Discussion on, "High Power Surges in Electric Distribution Systems of Great Magnitude", and "An Experimental Study of the Rise of Potential on Commercial Transmission Lines, Due to Static Disturbances such as Switching, Grounding, Etc."

H. G. Stott: In opening the discussion on the two important papers presented this morning, I think very little can be added to either of them, except to outline what has been done in the endeavor to prevent a repetition of this very disastrous rise of potential which, besides putting one generator out of commission for a week or two, destroyed the insulation on, I think, 13 cables. Each of these cables was punctured in one, two, or three places, apparently without relation to their distance from the power-house. Singularly enough no damage whatever was done in the sub-stations. After that occurrence the Interborough Company took up the matter with both Mr. Steinmetz and Mr. Thomas, who aided us in proposing different methods for preventing such a rise, and in the general investigation of the whole subject.

In the first place it has been invariably noticed that the static ground detectors indicate the presence of a ground on one phase before a short circuit occurs in the feeder. The indication might come from 5 to 25 min. before the short circuit occurs. In this case the indication was given several minutes before the short circuit took place, as shown by the fact that the sub-stations telephoned to the main power-house that they had static display on insulators, oil-switches, etc. From this it seems that if the cable which had the ground in it could be isolated and cut out of service before the current had burned the insulation on the neighboring phases no damage would be done. With something like 35 feeders it is a very tedious process to isolate a feeder having a ground, as it would not be possible to test all feeders in less than 45 min., because an oil-switch would have to be opened at each end of each feeder; meantime the sub-station would have to be communicated with and arrangements made to carry the load on other feeders. If the feeder in question happens to be the last one to be tested it might be 45 min. before it would be reached; chance might determine that it be the first one tested, but this kind of good luck is rare.

If the feeder in trouble were isolated what would happen to the lead sheaths on the surrounding cables in the manhole? If the short circuit occurred in a feeder would the feeder not be carrying more current through the lead sheaths than they would safely stand? and would the short circuit burn places through these lead sheaths, especially in the manholes where there is more or less ground on the cable hangers? In order to get around that we have put in a resistance of large carrying capacity, one with a resistance of 6 ohms, and a rated capacity of 1 000 amperes for 2 minutes. The reason for this is, of course, the Y voltage is approximately 6 300 and sufficient current must pass through that ground resistance, and through the ground which might occur at any future time, to make certain of opening the oil-switch on an overload. That in itself will evidently discriminate and pick out the bad feeder immediately, and ought to do so at both ends simply by the use of plain overload relays on each end of each feeder. This system is now installed. Putting the system into service has been delayed by the fact that two power-houses are operating in multiple, and grounding one set of generators without the other has been purposely avoided. In future it is expected that any cable which grounds will be cut out of service automatically long before it can do any damage.

Another point which was brought out very strongly by Mr. Steinmetz was that we ought to guard in every way possible against the open arc. This is well taken care of in an oil-switch, as more than three and one-half years experience under all conditions of operating have failed to shake confidence in the ability of the oil-switch to perform its functions satisfactorily under the most severe operating conditions.

In the ducts the cables are enclosed so that a flaring arc is impossible. We have never seen any indication of a rise of potential from a fault which happened in the duct. The only case where we have had a rise of potential—there have been several—has been where the arc was free to play in the air, so that the cables in the manholes were the weak point.

After a great deal of thought, it was decided to surround these cables with an iron sheet which would probably be heavy enough to withstand the short circuit incurred until the oil-switch opened, and so prevent a flaring arc. These cables were already covered with two layers of asbestos tape wrapped spirally in opposite directions, and then wrapped with steel tape. Covered as they now are with an iron sheath, every cable is completely enclosed. Since covering these cables—they have been covered now for some time—short circuits have occurred, but there have been no indications of a rise of potential in the manholes where they are covered.

There is another advantage to be gained by the grounding of the neutral, which is this: the Y points of the generators probably have zero potential relatively to the earth, in fact tests show that there is no perceptible difference of potential whatsoever. That of course is due to the effect of the balanced system, free from disturbances at the time. What the result might be during short circuits is of course difficult to foretell, but by grounding the neutral the sudden change of potential from zero at the neutral to zero on one of the phases is prevented. It seems to me the effect of sweeping a charging current, of something like 160 amperes, across the generator windings (that is to have a capacity current traveling through inductance), must result in a large rise of potential in the generator windings. On making the ground connection, the charge will sweep backwards and forwards across the generator windings from the zero point to the phase which is being grounded. That in itself will, I believe, cause a very serious rise of potential on the generator.

P. N. NUNN: The papers by Mr. Steinmetz and by Mr. Thomas apply to the weakest spot in the weakest branch of electrical work. The question is frequently asked by investors and business men, how far is it really practicable to transmit power electrically? They are usually referred to what is being done in Canada, in Washington, in California, and in Mexico. But when it is asked whether more or less trouble is not being experienced in the operation of the plants the electrical engineer has no clear and conclusive answer.

The time was when it required a machine shop to operate a few motors, and an expert winder to operate generators. To-day the mechanical apparatus involved in the application of electrical power has been perfected to a greater degree of continuity of service and to a lesser cost of maintenance than that of steam or water-power. The transmission has reached no such perfectness. A few years ago the limiting factor was the transformer; nowadays just as reliable transformers are built for 60 000 and 80 000 as for 5 000 or 10 000 volts. Later the question became how to construct the insulator, and 75 cents each seemed a large price. To-day we cheerfully pay $3.00 or $4.00 for an insulator which is reliable for 60 000 volts, perhaps for 80 000 or 100 000 volts, yet the history of daily transmission operation impresses one with a feeling of uncertainty.

The simple pole line carrying three or six wires, has given place to the more complex transmission system with trunk lines in parallel or in triangle and with branches from many points in all directions. A generating system of equal complexity is equipped with apparatus whereby each generator, when in trouble, may be automatically cut off without serious disturbance to the remainder of the system. As yet, however, there is no means whereby a section of a long high-pressure transmission may be cut out without danger of interrupting the whole system.

It is not a question of lightning. If lightning puts a plant out of service, there is some dignity about that; it is an "Act of God". But when an operator in the usual course of operating attempts to cut out a defective section of line, and a moment later finds the entire system shut down, he feels that there must be a glaring defect both in his science and in his application of it to the problems of transmission.

To quote a sentence from Mr. Thomas' paper, " Our knowledge of the phenomena of static disturbances in commercial circuits is in a much confused and comparatively undigested form". Although it seems that we know much of the theory involved, yet this statement appears true. One reason for this may lie in the extreme difficulty of testing the theory and working out the values of its factors upon practical transmissions. 100-mile, high-pressure lines cannot be taken into the laboratory and treated with the exactness and refinement of laboratory methods, nor can research work bear the expense of building long lines for experimental purposes. No sooner is a commercial line completed than it is put into service, frequently without allowing even a few days for test. Therefore opportunities to conduct experiments so prolonged and unbroken and under such constant conditions as those reported by Mr. Thomas are extremely rare.

The expression " without interruption " in Mr. Thomas' paper may be misleading. It is true that the purpose at first was to attempt only such experiments as could be conducted without interrupting or crippling the system, with the result that Mr. Olmsted became so engrossed in the theme that his demands upon both customers and operators became broader and broader, to the serious embarrassment of operating the plant.

To make this discussion the more complete some further tribute should be paid to the memory of Mr. F. D. Olmsted, a Member of the INSTITUTE, who died in September, 1903. As stated in the paper, the greater part of the experiments were conducted on the lines of the Telluride Power Company. Mr. Olmsted had immediate charge of these experiments; and to his personal efforts and coöperation throughout were chiefly due the rare opportunities for making the tests and the completeness and accuracy of the results secured.

S. M. KINTNER: Mr. Steinmetz has given an exceedingly plausible theory, if nothing else, and such experience as I have had with lines of this character seems to bear out that theory. I have made certain laboratory tests, which, as Mr. Nunn aptly states, are exceedingly limited in regard to any conclusions of value that can be drawn therefrom, but which also seemed to verify this same conclusion. I have succeeded to a limited degree in producing an open-air oscillating arc, and in getting excessive voltages therefrom. In only one case have I noticed this in practice on an actual transmission line, and there the data were not sufficiently accurate to warrant accurate conclusions. I was present on only one occasion when these phenomena occurred, although I was told by the operators in the station at the time that they had occurred in exactly the same manner on other occasions. The phenomena occurred in somewhat this order: a ground was indicated first of all on the ground-detectors; the telephone lines paralleling the circuit became noisy; and it was a question of only a few moments when the other disturbance came on, and a voltage much greater than normal, probably several times greater occurred, flashing over the terminal of the circuit as it entered the power-house. The arc that jumped across the open air-space must have had a voltage of two or three times normal value. The question of the steepness of the incoming wave, as Mr. Steinmetz has pointed out—his reduction of this to a certain wave-front steepness, if we may call it such, of a higher frequency circuit—is particularly interesting, and I have found it convenient to employ this same idea of looking at these phenomena though I had not formerly reduced it to a mathematical expression.

I have made some tests along this line in connection with choke-coils for determining their reflective power, etc., in which an attempt was made to produce the same wave-front steepness in each test. This has been a very interesting work, and a very difficult one on which to get any accurate data. The measuring implements for such work are as yet exceedingly crude, and it requires the averages of a great many tests to get any thing like consistent data.

F. A C. PERRINE: When hearing these two papers the first thought was that Mr. Thomas had given data which could be used directly in designing plants, while Mr. Steinmetz had given the explanation of circumstances that may arise, but which can not be guarded against. In this thought the obvious remedy which Mr. Stott has described to us was missed; namely, that Mr. Steinmetz's paper points out that anything that can be done to suppress the third frequency of the train-wave will tend to prevent the occurrence, and anything that can be done to prevent an open-air arc on the system will reduce the train-wave to such frequency and amount that its effect cannot be destructive.

Though, of course, the method that Mr. Stott has proposed of making cables always enclosed so that no open arcs of high enough frequency can occur to produce destructive effects, may be applied to certain systems, it may not be applied to others. One of the first and most serious occurrences of this nature to which my attention has been called happened in California, where a destructive arc occurred at the time when an oil-switch under short circuit was opened and blown to pieces by the arc, the oil scattering over the station. At that time the surge is said to have produced inductive currents in the iron structure of the power-house, so that one could see flashes all over the roof. There has been another occurrence in Hartford, experiments I think, performed under Mr. Steinmetz's instructions with lightning-arresters, where they attempted to perform a series of experiments on lightning-arresters attached to an idle line paralleling another carrying a current for lighting a theatre, without interfering with the service, but when the lightning-arresters acted the lights in the theatre went out and people in Hartford were left without light. That is to say the surge was so intense, that it opened the circuit-breakers on the parallel line, without destroying the insulation of the parallel line.

Mr. Steinmetz has intimated that lightning-arresters may stop the generating current very quickly. This difficulty is liable to be encountered, because stopping the generating current which would follow a lightning discharge, with great rapidity, might cause an exceedingly steep wave which might cause this result.

In Mr. Steinmetz's paper there is an observation that I think leads to a possible misunderstanding. He writes of the third frequency of the train wave as being independent of the line constants. He obviously does not mean this. The train wave must have a frequency that is largely dependent upon the constants of the circuits, but which is principally dependent upon the rate of interruption of the short-circuit current. In consequence it is not susceptible of calculation simply from the constants of the circuit, but also one must assume some rate of interruption of the short-circuit current in order to assume the steepness of the interrupted wave, in order to obtain the frequency of the train wave. The effect is exactly similar to the method of producing high rate of alternation by interrupting a circuit of known capacity and self-induction by means of a magnetic blow-out.

We are at this time greatly indebted to the conditions prevailing on the Manhattan Railway circuit which were so simple as to admit of calculation, but more especially to the care with which all the conditions were observed by Mr. Stott's assistants. The calculations given by Mr. Steinmetz are not open to objection if one allows his assumptions as to frequencies. The two ends of the calculations are tied together, and I do not think it can be said that this is in consequence of theoretical reasoning only. There are definite results here.

Finally, Mr. Steinmetz has pointed out the importance of the effect of the static discharge. There is no such thing as harmless static discharge. For a number of years engineers have been observing static effects. People say, "That is nothing but static discharge". But there never has been a static discharge that did not represent defective insulation and a leak. The result of the particular instance considered by Mr. Steinmetz shows how serious may be the consequences following static discharges; which invariably can be prevented by making insulation perfect. Such discharges invariably indicate defective insulation.

Mr. Thomas's paper shows the result of switching, and what may be considered as the worst conditions under switching. In consequence in the paper there is a very clear plan on the basis of which a remedy which can be definitely provided for the matters that are to occur every day. They do not represent, however, the worst conditions that may occur on identically the same lines; for example, the circuits that were made and broken under the conditions described in Mr. Steinmetz's paper.

H. W. Fisher: About 12 or 15 years ago I discovered the dangerous effects produced by breaking the capacity current going to cables. For several years I thought that large disruptive rises in voltage were only produced in power-houses where considerable cable was employed; but recently a rise of voltage of 6 to 8 times the normal was produced in a piece of cable about 20 ft. long. In this case the insulation was broken down but the lead was not punctured, showing that it is possible to get a very abnormal rise of voltage without a direct arc in air.

PRESIDENT LIEB: In connection with these papers I should like to say a further word on a matter that has been referred to by one of the speakers, and that is the extent to which the human element enters into the disturbances that are likely to take place on large transmitting and distributing systems. In the transmitting and distributing system of the New York Edison Company, I believe ten times as many disturbances take place due to mistakes and failures on the part of the operators as to any other cause. One of the serious problems that have to be contended with is to reduce the number of possible mistakes from this cause. In many of the plants of this company it is possible to reduce the number of probable mistakes by interlocking switching gear, and such a method of throwing switches in and out as would make it necessary to follow a preconceived method of procedure, thereby eliminating mistakes in the sequence of operation. But this is not always practicable.

Another important element that should be referred to is the difficulty of starting up large systems when once shut down. That difficulty is, of course, less with a railway system but it is great with a large lighting system; and the proper precautions and method of procedure which should be followed in case of a general shutdown of an extensive system with 20 or 30 sub-stations, with synchronous converter equipments and storage-batteries is a matter of very serious importance. These are systems which, unlike that of the Telluride Company, it is not possible to play with.

The Edison Company has desired to make tests on a large scale of the starting of such a system from a complete shutdown; not temporarily to deprive the whole city of New York of electric light and power but to undertake to start up a generator with converters connected with it, and also with their load. This was done satisfactorily on a small scale recently, by putting New York in connection with Brooklyn and starting up " Dreamland ", at Coney Island, from one of the New York stations; but unfortunately it was on a limited scale. We should like to establish the possibility of doing this on a larger scale, but the requirement of absolute continuity of service does not permit an opportunity of making such a test.

SAMUEL SHELDON: I should like some information from Mr. Steinmetz or Mr. Thomas. As I understand Mr. Steinmetz, the excessive rise of potential upon opening the circuit is due to the high *natural* frequency of the circuit. This high frequency makes the inductance and resistance different from what they would be at ordinary frequencies, and also brings into effect the distributed character of the capacity. The obtaining of this high frequency is dependent upon all of these quantities—the inductance, the capacity, and the resistance. Is it not a fact that upon opening a circuit the resistance becomes the determining factor, and that the resistance of the arc, varying as it must because of air current fluctuations and of its temperature, is the determining factor that gives rise to these high frequencies?

CHAS. P. STEINMETZ: My conclusion is that the origin of the disturbance and of the breakdown was due to the high-frequency oscillation of the traveling wave. But the high voltage was due to the oscillating short-circuit of the cable caused by the traveling wave, and was not an effect of distributed capacity, but due to an oscillation of massed capacity (that of the cable system, which has very little inductance) and massed inductance of the generating system. In this latter oscillation, the frequency was low and the destructiveness great, but it would never have started if there had not been a very high-frequency traveling wave preceding it.

P. H. THOMAS: In spite of the unusually full detail available in this case, it is impossible to establish any particular theory of the phenomena as the correct theory. As is almost universal in such cases, it is necessary to consider all possible theories and to accept provisionally that which seems most reasonable and most nearly fits the observed facts.

One cannot consider that the theory put forward in this paper, involving a self-interrupting arc, to be *demonstrated* to be a correct theory of what took place. This explanation may or may not be the true one. Personally, it has always been very difficult for me to conceive of a series of rapid self-interruptions of a very severe arc associated with an extreme rise of potential at the point of interruption, such as assumed in the paper. On the other hand, it is a fact that very often things that are not easily understood may, nevertheless, be true.

The extremely rapid heating and cooling of the gas which is taken to have a more or less steady condition of interruption, together with the fact that such a large majority of severe arcs occur without noticeable rise of potential, make it seem probable that in those cases, such as the present instance, in which a rise of potential is actually observed there is some other condition in addition to the presence of the arc, which is really the essential condition causing the extraordinary voltage.

In a considerable number of cases within my knowledge, prearranged for the opening of a short-circuit, apparatus for measuring instantaneous voltages has shown no sensible rise of potential. The opening of the charging circuit to an open-circuited line is another matter.

A careful examination of the details of the breakdown at the Manhattan Railway Co.'s power-house has suggested to me the possibility of another explanation of the phenomena, which differs from that proposed in the paper and does not involve a self-interrupting arc.

Consider the outline of circuits shown in Fig. 1 in which a number of generators in parallel feed three-phase bus-bars, which in turn, feed three-phase feeders, each feeder supplying a group of step-down transformers connected with synchronous converter. Assume a ground to occur on one leg of one feeder, as indicated at the point a; the full charging current of the system then flows from wire to earth at this point. This current is between 100 and 200 amperes. This will produce a certain amount of unbalancing of potential together with a low static noise at the cable heads, which is probably not sufficient,

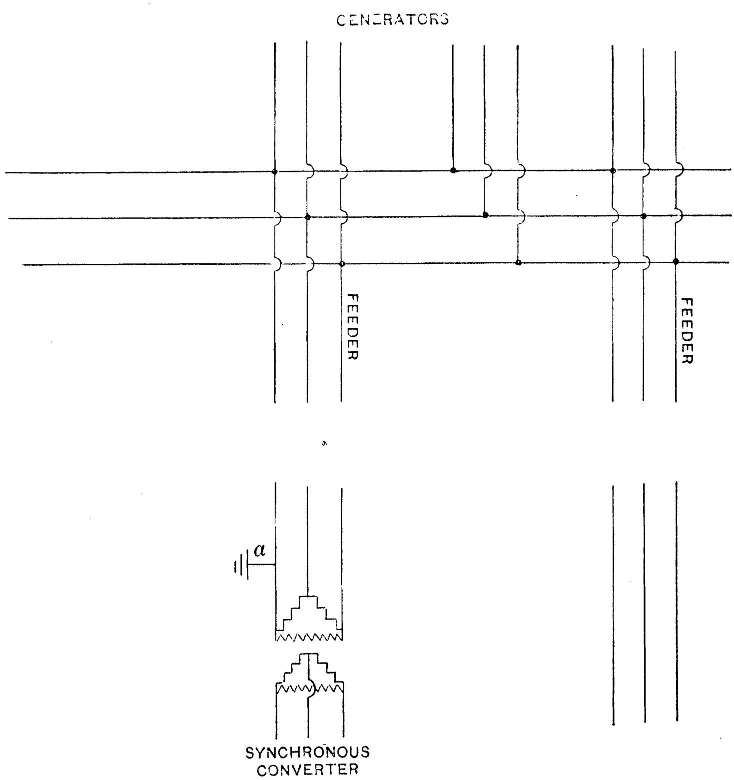

FIG. 1.

however, to account for the hissing observed in the sub-stations immediately before the breakdown. Suppose, again, that this charging current ultimately burns off the feeder at the point a, as shown, and that the charging current to earth continues on the end of the cable toward the converter, but drops out at the other side of the open circuit. The charging current is now passing from ground to the short end of the cable through the step-down transformers to the capacity of the rest of the system, and the leading current passing through the inductance of the transformers, which are built with a large magnetic leakage for the purpose of automatic regulation in the synchronous converters, with the result, provided the frequency be right, that resonance must occur tending to build up a high voltage between line and ground and across the transformers. A calculation of the capacity of the high-tension system and the inductance of the transformers indicates that the frequency of the system is not far from that required for perfect resonance. The calculations do not show, however, that the normal frequency is " the exact frequency for resonance ". The electromotive force supporting the resonance must come in this case from the rotary transformer.

If the frequency be assumed to be somewhere near but not quite that of perfect resonance, there must be a complete building up of voltage to a certain maximum, and then there will be a decrease of the electromotive force as it gets out of step with the resonating circuit, down to normal again; then later a repetition of the rise of potential, and so on indefinitely. If the rise of potential is assumed to be insufficient to break down the insulation at any point, the hissing noise observed in the sub-stations can easily be accounted for; and then if some slight change in conditions of load or speed is assumed to cause a higher resonance rise so that a breakdown occurs, then there occurs a short circuit across the generator, probably on one of the other feeders, or possibly on one of the static dischargers, which may open the circuit-breakers on some feeder other than the one originally causing the trouble. In this case the short-circuit is eliminated and resonance will again start, causing another breakdown, and the opening of another circuit-breaker, and so on until the entire plant is shut down. According to this view of the phenomena that may occur the large number of breakdowns are accounted for by the permanent condition of resonance, which causes breakdowns and short circuits, the short circuits being immediately cut out by circuit-breakers. Naturally, the damage is finally stopped by the shutting down of the plant.

It should be noted here that it would be likely for the cable that was originally grounded to remain in circuit, since it was grounded and not short-circuited. On the subsequent starting up of the plant this cable would operate properly for a time until some circumstance causes the ground to be re-established, in which case a second resonance condition would be established, as in the first case, causing other breakdowns. A second breakdown actually followed a night after the original breakdown, and, subsequently, a cable was found with one wire open-circuited, but without short-circuit between conductors as has been assumed above.

Mr. Stott has stated that in many cases cables that have been grounded and seriously burned have subsequently failed to break down on test until as high as 20 000 volts between conductor and ground has been reached. This statement should be taken in connection with the assumption above that it was feasible to operate with one leg open-circuited and a puncture to ground. In this connection, it is important to notice that the synchronous converter at the end of the first injured cable will presumably keep in step in view of the fact that one phase remains intact, even after the opening of one leg at the point *a*. As a natural result, the open end of the conductor on the injured cable on the side toward the generator will not receive the potential to ground that is impressed upon the rest of the system, by an amount equal to the generator voltage.

A careful detailed study of the different arcs and punctures indicated that the results could all be readily explained by the presence in the circuit of abrupt changes of potential of not over 40 000 to 60 000 volts. In a number of cases considerable air-spaces apparently were jumped, but it seemed always possible that the original exciting spark causing the arcs started by a discharge over the surface of the insulation, and that the same subsequent arc so transferred itself to some other point as to give the appearance of having jumped a considerable distance. According to the above theory the breakdown in the cable at the street was the last rather than the first of a long series, as assumed in Mr. Steinmetz' theory. This subject is of sufficient interest and importance to warrant a much fuller discussion of the phenomena, but the above outline of an alternative theory is all for which space will be taken here.

A similar occurrence of less magnitude, in Berlin, has been described in an electrical magazine. Investigation and discussion of the accident showed conclusively that a cable system was made to resonate through the inductance of a small step-down transformer on account of the opening of one leg of its feeder. In general wherever it is possible for one leg of a circuit, supplying apparatus containing inductance, to become opened without the complete cutting off of the apparatus, there is a possibility of resonance, if the system has a considerable capacity, as will usually be the case with underground systems. This is a real danger, though it will not often be met with because only occasionally will the constants of the circuit be such as to cause resonance with the normal frequency of the generator.

Every engineer operating a plant should make calculations to determine whether any of the circuits contain the proper amount of inductance and capacity to resonate at normal generator frequency in case an accident should occur that might produce the necessary electrical connections. Usually it is easy to avoid the danger.

CHAS. P. STEINMETZ: To refer to the last question first: I have also been of the opinion that fuses are not permissible in a very high-voltage transmission system. However, in the last years we have made a number of tests with fuses in cutting off branch-lines of moderate power in large, high-capacity and high-voltage systems, and found that with certain types of fuses the oscillograph showed practically no voltage rise; that is, these fuses apparently did not cause instantaneous rupture, so that for branches of systems, (not the main line), that carry only a moderate amount of power, and for which, therefore, this elaborate and expensive system of control by automatic oil-switches, etc., is rather undesirable, the question of fuses may be reconsidered. I cannot yet say that I should recommend it broadly, but it may be taken into consideration in special cases.

In regard to Mr. Thomas's paper, I believe the statements made by Mr. Thomas on page 320 are important general discussion of the phenomena resulting from what I call wave-trains, or traveling waves, and of which in my paper, I endeavored to give the general outline of the theoretical equations; that is, oscillations resulting from a disturbance in a system of distributed capacity and inductance. I have not had time carefully to digest Mr. Thomas's paper, but it seems to me from the data of tests given therein that the phenomena observed by him were not so much the phenomena of a traveling wave as the phenomena of a surge of the system of fundamental frequency. The observed distribution of potential along the circuit, rising from the end where the switching takes place, towards the end where the circuit is open and the wave reflects, is the distribution of potential on a circuit resulting from a sudden change of circuit condition. This consists essentially of the fundamental wave but it is not the same as the traveling wave to which I have referred above. This would also account for the observations on branch lines, that the triple and quadruple voltage that a traveling wave should give on a branch line was not observed by Mr. Thomas, but that the branch line is merely a localized capacity oscillating together with the rest of the system. I had occasion to carry out investigations of this character a few years ago on a transmission system at Kalamazoo; but there I was able to double back a number of lines so as to get a considerable capacity, and also to choose the load, and to experiment with a non-inductive load, and with a load of very high self inductance; that is, a load of very low power-factor, and with a combination of both. I got rises of potential, with an impressed electromotive force of 30 000 volts, showing peaks of 100 000 to 118 000 volts. In these experiments I got a surge of the fundamental frequency of the system. I believe that the observations recorded in Mr. Thomas's paper are mostly of the same character.

A number of causes of such disturbances are mentioned on page 322, but what I consider the most important cause; that is, the oscillating or self-rupturing arc, is not given, possibly because Mr. Thomas is not quite satisfied with the existence of such phenomenon.

There is, however, no doubt that an alternating arc may be self-rupturing; that is, blow itself out with extreme suddenness. Such a self-rupturing arc becomes an oscillating arc if the supply voltage of the circuit is greater than the striking voltage of the gap between the arc terminals; that is, after the rupture of the arc, the supply voltage, by striking across the gap, restarts the arc; it again ruptures itself, to be restarted, and so on. As seen, the oscillating arc is a natural consequence of the self-rupturing arc.

This phenomenon of the self-rupturing arc was first brought to the attention of engineers a number of years ago by Mr. A. J. Wurts, in his paper on non-arcing metals. The discovery of the self-rupturing alternating arc announced in this paper has not made the impression it deserves, possibly because it was coupled with the announcement of a new form of lightning-arrester, and also because the conditions under which the phenomenon occurred were not completely known. As a result thereof, when repeating the experiments myself it frequently did not succeed. For instance, in starting an alternating arc between non-arcing metals, with a non-inductive resistance in series to limit the current, the arc is not self-rupturing, but is maintained.

This feature of self-rupturing arc is, however, now extensively used in lightning-arresters, and is practically the only known method of producing oscillating currents of very high frequencies. It occurs not only with the non-arcing metals, but more or less with all metals, and even with electrolytic conductors, and is, I believe, the explanation of the action of the electrolytic, or Wehmelt, interrupter.

The conditions most favorable for the production of an oscillating arc are that the flow of current the instant after the arc strikes is practically unlimited, and that after the striking of the arc the voltage drops practically to zero, and remains low for a finite, even if extremely short, time after the rupture of the arc. The first condition is fulfilled by a condenser or equivalent device in shunt to the arc; the latter by an inductance in series with the arc and the condenser. When the arc strikes, a larger rush of current, (the discharge current of the condenser) passes, and since, due to the series inductance, the supply current cannot instantly rise, the voltage drops. At the moment of rupture of the arc, the supply current still continues to flow into the condenser, and the voltage across the arc-gap therefore remains low, rising gradually while the condenser is being charged. If the supply voltage of the system is greater than the striking voltage of the gap, as soon as the latter voltage is reached, by the jumping of an electrostatic spark, the arc is restarted, and ruptures itself by the explosive effect of the sudden heating due to the condenser discharge, etc., and so the arc becomes oscillating. As seen, then, by reducing the arc-gap, the striking voltage, and thereby the time required for the condenser to be raised to the striking voltage, is reduced; that is, the period of open circuit of the arc-gap is decreased; and because of the decrease of the condenser discharge resulting from the lower voltage, the duration of the arc flow is also reduced; that is, the frequency of oscillation is increased. I especially desire to call attention to this very interesting feature of an electric circuit, in which the frequency of oscillation not only depends upon the circuit constants, inductance, capacity, etc., but also very largely upon the length of spark-gap and supply voltage; the frequency of oscillation increases with decrease of the gap-length, with increase of supply voltage, with decrease of capacity and of inductance. The frequency can be varied by varying the length of the spark-gap. As is well known, this is the usual method of varying the frequency in apparatus for producing very high-frequency oscillating currents.

It is obvious now, how an alternating arc, with resistance in series with the arc, cannot well be oscillating, since coincident with the breaking of the arc the voltage would reappear at the arc-gap and so keep the arc from breaking. It also shows how the discharge between a conductor of a cable system and ground is specially liable to be oscillating, since with the passage of current between ccnductor and ground the potential difference that produced the discharge, disappears by the grounding of the conductor. The meaning and the effect of the inductance in the electrolytic rectifier, etc., is now easily explained by considering its action as due to an oscillating arc.

Under conditions like or similar to those described above an arc is oscillating, not only in an alternating-current circuit, but also when the supply voltage of the curcuit is constant or unidirectional.

The phenomenon becomes somewhat more complex when instead of the localized capacity and inductance, as described above, a circuit of distributed capacity and inductance is considered as in my paper. In its general character, however, the phenomenon is essentially the same, and an attempt at a mathematical investigation has been given in my paper.

Speaking in favor of this explanation of the oscillating arc, a rather strange coincidence is patent in Mr. Stott's statement that short circuits were almost always preceded by ground and static displays.

In regard to the numerical values given in my paper and in Mr. Thomas's paper, it is obvious that these values must be considered only as approximate, or restricted to the conditions under which the tests, or the assumptions, were made. Especially is this the case with the frequency of the traveling wave. This frequency is merely assumed by me, and it may be different.

The numerical values of the voltage rise given in Mr. Thomas's paper, I believe, do not mean that the voltage can never rise more than 30% or that it will always rise up to 30%. In all such cases where numerical values result from definite experiments they must be considered as merely showing the character of the phenomenon but not its magnitude. One may observe, for instance, that if the circuit of an electric conductor is closed the conductor rises in temperature by 30° cent. Now the conclusion would be, that the electric current heats the conductor, but not that it raises its temperature by 30°. The numerical value of the effect depends upon the conditions of the particular instance. So here the rise of voltage can not be determined generally, but frequently one can get at least the maximum possible values, and this may be sufficient. If the voltage of the surge were over 100 000, as it sometimes may be, and as I have observed by the oscillograph record, and the current during the surge as high as 9 000 amperes, then there is no chance to insulate and protect against these surges, and the only thing to do is what Mr. Stott has done, to avoid the cause of the surge, by eliminating the continued occurrence of a spark discharge between the conductor and ground, by disconnecting automatically that particular cable in which the spark discharge appears before the damage can spread further and cause the destructive short-circuit surge of the system, of high-power and low-frequency surge.

P. H. Thomas: Mr. Steinmetz in stating that the result of certain tests in my paper does not support the statement that a rise of potential at the end of a short line that is connected to the end of a long line, indicates that Mr. Steinmetz has misinterpreted my experiment. The rise of potential occurring at the end of the short line results only in the case where it acts as a continuation of a longer line, or, in other words, where the wave of the longer line is forced to enter the shorter line. The short line referred to in the test is a branch line and furthermore has the same capacity as the main line. Mr. Steinmetz's statement that the experiments given in my paper show nothing with regard to other line conditions on other plants is, I think, hardly justified. The object of the tests was to verify or disprove certain fundamental laws, derived theoretically. It appears to me that these laws have received a strong confirmation by the tests, which means that they are to that extent applicable to other cases. Because Ohm's law has never been tried for every possible case it is not assumed that it does not apply in any new problem that may arise.