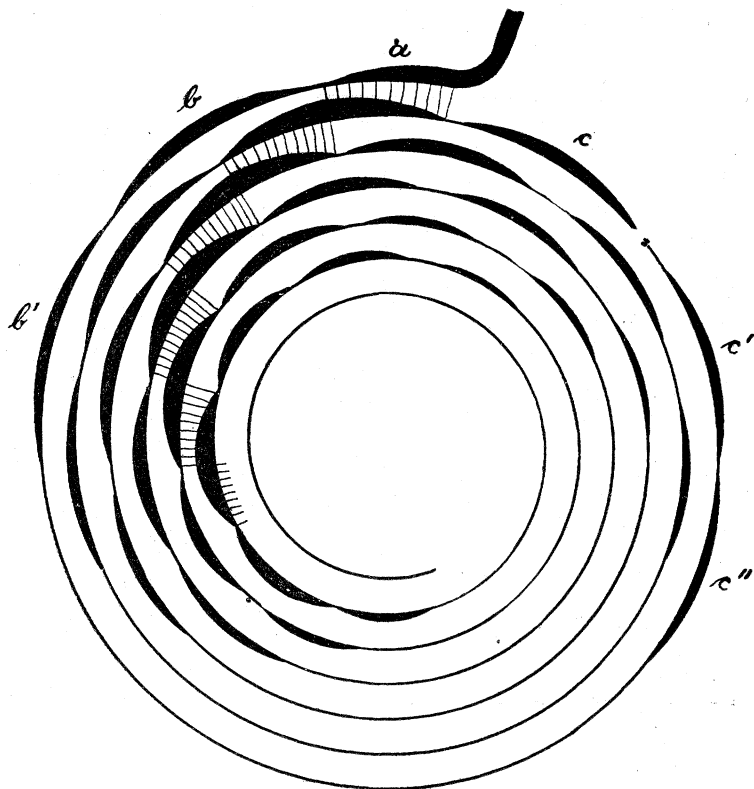


FIG. 2.

happens; that is, the switches burn up by a flaring arc and the short-circuiting arc ruptures itself spontaneously, explosively, as such arcs occasionally do at the maximum of the current wave. That means a rupture of the short-circuit current. That current cannot instantly cease in the system, but continues to flow, and not having a path merely backs up as voltage. It is obvious that in any large system the voltage produced by the instantaneous rupture of the maximum short-current circuit cannot be appreciably relieved by the discharge over a 400 ohms resis-

tance. A circuit with 400 ohms resistance will not reduce the destruction to any appreciable extent. For instance, at the Milwaukee convention last May, Mr. Osgood of the New Milford Power Company reported on the low-frequency surge in his system produced by some person who threw an umbrella handle into the transmission line at 33,000 volts. Or in cases like that of a metropolitan system, where a short-circuit oscillation or surge occurred with a current sufficiently large to bend heavy copper bars, and at a voltage jumping across seven inches of air. No protective device with 400 ohms series resistance would have any appreciable effect in relieving such a surge. In

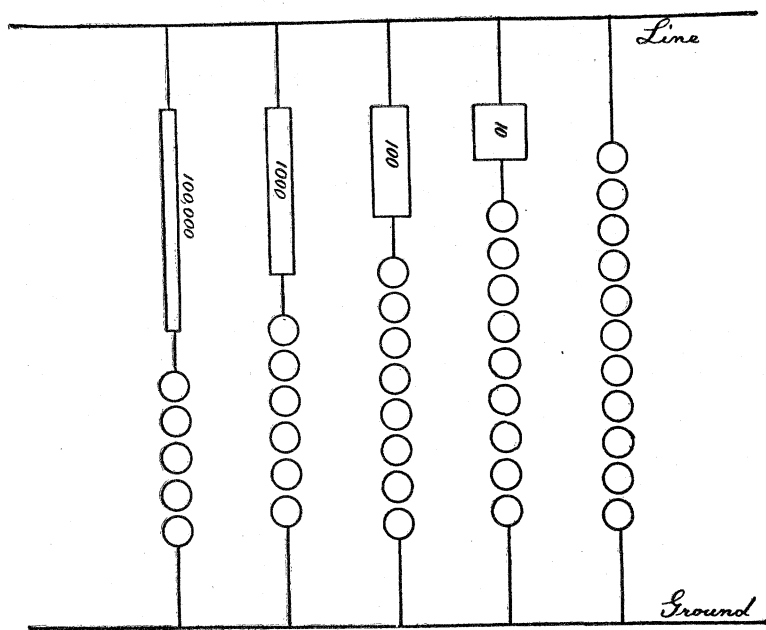


FIG. 3.

the case of 400 ohms series resistance, or any series resistance, there always comes a point where the magnitude of the surge is such that the series resistance becomes fatal.

In regard to the electrolytic arrester, I may say that it is a very interesting apparatus. I know that Professor Creighton has been working on this type of lightning-arrester for several years, and I believe some such arresters have been out in commercial service on high-potential lines for a year or two. I expect we shall hear something of the performance of these arresters either to-night, or at the meeting of the Institute for which Professor Creighton promises a paper.

In regard to Mr. Merzhon's proposition, I approve of his type

of lightning-arrester, a number of spark-gaps set for different voltages, with different series resistance, a low-voltage spark gap with a very high resistance, and then a little higher voltage spark-gap with somewhat lower resistance, etc., so giving the current the choice either to jump only the last spark-gap with high resistance limit, or the next one with lower resistance, or the next, etc. We know that a number of small gaps in series are more effective than one large gap in opening the circuit, so that several gaps in series are preferable. Suppose the first path contains 100,000 ohms, with a certain number of

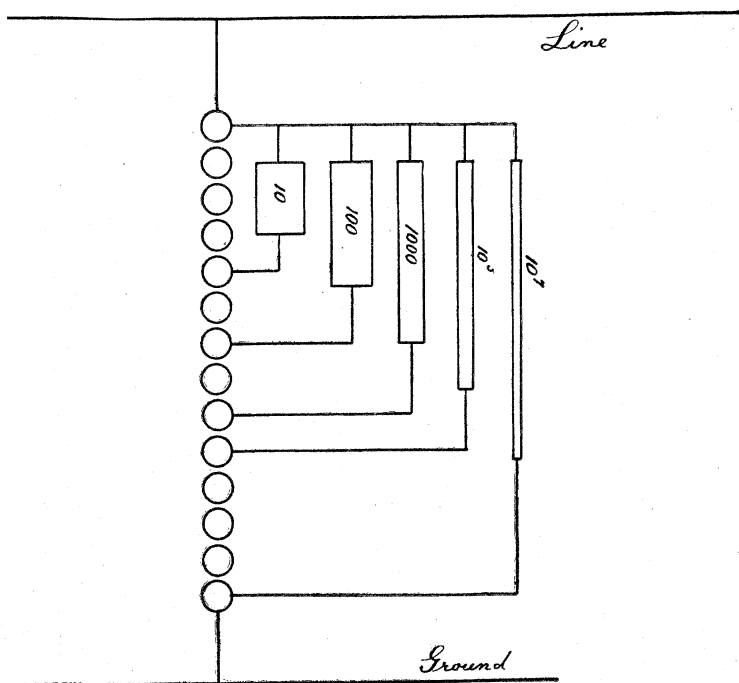


FIG. 4.

spark-gaps; the next arrester contains 1,000 ohms, with a few more gaps; the next one is 100 ohms, and still a few more gaps so as to require a higher voltage; then the next one is 10 ohms and still a few more gaps. If the designer of the lightning-arrester has sufficient confidence, the last path may contain still more gaps, and no resistance, as sketched in Fig. 3, diagrammatically. There seems to me no reason why instead of separate spark-gaps for each path, the same spark-terminals could not be used for all, and the protective device built as sketched in Fig. 4. Even the same resistances may partly be used. Possibly we might go still further and connect on to

the next or to the ground line with a high resistance, so that a gradual accumulation of voltage can discharge steadily; this results in a very satisfactory arrangement for the discharge of lightning, because it would select the resistance according to the severity of the discharge and always use the least number of air-gaps and the highest resistance permissible by reason of the character of the discharge.

**Percy H. Thomas:** Somehow or other we do not seem to lose our interest in lightning-arresters, and I hope Mr. Mershon will not take away all of our discussion of theory, because if he does I do not know what we shall talk about.

I think a little more explanation of the method by which a series choke-coil protects the transformer winding is worth while. The point I want to bring out is that the concentration of potential on the outer turns results from the electrostatic capacity within the winding of the transformer. Suppose we have a transformer winding connected to earth on one side, and a static disturbance comes from the line; assuming that there is no capacity between the turns or to the ground in that winding, we will not get an uneven distribution of potential, severe at the line terminal and light at the other end, but a perfectly uniform distribution of potential throughout the winding, the same number of volts for each turn. Suppose we put a choke-coil between line and ground, and suppose the same disturbance to come from the line; as before we will get no concentration of potential, simply a distribution through the total winding of the transformer and the series coil; and each unit of induction will have the same voltage impressed upon it. Suppose, on the other hand, we have the actual case occurring in practice; that is, a winding with electrostatic capacity between each turn and ground and between adjacent turns (the latter having very much the same effect as the former); the capacity of each turn may then be considered as equivalent to a small condenser. Before the discharge from the line reaches the first of these condensers, the potential of the corresponding turn remains practically zero and there will be no change until the discharge from the line has flowed from the terminal to this first condenser, as Dr. Steinmetz has explained; and for a brief instant of time full potential is impressed between the terminal and this point. Then, as the charge penetrates, this potential is distributed on more and more turns. Suppose we assume *A* in Fig. 1 to be the line end of the transformer winding, and that the other end *B* is connected to ground. Then, in the first case where there is no capacity in the winding and no series coil, the maximum strains will be shown by Curve *I*, in which is plotted as ordinates the maximum potential which will be found on each turn. The resultant curve will be practically a straight line.

In the case in which we have capacity in the winding, however, and no series choke-coil, the curve of maximum potential

between turns is shown by Curve II. Taking the case in which the winding has no capacity, and a series choke-coil is introduced at the point C, the distribution of potential will be as shown in Curve III, where each unit of inductance receives the same impressed voltage. In the case where the winding contains inductance and we have a series choke-coil, as usually met with in practice, we have a distribution of the potential as shown in Curve IV. The effect of the choke-coil is thus seen, in practice, to be the reducing of the maximum strain on the first turns only.

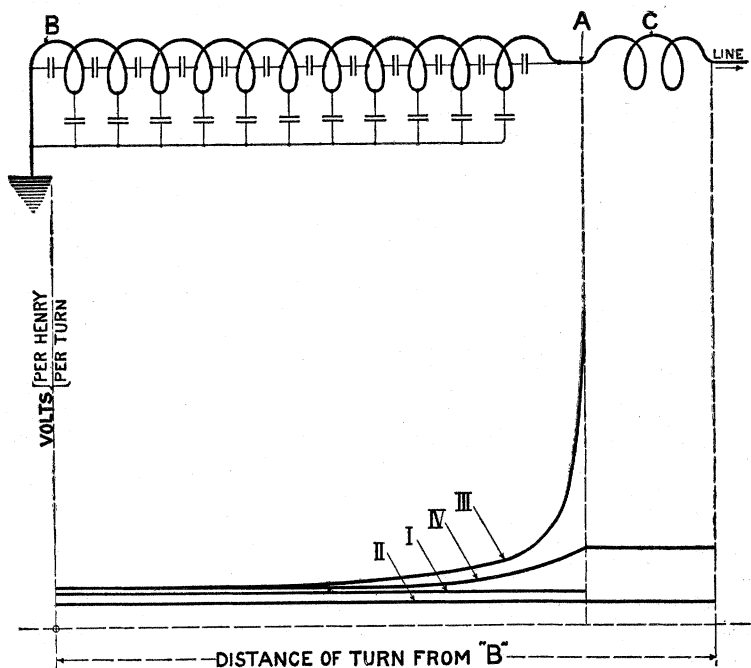


FIG. 1.

Of course the condition which determines how much potential will be impressed on the outer turns of the winding is the rate at which the charge penetrates the coil, and is controlled just as much by the capacity of the winding as by its inductance. The greater the inductance and the greater the capacity the slower will the discharge penetrate, and the greater will be the concentration of potential.

I think it will generally be admitted that one given value of inductance in a series choke-coil will not be suitable for protecting all sizes and types of transformers.

Mr. Jackson has brought out an interesting point: that a

condenser which is stretched out over a long distance; that is, having distributed inductance and capacity, as a transmission line, charged to a given potential, cannot produce during discharge more than a certain current, and that using a definite resistance in series with such a discharge would always produce a potential proportional to the potential to which the line was previously charged. This condition, which is not true of a condenser where there is not a uniform distribution of capacity and inductance, is analogous to the discharge of water from a long trough or canal of uniform cross-section, in which case when once started the liquid contents would flow out at the mouth at a constant rate, neglecting resistance losses. However, it is hardly safe to apply this conclusion to a practical transmission line, since we may not have one, but several lines discharging through the arrester at once, and since we may have a direct lightning discharge passing to ground which will, of course, be controlled as regards its current strength by considerations other than line capacity.

I wish to call your attention again to another system of lightning protection, differing from the arrangement suggested by Mr. Mershon. Suppose we have a transmission line and have standard lightning-arrester apparatus of a type capable of caring for ordinary discharges continuously and without renewal. We may then add at some point, possibly between 1 and 5 miles from each station, a number of fuses in parallel, connected between line and ground in series with a spark-gap, each fuse having in addition a gap of its own. We then have an arrangement which will not only care for ordinary disturbances without attention or renewing of apparatus, through the arresters at the stations, but also for relieving severe discharges or passing direct strokes to earth through one of the fuses, and thus interrupting the generator current. The use of several fuses and series air-gaps insures that a number of severe discharges can occur without leaving the line unprotected. These fuses can also be easily arranged to be renewed while voltage remains on the line.

This system of protection is brought up at this meeting on account of the tests reported by Mr. Jackson, which indicate that a fine wire inclosed in a tube opens the circuit very quickly—in this case at the end of the first alternation—without rise of potential and without opening circuit-breakers, and presumably without disturbing synchronous apparatus. This result, if substantiated by later experience, as seems very probable, is of the greatest importance, as it eliminates one of the chief presumptive difficulties of fuse arresters: namely, the interruption of service from temporary short-circuit on the line. I suggest, however, the use of a German silver wire in place of the fine copper wire, as this will blow at a smaller current.

The electrolytic arrester is, of course, the item of greatest interest in Mr. Jackson's paper. There seems to be a general

impression that this will work out satisfactorily and will eliminate a great many of our lightning-arrester troubles, both theoretical and practical.

**E. E. F. Creighton:** In the matter of equivalent needle-gap of apparatus, resistance, etc., the mysteries are gradually clearing away. In measuring the equivalent needle-gap of a resistance there are a number of factors involved which give variations. The equivalent needle-gaps of rods in series and parallel are given below:

The  $G$  gap on the static machine was set at 4 in., the electrodes on the static machine were 1.4 in. in diameter. The inner coatings of three one-gallon Leyden jars were connected to each terminal of the machine, and the outer coatings of each set were connected to the resistance terminals. The equivalent needle-gap of three rods (750 ohms) was 1.59 in. With another equal resistance laid in parallel, the equivalent needle-gap was 1.27 in. With the third equal resistance laid in parallel, the equivalent needle-gap was 1.09 in. With the resistance short-circuited, the equivalent needle-gap was 0.15 in. If the three values of equivalent needle-gap of the three resistances are plotted, there is a proportionality which approaches a straight line. If we take into account the impedance in the circuit, we do not in this case get the concordant values shown later. There is every reason to believe that the same laws apply to a needle-gap used to measure voltage as apply to meters. In this case we are attempting to measure the impedance of a circuit 16 in. long with a needle-gap connected to leads which are more than three times as long, therefore we may scarcely expect to get correct values of the inductive drop across the 16 in. Furthermore, it requires a certain time to elapse after the potential is applied to the needle-gap before the gap begins to spark. If we put the needle-gap, as an instrument of measure, under better conditions of operation; that is, make the needle-gap circuit of less inductance than the circuit to be measured, it gives, at least in most cases, reasonably good results. Following is given the relation of the equivalent needle-gap of resistance made up in two ways:

1. As a sample rod of 250 ohms;
2. As seven rods in parallel and seven sets in series, making a total of 250 ohms.

The equivalent needle-gap of the single rod was 0.47 in. ( $G-1$  in). The equivalent needle-gap of the 49 rods was 0.86 in. The circuit composed of the 49 rods was necessarily very much longer than that of a single rod, consequently a short-circuiting wire was laid over the same path and the equivalent needle-gap taken of the inductance. The value was 0.6 in. It will be seen that the equivalent needle-gap of the inductance and the equivalent needle-gap of the resistance will combine vectorially to make 88% of equivalent needle-gap of the impedance of the 49 rods. This error of 12% can be accounted for.

The same set of resistances was tested with a machine gap of  $G = 7$  in. We obtained the following equivalent needle-gaps:

250 ohms in a single rod,	0.59 in.
250 ohms in 49 rods,	1.35 "
A copper wire in place of the 49 rods,	0.95 "

The combination of the resistance, 0.59 in. and inductance 0.95 in. vectorially gave 1.12 in. for the equivalent needle-gap of the 49 rods instead of 1.35 in. Again, the conclusion is that the discrepancy is within the degree of accuracy of measurement. These rods were made of standard composition with carborundum as a base. The resistance seems to have the same paralleling properties as metallic resistance. In fact, the same ohmic resistance of either non-metallic rods or metal wire gives the same equivalent needle-gap. There is a case, however, where parallel resistances made up of non-metallic composition will not have the paralleling properties. This kind of resistance may be placed in the category of coherers. If the substance of the resistance is composed of particles which are normally in separation and a static spark takes place, the particles cohere along a definite line and suddenly reduce the resistance to a comparatively low value. If the resistance is sufficiently reduced or the quantity of electricity is sufficiently small, the coherer thread of contacts relieves the potential, and there is no tendency for the material to break down in any other line. Under these circumstances, placing a parallel resistance in circuit will not affect the equivalent needle-gap.

As a matter of comparison, the equivalent needle-gaps are given herewith for rods of higher resistance. In each case the machine gap,  $G$ , was 4 in. The length of the rods in the following test was 8.5 in. The equivalent needle-gap of one 3200-ohm rod was 1.52 in. The equivalent needle-gap of two of these rods in parallel was 1.14 in. It should be noted that the equivalent needle-gap of this 3200-ohm rod is less than the equivalent needle-gap of 750 ohms, due to the fact that the three rods making up the 750 ohms gave a longer length of circuit than the one rod of 3200 ohms.

The equivalent needle-gap of one 220,000-ohm rod was 2.15 in. The equivalent needle-gap of two of these rods in parallel was 1.79 in. It should be noted in this test that the resistance of the rod as compared to the inductance of the rod is becoming predominant.

Since these results can be explained by conditions of the inductance, capacity, and the method of measurement, it would seem that an equivalent needle-gap taken under any other condition need only have all the conditions given to make it intelligible. If the frequency of the circuit is lowered the inductance factor in the above tests becomes more negligible.

The speaker has been working for several years on electrolyte cells, especially in their application to lightning-arresters. Two years ago one of these arresters was installed for test on a line

during a short period, and last year we had an aluminum cell arrester on a 33,000-volt line during practically the whole lightning season. The speaker was scheduled last year to read a paper on this subject before the Institute, but it was thought advisable to put the arrester in commercial form with the experience of a season back of it before describing it. There is much to be said in its favor. We have collected a considerable amount of experimental data concerning its operation which we hope to present at the March meeting. These cells can be so made that the resistance above the critical voltage will be but  $\frac{1}{10000}$  of the resistance below the critical voltage. In other words, a cell has a high resistance for normal potential, but a low resistance for potentials much above the normal. It has been our practice to install the arrester with its critical potential about 25% above normal. The current that this cell will discharge without increasing the potential to a dangerous value depends entirely upon the construction.

Below will be found some information regarding screening, chosen from tests on the multigap arrester. There were 190  $\frac{1}{2}$ -in. gaps in series. Without a screen on the multigap arrester, the spark-potential on a 60-cycle circuit was 68 kv. With a screen around the multigap arrester, the spark potential dropped to 60.4 kv. With one terminal permanently grounded, the spark potential was 47.5 kv. without a screen; with a screen the spark potential rose to 53.9 kv. With one terminal arcing to ground and no screen, the spark potential was between 34 and 36 kv. Under the same conditions, with a screen, the spark potential was between 40 and 43 kv. It will be seen from these tests that the tendency is to make the spark potential more uniform for all conditions, but the screen does not entirely accomplish the result. The equivalent needle-gap with an impressed frequency of three million was then taken with the following results:

The equivalent needle-gap with the screen was 2.45 in.; the equivalent needle-gap without the screen was 2.67 in. The sum of the 190 series gaps is 6 in. The two halves of the arrester were connected by a wire of considerable length which makes the equivalent needle-gap higher than that of the normal installation.

In regard to the form of the potential wave. I presume that the direction of movement in Fig. 8 is from right to left and that a current transformer was used in getting the current record, but I cannot understand why the potential wave is all on one side of the zero value. Did not this oscillograph have a very low natural period of vibration? In Fig. 9 I note again that the deflections of the potential wave are greater on one side of the zero than on the other side, and that the generator wave of potential had already reached a considerable value before the switch was closed.

In Fig. 8 the oscillogram shows that the current apparently

reversed in direction and then came gradually back to zero. Experience demonstrates that the current will continue to flow during most, at least, of the second half-cycle if it once gets started in the reversed direction. The false record of the oscillogram is due to the use of a current transformer. The magnetic leakage in the transformer prevents the current in the oscillograph rising to its true maximum value. The decreasing current is less sudden, the magnetic leakage less, and therefore the deflection is carried across the zero and returns along a logarithmic curve to zero.

**H. B. Alverson:** As the testing of lightning-arresters comes at the operating end, I can merely speak of certain results obtained in stations having 700- to 1200-kw. circuits, with a station capacity of 3,000 to 6,000 kw., with standard forms of lightning-arresters. The experience extended over a period of several years. It was soon found that arresters without series resistance on these circuits were of no value. The standard forms of lightning-arresters were used under ordinary conditions, with care and inspection, the limiting resistance producing a condition that gives operating results approaching continuous service. We have one of our stations equipped with choke-coils and low-equivalent arresters. With this outfit no interruption to the service has occurred; whether this covers all conditions or not of course we cannot tell. As Dr. Steinmetz has said, we cannot obtain arresters that will cover every condition, but it appears to me that on the lower voltages there is apparatus with which results may be obtained which will answer all purposes.

As I read it, this paper gives a method of determining the proper choke-coil to be used for any particular apparatus. With that data it should not be a very difficult matter to obtain proper proportions of apparatus so as to avoid suffering any severe interruptions except in extraordinary cases.

**P. M. Lincoln:** The collection of data on this subject of lightning protection is one of the most difficult with which the electrical engineer has to deal. It is difficult on account of the impossibility of observing what takes place in practice. It is impossible to tell the exact strength of the blow of the lightning force in any given case, and it is almost impossible to tell what its results are on account of the lack of observers at the time the thing happens and the varying tales one gets from casual observers after the thing happens. As I look at it, there are three methods by which we can collect data on the general subject. One is that just mentioned; viz., the observation of lightning phenomena themselves. This is unsatisfactory, for the reasons just stated. Although it is impossible, or difficult, rather, to judge of the reason why certain protective apparatus fails or succeeds in actual practice, still on its results in actual practice must depend the final judgment as to the value of that apparatus.

The second method of obtaining data on this subject is that of pure reason. In that category I place the first part of the paper read this evening, and also the interesting arrester arrangement which Mr. Mershon has just described. I would also place in the same category the very interesting exposition which Dr. Steinmetz has given us in regard to when a choke-coil is not a choke-coil. These things I would place under the head of pure reasoning on this subject, and we can get a good deal of information in that way.

The third way is to manufacture our own lightning and discharge it through set conditions in certain circuits, and by varying the conditions which obtain in the circuits, derive the information sought for. By creating our own artificial lightning and discharging it through given conditions, and making observations, by that method we can gain our most reliable data. That is the method pursued in the historical experiments by Oliver Lodge, as well as those pursued later by Mr. Wurts and still later by Mr. Thomas and others.

One more point, and that is in designing lightning apparatus we have two things to protect; one, the protection of the apparatus in the circuit; the other, the protection of the service. A simple spark-gap, nothing in series with it, is undoubtedly a most perfect protection to the apparatus. It allows the accumulated charge to get off the line, but at the same time it allows the dynamo current to follow and thereby interrupt the service, unless there is some arc-interrupting device. I think that these two things should be kept quite distinct: protection of the apparatus and the protection of the service. Most operating engineers will be willing to sacrifice some apparatus to save the service.

**Ralph D. Mershon:** Referring to the suggestions made by Dr. Steinmetz relatively to using a single resistance, I have preferred not to do this because it seems to me an advantage to have several paths, thus reducing the inductance as well as the resistance of the combined path to ground.

One reason for not using the number of gaps shunted in the way he described is that my experience with a series of gaps has not been a very happy one, due to the peculiar distribution of potential over these gaps by reason of capacity effects. I prefer something like a horn arrester which is not easily burned up, and is not subject to the uncertainties to which a series of gaps are liable. I am especially in favor of the horn arrester because it can be put out of doors; whereas a series of discharge gaps is not well suited to this.

I think that fuses on the line would not be effective in protecting station apparatus, judging from some things which have happened from time to time on transmission lines under construction. I have known of cases where a line in the course of construction, with the line conductor grounded at the point where the construction work left off, has been struck by lightning which,

instead of going a mile along the line conductors to ground, has preferred to smash through insulators, presumably in the neighborhood of the point where the disturbance originated. I am sure that fuses, in order to protect the station, would have to be at closer intervals than those suggested by Mr. Thomas.

**R. P. Jackson:** Mr. Mershon asks about Fig. 4. In that case the static disturbances were impressed upon both ends of the transformer. I left off the other end of the curve, as it was a duplicate of the end shown. We got no record different from the end which is shown. As to what the effect of the disturbance on one end would otherwise have been on the other we cannot tell; but tests have been made with transformer coils, with iron and without iron, showing no material difference, in choking effect, etc.

In regard to oil choke-coils, and the closer spacing of the turns, another point I did not mention was that this choke effect is not directly a function of its total inductance, but of its inductance per unit length; and naturally a coil which could be made more compact and have greater inductance per unit length of wire would have a greater reflecting effect. It is true, as Dr. Steinmetz pointed out, the capacity effect would come in, and a coil would be ineffective for very high frequency and very low frequency, but there is a wide range which appears to include most lightning disturbances which a choke-coil will handle.

Regarding the 400 ohms as a critical resistance, it was not meant that this was the only permissible resistance without any question whatever. It was a value which, under the conditions given, would just eliminate a rise of potential and reflection at the lead of the apparatus, meaning that lower resistances were desirable, if possible. Therefore, from that calculation it appeared to be that 100 ohms, or something in that region would be more desirable than anything above it. It would not mean that 1,000 ohms would not do any good, but that it would do so little good that great effort should be made to keep below the 400 ohms, because, under the conditions indicated, using 1,000 ohms, while there is some discharge, there is still a rise of potential and reflection which will do harm. While the rise of potential is not the same for any resistance whatever, still it would be there to some degree; 400 ohms would prevent rise of the deflection, but still give a rise equal to that of the original incoming wave, while with zero resistance there would be no potential whatever existing there. What Mr. Thomas says about parallel lines requiring lower resistance is perfectly true.

In regard to the oscillograms, I did not operate the oscillograph at the time the records were taken, and I cannot say why the one on Fig. 8 is not symmetrical, but any one who has worked with an oscillograph knows that they do become erratic at times and deviate considerably, probably due to static influences.

This effect is not so noticeable on Fig. 9, but still the curve is somewhat distorted, due to some lack of adjustment in the oscillograph, or failure to ground the frame.

**J. F. Vaughan** (by letter): In view of recent progress made in special devices for the protection of lines and apparatus there seems to be good prospect of accomplishing proper protection against ordinary disturbances due directly to internal or induced by external causes. Little attention, however, has been given to the possibility of protecting lines against direct lightning stroke. It is unreasonable to expect to provide sufficient line insulation to prevent such a stroke from going to ground, or sufficiently frequent

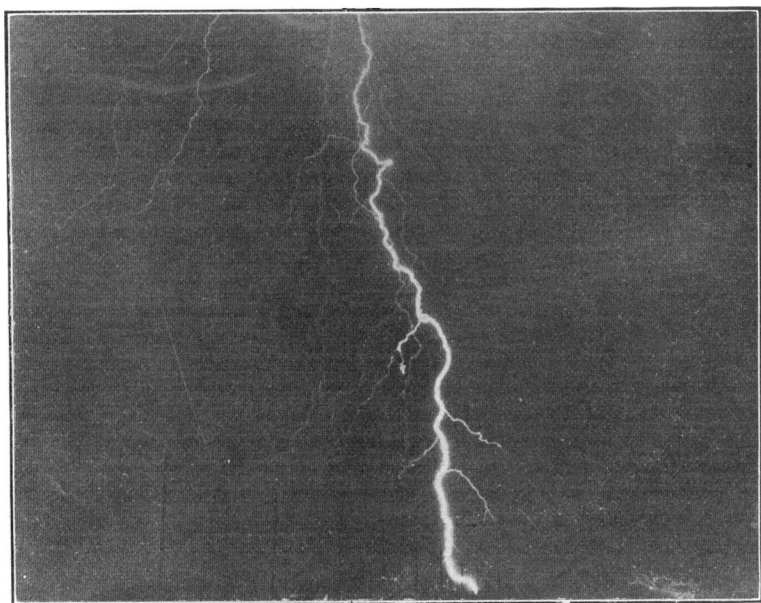


FIG. 1.

arresters safely to carry the excessive charge to ground. Why not divert such strokes from the lines? Lightning rods on the line poles and overhead grounded wires have been of some value in preventing damage to lines and poles. Why not go a step farther and provide entirely separate paths to ground by means of lightning rods mounted on separate poles well above and at one side of the line. With this in view, the 50,000-volt Taylor's Falls transmission line in Minnesota, in addition to a number of other devices, was protected last summer for two miles through the most exposed region by poles at the side of the line carrying rods 25 ft. above the upper transmission wire.

Although the storms last summer were unusually few and light, the photograph of one direct stroke to earth shows the main discharge branching off into many secondary discharges like an inverted tree, covering an area of ground of probably over a mile in diameter, indicating clearly that the territory affected was not restricted to the immediate vicinity of the bolt. It is interesting to note that while six transmission line poles in different parts of the line were splintered the previous summer before any wire was strung, last summer several of the lightning-rod poles showed punctured tell-tale papers inserted in their ground connections, one puncture indicating a heavy discharge to ground, while the line itself, though not in operation, did not suffer.

**A. Henry Pikler** (by letter): The present paper, it seems to me, although its title in general refers to lightning protective apparatus, deals in reality with such elements of it as are protective not against lightning directly, but rather against its secondary effect—induced high potentials; still more efficiently against surges due to short circuits, sudden and great changes of the line current. Furthermore, this apparatus is suitable to protect only particular points of an electric power transmission equipment—namely, those located in the power house or in the sub-station and not the transmission line.

In discussing the devices brought forward in the paper, I shall restrict myself to the choke-coil. Of late the choke-coil appears to have been much neglected. I have seen large power installations in connection with a 35,000-volt, 30-mile transmission line, made by one of the leading manufacturing companies of the country, where the choke-coil was omitted. The consequence was that during lightning storms, or, in the case of grounds, sudden changes of loads, short circuits, the ensuing surges ruptured the insulation of the main switches in the power house and grounded the line, although the lightning-arresters were discharging profusely.

In order to illustrate the powerful protection offered by a few turns receiving tremendous shocks directly, I want to mention that in the same power plant one of the little synchronizing transformers on the auxiliary bus-bars was connected up in the wrong way and when two transmission lines were to be paralleled, this was done in full opposition of the operating generators. A tremendous short circuit and rise of potential was the result and almost all the transformers broke down. Upon investigation it was found that only the very first turns of the end-coils were punctured through many small holes. It will be interesting to note that these end-coils had very heavy insulation on them, (also the end-turns were extra heavily insulated) sufficient to stand about 100,000 volts (though they were not at all intended to be choke-coils), whereas the other coils, many in number, were almost bare. These latter were entirely uninjured.

I was very much surprised to hear Mr. Mershon, the chairman of the High-Tension Transmission Committee, recommend the use of the first few turns of the transformer as a choke-coil by placing extra heavy insulation on them, thus saving the expense of an extra choke-coil. While theoretically this seems plausible, from the practical standpoint I most decidedly disagree with him. The duty of the protective apparatus is to save from injury the vital elements of a transmission equipment, even at the cost of life of the protective apparatus. This is necessary for two reasons: to avoid interruption of the service, and to save the more expensive power station equipment from break-downs and burn-outs.

To have the choke-coil form the internal part of the transformer would mean to provoke just this trouble. There exists no commercial insulation or method of insulating that would save the choke-coil from a flash-over and ensuing burn-out between adjacent layers and turns, if the relation between inductance and capacity of coil and the periodicity of the disturbance is such as to cause resonance. Such and similar disturbances would mean to cut out that transformer and cripple the service for some time. Besides this, it means damaging and repairing a piece of apparatus worth several thousands of dollars, whereas if the choke-coil is made independent of the transformer it means only the damage of the choke-coil, worth perhaps a few hundred dollars.

Furthermore, from the standpoint of the designing engineer I do not consider it reasonable to have two pieces of apparatus, serving different purposes and involving entirely different methods of calculation, design, and manufacture combined in one. Both would suffer in the end, the transformer as well as the choke-coil. At the same time I do believe and strongly recommend the insulating of the first few turns next to the line with special care and precaution on every piece of apparatus, but I would like to see the choke-coil in series with it. On high-voltage induction motors operating at 5,000 volts and above, break-downs used to be very frequent, and there seemed to be no insulation good enough to resist potential rises due to sudden variations in load, etc.; the choke-coil was put in series with the terminals, and the trouble was eliminated at once.

**H. W. Buck** (by letter): The tendency of this paper and its discussion, which is common in the treatment of lightning disturbances, is to regard the problem solely from the standpoint of the mathematical theory of oscillations. This is undoubtedly wise to a certain extent, but there are very important lightning troubles which lie quite outside the realm of calculation. I refer particularly to direct strokes upon a transmission line from lightning bolts of great violence. Here the problem before the engineer might be considered more one in fortifications than in oscillations or surges. There are many discharges which take place in thunderstorms between clouds and

earth which apparently are not only of very high potential but also of very large current volume. Trees and poles are sometimes completely shattered by such strokes. The explosive violence with which wood-fibre flies to pieces at such times seems only explicable on the theory that there is sufficient current to cause either instantaneous evaporation of the juices in the wood and consequent expansive force, or else the immediate expansion of the gases held in the pores of the wood. In either case the volume of current must be very large, and the ordinary lightning-arrester resistances used for the discharge of transmission lines is entirely inadequate. My feeling is that the electrolytic arrester described in the paper, if selected for the ground path of one of the above lightning bolts, would meet much the same fate as that of the tree.

The most promising system of protection against direct strokes on the line seems to be that of the overhead ground wire, or preferably a grounded network supported on the transmission poles or towers above the conductors. Such a system if properly installed and grounded at every support should afford almost complete protection against the striking of transmission conductors or insulators. If more than one ground shield wire is used, and the two or more wires are connected together electrically at frequent intervals, a further protection is provided, at least part, by this short-circuiting shield against the induced disturbances in the conductors from neighboring lightning discharges.

There is another source of disturbance from lightning which is not usually referred to in discussions of lightning troubles. I have known of a number of instances where direct strokes upon objects such as trees immediately adjacent to a line have been followed by a simultaneous short-circuit between phases on the transmission line at that point. Such action may be explained on the theory that the air surrounding the conductors becomes ionized and conducting by the influence of the stroke near by. Those who have handled high-voltage switches without barriers between them have observed how easily a short-circuit is started in a similar way by the influence of a neighboring arc. Lightning trouble of this kind cannot be prevented by the ordinary type of ground-discharge arrester.

Deductions as to the suitability of various types of lightning-arresters from the experiences of individuals are very misleading. One man who has had no lightning trouble during a season attributes his success to the particular type of arrester he has installed in his plant. His success quite possibly might have been the same with no arrester at all on his lines. Another operator whose arresters have been completely destroyed, probably by some direct stroke on the line, discards the type as useless although it may have successfully taken care of all ordinary disturbances.

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