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# THE PRESENT STATUS OF ALUMINUM-CELL LIGHTNING ARRESTERS

BY E. E. F. CREIGHTON

ABSTRACT OF PAPER

This paper gives a brief survey of the conditions of operation of aluminum-cell arresters, without any description of the forms of the arresters. References are made to recent investigations of lightning phenomena and their possible effects on the design of protective apparatus used at present. The d-c. aluminum arrester is most economical and represents the highest possible grade of protection. In connection with the a-c. aluminum arrester the following points are discussed: dielectric spark lag, dissolution of film, charging resistance, oscillations, damping, degrees of surges due to natural operations and accidents, and insulations which withstand these surges. Charging resistance on aluminum arresters is chosen to make surges harmless, and the charging resistance gives great immunity from damage to the arrester itself by any accidental and temporary local condition in the arrester. In conclusion, the aluminum-cell arrester may justly be regarded as a standardized electrical device founded on solid fundamental principles.

ALTHOUGH the aluminum-cell lightning arrester is now many years old in practise, there is available in the TRANSACTIONS of the Institute very little definite scientific information on this subject. It has seemed preferable to produce certain results rather than describe beforehand how such results were to be obtained. The practise of the aluminum arrester has now settled down to definite sets of conditions, and it is the object of this paper to consider standard conditions and open up the subject to discussion. Aluminum lightning arresters will be treated in general on points that may seem debatable. No detailed description of apparatus will be given herein.

The question is often asked—Will certain types of arresters be superseded? In very few cases has it been possible to give a definite answer to such a question, owing to incomplete knowledge of cloud lightning phenomena. It has been possible to say that if future investigations of cloud lightning prove that every lightning stroke is of high frequency and steep wave front, certain changes would come about under these conditions; it would be possible to prophesy, with considerable confidence, that many types of lightning arresters now in use would disappear. The natural growth of protection would be along the line of various types of high-frequency absorbers.

If, on the other hand, it should be shown that lightning is always of low frequency, and gives the surge a sloping wave front, then again, it would be fairly safe to prophesy the contrary—that very few of the lightning arresters now in use would disappear, and that probably no other devices would take their place.

Recent investigations of lightning phenomena have confirmed our views that cloud lightning has wave fronts of various degrees of steepness, and without question some of the lightning strokes are not high-frequency effects but are of the nature of simple impulses. The writer's recent experiences along this line have been gained by indirect methods. Lightning arresters have been put out which were sensitive to very high frequencies, and at high frequencies had very good protective qualities; but at very low frequencies their spark potentials were greater than at high frequency. Other arresters equally sensitive to both high and low frequencies have been installed in the same locality. This experience has indicated that many of the strokes are of low frequency. The most valuable and practical investigation of lightning arresters that has yet been made on a large scale has been carried on by Mr. D. W. Roper, and no doubt these results, which are incomplete at the present time, will be made available at some later date. More direct measurements of lightning taken with an oscillograph have been made by Mr. L. A. De Blois. These, I believe, are the most valuable direct tests that have been made in many years. I am personally indebted to both Mr. Roper and Mr. De Blois for information on their researches, and I understand that their valuable work will be presented to the Institute at some future meeting.*

In the development of the present standard arresters our knowledge of lightning gave us no alternative but to assume that lightning had all the characteristic qualities of the various surges that could be produced in the laboratory. For example, we have assumed:

That the frequency might be from zero to 5,000,000 cycles per second.

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*See paper by L. A. DeBlois, *Some Investigations on Lightning Protection for Buildings*, page 519, this volume.

That the wave front might be either vertical or angular.

That the quantity of electricity was both large and small.

We have known from our earliest investigations that several strokes came in succession. It was also necessary to take into account the effects of the energy from the generator which followed the lightning discharges. In this way we have endeavored to be prepared to meet any new information that might come concerning lightning strokes. Naturally, all these different factors could not be given equal weight in the design, and therefore, as more definite information regarding the nature of lightning is obtained, the designs will be strengthened in the features that these investigations may show are weak. It is a matter of increasing the ultimate efficiency by a small percentage.

The direct-current aluminum arrester is practically ideal from the standpoint of protection. It has no series gap and therefrom it gains two valuable characteristics: the first of these is the elimination of any dielectric spark lag; and the second is the absorption of high frequencies which have a less potential than the circuit potential. Commenting on these two conditions, the dielectric spark lag, although it is ever so small, is still appreciable as compared with the time of movement of a surge along overhead lines. A surge will travel a mile (1.6093 km.) in about five millionths of a second. If the surge is a mile long, and the dielectric spark lag is five millionths of a second, such a surge will have passed along the line without starting a spark across the gap. The only means of discharging such a surge would be by introducing a choke coil in its path and thus delaying its movement sufficiently to allow the spark gap to become ionized. Since the spark gap of the a-c. aluminum arrester has a setting which may be only 25 per cent above the line potential, high-frequency surges can be deflected into the arresters if the potential either of the surge or the superposed value on the 60-cycle potential reaches the spark value. If the generated potential happens to be zero at the instant, it is evident that the surge itself must have a value 25 per cent above normal in order to cause the arrester gap to spark. The d-c. aluminum arrester, by its direct connection, is able to pick up surges of all frequencies and all potentials immediately on their arrival at the terminals of the arrester.

The practical demonstration of the protection afforded by these d-c. aluminum arresters confirms the theoretical work and experimental tests made on the cells. The discharge rate at double potential is more than a million times as great as the leakage current at normal potential.

From a practical standpoint, the cost of such arresters must be considered. While the cost and upkeep of the d-c. aluminum arrester is greater than for the older types using gaps and series resistances, still the aluminum arrester is the more economical one to use. The higher protection given by the cells would justify some increase in expense on account of the better service that can be maintained. But, as a matter of fact, the actual expenditure for the protection as a whole becomes less, due to the fact that good protection on the cars makes a less demand for the use of arresters along the trolley line. The saving in the cost of line arresters will more than compensate for the extra cost and upkeep of the aluminum arrester. Moreover, even with the very best types of gap arresters on trolley cars and trolley lines it is impossible in lightning-infested districts to maintain the car service. The percentage of protection from the gap type of arresters is not high enough even when the best arrangement of wiring and choke coils is used in conjunction with the arresters.

There is one further function of the d-c. aluminum arrester that has considerable value, and that is the absorption of electromagnetic surges coming from the interruption of accidental short circuits on the trolley line. Such high potential across loaded motors has a tendency to cause flashing around the commutators. If the flashing around the commutator is caused by the excess potential, then the d-c. aluminum arrester will relieve the trouble.

Answering, then, the frequently asked question—Will the d-c. aluminum arrester be superseded?—the answer is, in principle, no. Improvement in details may be made, and there may be discovered some new and better substance than the aluminum film, but none is yet known. Any degree of protection that is desired at its terminals can be obtained by the use of this arrester. An improvement in the length of life of the arrester is desirable, but this will not be superseding it. The discovery of some new substance that will give the same electric valve effect at a definite voltage only slightly above the operating voltage would be no particular improvement, unless perhaps it might be something that would not deteriorate when left disconnected from the circuit.

Turning next to the a-c. aluminum arrester, it was found impracticable to maintain simplicity and long life in the arrester and at the same time keep the arrester directly connected to the circuits. For this reason the horn gap was introduced in series with the aluminum cells. Since the hydroxide films on the aluminum plates gradually dissolve in the electrolyte it becomes necessary to introduce a method of charging the cells. The simplest method was first tried: it consisted of bringing the horns near each other and reducing the gap to a very small value. Many trial installations were made under these conditions and no bad effects were obtained. When the number of arresters in use ran up into the thousands, then an occasional trouble resulted from the rush of current into the aluminum cells.

The aluminum cells are condensers and as such will take initially a considerable rush of current. Furthermore, the dissolution of the aluminum films required a considerable quantity of electricity from the line to reform them. Where the films had been subjected to unusual dissolutions either by standing in hot electrolyte, resulting from atmospheric temperature or long periods of discharging, or from neglect to charge, the current rush into the aluminum cells became a serious menace, mostly to the arrester itself. Since there is no external indication of a bad condition of the aluminum cells, even an expert would be unable to know if it were permissible to close the charging gap of the arresters. This led naturally to the use of charging resistances in series during the ten seconds a day needed to charge the arrester. The charging resistance is an added expense and an added complication. But the added complication is relatively small, and the all-around increase in the safety of the arrester is great enough to justify both the cost and complication, from the user's standpoint.

The subject of possible surges accompanying the charging of aluminum arresters is one far more pertinent in an article written for foreign readers than in one for American engineers. The foreign operators seem to have had misfortunes with their arresters that have not been duplicated in America. The reason for this might be attributed to a number of different causes, depending upon the country and the localities. These reasons might be enumerated as methods and care in manufacture, the lack of definite and emphatic instructions to operators, poor distribution of insulation in transformer coils, and difficult situations caused by any one of several factors, such as, for example,—high temperature, bad regulation of the line, and insufficient care after an arrester had been called on to discharge continuously during an accidental ground.

The general results from any one or more of the foregoing enumerated factors may be classified under two heads: first, a short circuit in the arrester and consequent interruption on the line; and second, surges set up on the line without any damage to the arrester. Nearly all these conditions can be rendered harmless by the use of charging resistances. The one important exception is the matter of bad regulation of a line in which the power voltage is allowed to rise to values above the spark potential of the arrester. Under these conditions of discharge the arrester is no longer being used as such, but rather as a rheostat to absorb the generated power. The arresters cannot, at any reasonable expense, be designed to act as rheostats. While it might, in special cases, be possible to develop arresters which would withstand these conditions, the better solution of the problem is to improve the regulation. If care in manufacturing the aluminum plates and the electrolyte is not taken, and the installation made free of dirt and impurities in the electrolyte, more or less deteriorated conditions will exist throughout the life of the arrester. Certain kinds of impurities have a strong destructive effect on the films. A condition of unusually high operating temperature may call for an electrolyte especially adapted to high temperatures, or it may simply be taken care of by charging two or more times a day. Dissolution of the film from standing in hot electrolyte after the arrester has discharged continuously for a number of minutes can cause no trouble if a reasonable charging resistance is used, as the series resistance limits the current to a value which will not damage the arrester. With the exception, then, of high generator potentials from bad regulation of voltage, there is no difficult problem connected with the use of aluminum arresters.

A discussion of the aluminum arresters would not be complete without some reference to the possible surges that may be set up by the charging of the arrester. Surges on an electrical system may be considered in a list of ascending degrees of severity. Turning on an incandescent lamp sets up an electric wave on the system by calling on the generator for more power. A surge of this kind is of the third order of importance, and therefore, entirely negligible. It is well known that any spark or arc in the circuit containing inductance and capacity tends to set up oscillations, but if the resistance in series is equal to, or greater than, the critical resistance, oscillations will be prevented.

It is common practise to-day to open and close circuits which contain inductance and capacity without introducing in series a resistance to absorb the transient surges that are thereby set up. It is also common practise to-day to use circuit breakers to open accidental short circuits in which there is a high value of surge energy, and sometimes high voltages.

Going still a step further, every circuit is subject to accidental arcing grounds, which produce continually on the circuit dangerous surges which are often but slightly damped. It is difficult to protect apparatus from these most severe conditions of surges. In general, however, apparatus is built to withstand severe treatment, and there is but a small percentage of loss. Therefore, when we come to consider surges on the system we should take into account the conditions of insulation in relation to the severity of the surge.

In all these graded degrees of severity of surges, where should the aluminum arrester be placed? If there were a demand for it, the arrester could be placed in the list next to the negligible surge of connecting an incandescent lamp to the circuit, and this could be accomplished by using graded resistance in charging. In view of the insulation of the apparatus that is needed for the usual condition of operation and to withstand the inevitable accidents which cause severe surges from time to time, the use of graded charging resistance would be a needless and inconsistent precaution. It is sufficient to say that it could be done if it were desired.

What is actually done is more reasonable. A relatively large value of resistance is used in the charging circuit, limiting the current to a range of 5 to 15 amperes. Charging resistances are an intrinsic part of aluminum arresters as now manufactured. Strong recommendations have been made to operators to add them to their older arresters. A characteristic answer is to the effect that "our arresters have been charged through a gap for six years without trouble, and we are satisfied." The change is brought about not by reason of surges, unless they cause telephone interference, but rather on the ground that the arrester is made more immune from damage to itself.

In foreign countries, with their water jets and resistance types of arresters, the controversy over arresters still waxes as warm as it did here in the formative period some eight or ten years ago. The following argument is advanced against the aluminum arresters: admitting that the charging resistance does away with the surges, what about the heavy strokes which cannot pass through the charging resistance and therefore jump the main gap directly into the cells to ground? To anyone familiar with the practise here up to 1913 an answer is unnecessary. If this discharge path were a menace, devices could be used to mitigate it. The nature of the menace can be understood by a review of the past practise. There are several thousand aluminum arresters in use that have been charged through a gap without series resistance. Good practise now condemns the method, but there it is. Ten seconds' charge a day produces over a thousand makes and breaks. There would therefore be more than a million total made per day and more than a billion in a few years. Judging by the rare cases of trouble in this vast number it cannot be much of a risk to allow a few discharges per year to pass directly to ground through the aluminum cells, especially in face of the fact that such a surge is so dangerously large that it cannot be relieved through the resistance, and therefore the surge itself is an undoubted menace to the insulation as it runs wild over the electrical system at 186,000 miles per second.

The status of the aluminum arrester, therefore, is that of a device founded on the solid principle of a safety valve. It has definite limits of maximum current discharge rate and of energy absorption, beyond which damage to the arrester will result. In this respect it is no different from other standard apparatus. Years of experience have demonstrated that these limits are far above the usual demands of practise, but naturally it is not impossible to pass them. The flexibility to meet special conditions is great. Film area, internal resistance, relative gap settings, external resistance—all are readily adjustable to the demands which may possibly come as our knowledge of lightning and other surge phenomena is increased.

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DISCUSSION ON "THE PRESENT STATUS OF ALUMINUM-CELL LIGHTNING ARRESTERS" (CREIGHTON), NEW YORK, FEBRUARY 27, 1914.

**V. Karapetoff:** I would like to ask Dr. Creighton whether he has had any experience with the glass condensers and valves made in Switzerland and known there as the Moscicki condensers and Giles valves.

**F. W. Peek, Jr.:** It is some time since I have been actively connected with work on the aluminum lightning arrester. A number of years ago I had the good fortune to be able to make a study of lightning and the operation of the aluminum arrester on a practical line in Colorado. We had the co-operation of one of the operating companies in the experiments on this system, which was high up in the mountains. It was a 17,000-volt network and a 50,000-volt main transmission, with a 50,000-volt idle line upon which to experiment. Various forms of lightning arresters had been tried by this company without success. It was practically impossible to continue operation during a storm. At this time the aluminum arrester was very new and we did not intend to make use of it as a practical protection; our idea was to make a study of lightning itself. However, in an attempt to improve operating conditions it was decided to install a few aluminum arresters. These arresters could not be obtained from the factory at that time. It was a very difficult country to get into. A sufficient number of aluminum cones was obtained, however; containing tanks were built in the mountains, and the electrolyte was compounded from chemicals bought at a local drug store. An arrester was thus built up and put into operation, and it did very good service. It was decided to install a few more. At a later period in the season these were obtained from the factory and were distributed to various substations. During the latter part of that season there were very severe storms and very little trouble. Many improvements have since been made in the arrester, notably in the electrolyte and in the addition of charging resistance.

The aluminum arrester is the only arrester at present that can take care of a condition of high-energy lightning discharges of moderately steep wave front or moderate frequency. This is often the only condition; generally the prevailing one that must be met. Good protection is thus obtained in the majority of cases, with an occasional miss during the season. There are certain conditions, generally in the minority, but which occasionally on a few systems are the prevailing ones, which no arrester with a gap can, unaided, satisfactorily take care of. These conditions are:

1. Lightning impulses of exceedingly steep wave front and high voltage.
2. Impressed high frequency of a voltage insufficient to discharge the gap.

In condition (1), the dielectric breakdown time lag of the gap may prevent discharge of the arrester before discharge takes place at some weak point in the system.

In condition (2), discharge does not take place at the gap because the voltage is not high enough, but the oscillations may build up high voltage internally in an apparatus containing inductance and capacity.

Both conditions (1) and (2)—which may be considered as more or less special—may be taken care of by the proper arrangement of resistance, inductance and capacity.

Good engineering requires as high system insulation as is economically possible, with the weak point at the lightning arrester.

**L. C. Nicholson:** Electrolytic lightning arresters are coming to be very widely used, and I think by this time they are recognized as the standard type of station arrester.

Frequently the question is asked—Are they efficient? Are they necessary? We operating people reply by saying, " Yes, they are necessary, if you think so," the result being that most of us are afraid to leave them off. As far as I am acquainted with the operating results of this type of arrester, there is seldom any apparatus damaged when protected by such an arrester, and I will also say that when the apparatus is not protected by such an arrester, there is very seldom any damage. So it appears that the arrester is all right. Except on extremely highly insulated transmission lines, damage to high-tension apparatus in the station by lightning is rare.

Usually lightning effects are so localized that the line has its own trouble and keeps it. I am acquainted with an installation which uses a pretty wide gap between the line conductor and earth, say 100 per cent over voltage, which discharges once a year, and which seems to be about all the protection that the station apparatus really needs, judging from the fact that no station apparatus has been punctured. I am acquainted with other stations which have electrolytic lightning arresters and which are not troubled by lightning and I am acquainted with some which have electrolytic lightning arresters and are troubled by lightning, so that it is very much of a question as to whether lightning will or will not do damage under certain conditions of station protection.

At least, the aluminum electrolytic lightning arresters have been developed to a point where there is no longer any danger of their exploding or giving any trouble on their own account if properly cared for, and the usual station attendant, with sufficient instructions, can properly care for the arresters and keep them in proper service. I feel sure that the addition of charging resistance has been of great benefit to the operation of this arrester.

The pity is that these arresters cannot extend their influence beyond half a mile from the station. In most cases the trouble is beyond that point.

**C. O. Mailloux:** Reference has been made to the character of the "front" of the wave which strikes a line or a portion of circuit protected by lightning arresters. It is known that the vertical front of a wave may be flattened out and sharpened to a point, so to speak, in passing through a reactance. It would seem therefore, as if one might expect that the character of the wave-front would depend somewhat upon the distance from the apparatus at which the lightning strikes the line. One might expect that the lightning striking the line very close to the lightning arresters would produce a current-wave having a squarer, straighter front, a more vertical one, than if it struck at some distance, owing to the difference in line-reactance. It may be that in most cases this would not make much difference. In any case, it should be possible to alter the wave-front, to some extent, by the introduction of artificial reactance.

**C. P. Steinmetz:** I wish to refer to only a few features. Setting aside failures of insulation due to weakness or poor design of bushings, insulators, etc., it occasionally happens that even a good lightning arrester fails to protect coils of transformers. The explanation of this is a feature which I have endeavored to make clear in my paper. These failures mean merely that when we speak of lightning we do not know the nature of the surge, and it is necessary to make such studies as will determine it—why at times the surges cause damage and other times they do not.

The aluminum arrester, with a gap in series, may protect against any surge which reaches the aluminum cells. Any disturbance of a voltage less than that which will jump the gap and thus reach the aluminum cells naturally cannot be absorbed by the aluminum cells. Therefore, if we have a high-frequency oscillation of a voltage sufficiently low not to jump the spark gap and incidentally sufficiently low not to do any damage to the line, such a voltage may not be able to do harm to the insulation from line to ground, but when massing of the surge occurs in a few turns of reactance, such as a single coil of a transformer, it may do very great damage, because, while the apparatus is designed to stand the line voltage, it is not designed to stand half the line voltage across say one-hundredth or one-thirtieth of the circuit. The main trouble due to high frequency comes from the local massing of voltage across the reactance.

In speaking of high frequency we may refer to various different effects, and we also usually mean a thing which is not high frequency at all, is not even oscillation—it is steep wave front. A steep wave front, to some extent, causes the same trouble, namely the same massing of voltage, but in other respects it is very different. Some types of protective devices, like the multi-gap arrester, are very sensitive to high frequency, and will discharge high-frequency surges of voltages much less than the operating voltage, but they are not sensitive to steep wave front and may allow steady voltages of steep wave front to rise far above the circuit voltage without discharging.

Another illustration of this difference is given by the application of a condenser. Where there is very high frequency, a condenser shunted from line to ground may bypass or practically short-circuit the high frequency, but where there is a unidirectional wave the condenser will take a charge and thereafter offers no obstruction to the rise in voltage.

We must realize that electrostatic capacity is not a lightning-protective device—is not by itself a protection. A capacity from line to ground merely is a thing which will charge and store the energy. The storage is transient and the energy in the condenser must be returned to the circuit. Thus the condenser in the line will have no effect at all on steady voltage, or on low frequency. The favorable action the condenser can have is apparently to short-circuit disturbances of relatively high frequency.

Such disturbances, in my opinion, are rare, if they exist at all on transmission lines. For the reason that the capacity of the transmission line is so large, compared with the capacity which can economically be provided for in a condenser, any small condenser which can be shunted across the lines at the station would not be capable of appreciably short-circuiting the surge. Thus the high-voltage and the high-frequency disturbances of such volume and such current as can come in over the line are not cared for by any condenser of practicable size.

It is different when the surge comes from the other direction—that is, where the high-frequency disturbance comes from the station. In the transformer, as in the line, the circuits have distributed inductance and capacity, but in the transformers the inductance is very much greater, and the capacity very much less than in the line, and therefore the ratio of voltage to current of the disturbance is very much greater. In other words, capacity has an appreciable effect on a traveling wave, when the capacity is shunted around the high-potential windings of the transformer.

The value of capacity in protective devices lies in the fact that it is a barrier against the passage of current at machine frequency without being a barrier to the passage of surge currents which are inherently of high frequency. Under these conditions it is possible to use a resistance of low value in series with the condenser without absorbing any appreciable power at machine frequency. At high frequency, however, the power factor approaches unity and the maximum possible energy of the surges is absorbed. Thus it is seen that it is not the capacity in itself that is protective, as the voltage absorbed by the capacity at high frequency is negligible, but it is the capacity allowing a properly proportioned resistance to give protection by absorbing the energy of the wave.

This is the condition in the aluminum electrolytic cells, where there is a high equivalent resistance in series with the natural capacity of the cells.

The capacity of the aluminum cell gives a moderate power factor at average machine frequency, but when there is applied a frequency of 100,000 cycles, the power factor of the aluminum cell is practically unity, that is to say, practically all the high-frequency current which goes through the cell is dissipated as energy and does not store itself as energy to be turned back into the circuit, as would be done by a simple capacity.

I believe that the action of the aluminum cell can best be represented by calling it a counter-electromotive-force device. It acts as a counter-electromotive-force shunt between circuit and ground after the voltage has reached a definite value. Up to this definite value, *i. e.*, discharge voltage of the spark gap, it is an open circuit, and beyond that voltage it is a closed circuit. In the closed circuit condition it has about the same effect as if in a d-c. system you shunt a storage battery from the trolley wire to the ground. If you connect between the trolley wire and ground a 600-volt storage battery, then no lightning or any other disturbance will be able to raise the voltage of that trolley line appreciably above 600 volts, because any attempt to raise the voltage would merely cause a discharge through the storage battery. The discharge rate depends on the internal resistance and voltage above the polarization of the storage battery; so it is in the aluminum cell, where the discharge rate depends on the voltage in excess of the polarization value and on the internal resistance of the cell, which, as we all know, is very low.

Now, as to the possible danger from the use of the aluminum cell, which has been especially discussed by those who have had very little practical experience with it—that is, the question whether it may produce high-frequency oscillation. One argument against the production of high frequency I have mentioned already: the power factor of the aluminum cell is unity and it has no capacity effect at high frequency, but it gives a thoroughly damped circuit of a resistance which prevents oscillations. But from another view-point, the best comparison is that given by Professor Creighton—it is a safety valve from line to ground, of very high discharge rate.

We would not think of installing a high-pressure steam boiler without a safety valve, and still, many of us know that every once in a while you hear that a safety valve is really a source of danger, because if a steam boiler is superheated, and water is low, and just at the point where it is near blowing up, and if the safety valve operates, then the sudden shock of the safety valve opening may set off the explosion. But that is no reason for saying that it is unsafe to use safety valves and that all the steam boilers should be operated without them. It is exactly the same case with the aluminum cell or any protective device. If you protect the system against over-voltage, and if the energy back of the over-voltage is very large, it means that to relieve the over-voltage strain we have to provide a device with a high discharge rate, and the sudden coming into play of that high discharge rate, which is required to relieve the strain, means a sudden shock to the system, and if you are near the breakdown point, that very shock may cause a breakdown.

But it has been said that it is not necessary to have a free discharge, and that a resistance may be inserted between line and ground—a critical discharge resistance which will gradually relieve the voltage without oscillations. That is very nice. By so doing the shock is removed only by keeping the excess voltage on the line and the apparatus for a considerable time, and for the time, in fact, that it takes to discharge, and since the disruptive strength depends on the time of applied voltage we wish to relieve, we must conclude that we are between two extremes. We have a condition of excessive voltage brought on by lightning or other disturbances. This voltage is dangerous, is certain to destroy apparatus and line if it stays long enough. We may gradually relieve, or we may suddenly relieve, but since the voltage is certain to destroy, the most effective way is to relieve it as quickly as we can, even if in the extreme case the very suddenness of the relief may accelerate the damage, which is, however, very improbable. I do not know of any instance where this has occurred, and I think the point raised in this connection is more theoretical than actual.

There is one point I want to mention about steepness of wave front. The steepness of wave front depends on the distance of the place from the point where the wave originates. Theoretically, if you calculate transient phenomena of the line, you will find, by an equation, that the wave shape is so steady that the wave starting as a steep wave front retains its steep front all over the line. Practical experience shows that this is not so, and that is one of the various points where theory and calculation do not agree, or where, in our theory, we make an assumption which we find is not warranted—that is, we assume the effective resistance and effective conductance to be constant, independent of the frequency, while in reality every decrement increases with increase in frequency.

If you assume that the effective resistance of the line is a function of the frequency, increasing with increasing frequency, then you would find in the equations (if the equation did not come out so complicated) which so far have been beyond the mathematical skill brought to bear upon them, that the steepness of the wave form decreases with increasing distance traveled by the wave.

But while the equations have not yet been solved to give the values of the increase in resistance of the line, experimental evidence is available. There were some very interesting tests, for instance, made by Mr. Faccioli some years ago, on the wave produced by opening the high-tension switch in a 90,000-volt circuit. In that case, at and near the point of opening of the switch, the steepness of the wave front was such as to give, across a choke coil the inductance of which was equivalent to 50 feet of line, a potential difference of 30,000 volts, but the same size of coil on the same line at 20 miles distance, gave no appreciable steepness of wave—that is to say, in the switching test there was no discharge on the spark-gap shunted around this small reactance. Within 20 miles of travel the wave front changed from an extremely steep one to a very flat one. This is the experimental evidence of the high resistance offered by the copper line wire when the potential is suddenly applied.

**E. E. F. Creighton:** I feel that there is no need to say anything further about the Moscicki condenser, in answer to Dr. Karapetoff's question, as Dr. Steinmetz has already covered the subject.

I am glad that Mr. Nicholson has thrown a little spice into the controversy by speaking of the cases where apparatus was not damaged and the arresters were installed, and also cases where the apparatus was not damaged and the arresters were not installed. Each one of us speaks from his experience, especially his own personal experience, and Mr. Nicholson, I take it, is speaking from his. If I may be permitted, I would like to analyze some of the conditions under which he has been operating and then contrast them with some other experiences which have been gained on other transmission lines where the conditions are different.

On that particular system to which Mr. Nicholson referred there was, a few years ago, an almost insurmountable problem of keeping the lines operating during thunderstorms. I have the greatest admiration for the way in which Mr. Nicholson has attacked this problem and obtained a workable solution. The point of it was that the insulators on the line had not only less factor of safety than they needed, but they punctured, and where every insulator on the line is a lightning arrester it is quite true there is less need of lightning arresters in the station. Under these conditions the principal need of a lightning arrester in the station is where the lightning happens to strike in the neighborhood, and that, I think, corresponds to Mr. Nicholson's remark that it is too bad the lightning arresters cannot reach out more than a half-mile from the station. I should say that it is too bad the lightning is so terribly concentrated at points on the line. That represents, to my mind, the experience gained in that particular case.

On two other lines I know of, where the insulation of the lines was made for operation at 100,000 volts and the operating voltage was only 20,000 and 40,000 volts, the results were quite different. Since the factor of safety of the insulators was about 10, they were not functioning as lightning arresters or protectors for the apparatus, and consequently every lightning stroke that appeared on the line came with horrible impetus into the station. Switch bushings, transformer bushings, and other insulation that had withstood the conditions of other circuits, immediately began to break down from flash-over or by puncture. Lightning arresters of the best type were then required.

This is a condition that is gradually growing all over the country. Everywhere operators find that insulation on the line is an important factor, and are increasing the factor of safety in the line insulators. Personally, I would never use a factor less than three times normal potential, preferably still higher. The extra investment in insulators is worth while. This ultimately necessary practise will increase the need of lightning arresters.

The lightning arrester in itself is not a surge protector, but an over-potential protector. The gap setting is 25 per cent above normal operating voltage, and the arrester will operate as a surge protector only after the gap sparks and connects the aluminum cells directly to the line. I am somewhat disappointed that there has not been more adverse criticism, as our foreign friends are finding a great many things to say. I feel that any criticism or any failure of the aluminum arrester to protect the circuit can be explained by some weak local condition, or, otherwise, the design of the arrester can be easily modified to meet new conditions. As Dr. Steinmetz has so well emphasized today, the great need at the present time is more definite information. A few years ago it was a very common thing to have bushings fail on transformers and switches, but today, due to the presence of the aluminum lightning arrester, these faults have almost entirely disappeared. Those that have not disappeared I hope to be able to give a reason for, at some not far distant time, as a result of the study of porcelain insulators at high frequencies. Porcelain insulators and bushings have a different strength at 60 cycles on which they are usually tested, from their strength at very high frequencies, such as 200,000 cycles per second—or its equivalent, expressed as steepness of wave front.