Discussion on "Comparative Tests of Lightning Protection Devices on the Taylor's Falls Transmission System", and "Studies in Lightning Performance, Season 1907." New York, May 19, 1908

H. W. Buck: The valuable data presented to-night include the most comprehensive and systematic record of lightning disturbances which has been presented to this Institute. In the old days of electrical transmission most of the trouble we had to cope with was due to the station apparatus itself, as the insulation of the lines was relatively high. As line voltages have risen with the progress of the art, the insulation of station apparatus has risen in proportion. Presumably lightning stresses have remained constant, so that at the present time we have insulation in our stations which perhaps on the high-voltage transmissions is high enough to withstand the original lightning surges, and the troubles seem to be shifting out upon the line itself. I think that this is the most noticeable feature of this paper. During the storms spoken of in the paper, many insulators were shattered, poles were shattered, and some cross-arms burned, and so on, and yet only one transformer bushing was damaged within the station.

It has conclusively been shown that these line troubles have been reduced by means of the overhead ground-wire. It is shown not only in this particular system, upon which we have the record to-night, but the experience over all this country with transmission lines, where the overhead ground-wire has been installed, shows similar corroborative evidence. There are perhaps three functions of this overhead ground-wire: it takes the direct stroke and it allows the induced charge to accumulate on the ground-wire instead of accumulating upon the transmission wire itself, so that when the cloud which induced this charge discharges itself through a lightning flash the corresponding charge of opposite polarity on the ground-wire can discharge itself through the ground connections on the pole, instead of having to spill over the insulators. Another important function of this overhead ground-wire consists in shielding the transmission wires from induced potentials between phases, due to neighboring lightning discharges, which are presumably of high frequency. The guard-wire forms one side of the circuit and the ground the other, so that we really have a short-circuited shield against induction on the transmission wires—the ground and the shield-wire being connected by electrical connections. If this theory be correct, it would seem to be a decided advantage to have two overhead ground-wires rather than one, a connection being made between these two shield-wires at every pole. Then we should have a shielding effect in the vertical plane and also in the horizontal plane against induced potentials, between the phases in the transmission wires. These short-circuited loops in fairly close proximity to the transmission wires might represent some induced loss on the normal frequency of the transmission system, but I doubt if it would be enough to be very serious; whereas at the frequency of the lightning discharge the possible induced current might be high and give a decided shielding effect to the transmission wires.

The evidence of the spilling over of accumulated charge in the insulators seems to show that the actual magnitude of the momentary current in this ground-wire is very large. I think it would be interesting if some form of current-recording device could be installed experimentally in some of these guard-wires, in order to give an indication of the magnitude of the currents. It would seem that along transmission lines there might be installed in circuit with the guard-wire a crude form of ballistic galvanometer, which would give a record of the maximum current flowing in the guard-wire during a storm. It would tend to indicate what conductivity ought to be established in these shield-wires to take care of discharges, and would give valuable records.

It is quite noticeable from the records of this paper that lightning storms follow certain well-defined paths throughout a region. There seem to be certain sections of the line which have borne the brunt of the lightning discharges; whereas other sections of the line have been practically free from trouble. I think that this accords with the experience of the Weather Bureau, in showing that lightning storms tend to progress along certain well-defined topographical paths. The frequent shattering of insulators as shown in these records indicates the desirability of developing some form of insulator which can withstand such a stress. The problem is a mechanical one, to get some material that can withstand the sudden application of the heat of an arc without it resulting in the insulator being shattered. It is not so bad to have a momentary short-circuit on a system, provided it blows itself out and leaves the insulator in comparatively good condition, but if every time a spill-over takes place the insulator is going to be destroyed, the operative difficulty becomes a serious one.

The horn arrester seems to have assumed a very important function in coping with the lightning problem. It is cheap and easy to insulate, and it can be put out of doors and withstand heavy rains without the insulation being impaired. It can also withstand very violent fireworks without the destruction of any valuable apparatus. In conjunction with the development of the horn arrester the problem of a good form of resistance is brought up. It seems to me that no really satisfactory form of resistance has yet been developed. The water rheostat is satisfactory under some conditions, but it is bulky, and in cold weather there is trouble from freezing. A resistance ought to be developed which can withstand frequent discharges and which can carry without destruction, for periods of several consecutive seconds, a large dynamic current from the generators. With a resistance of this kind, sufficient surge current could flow to ground without necessarily shutting down the system.

It is interesting to note in this paper that certain discharges have been noticed on the secondaries of the transformers. This accords with my experience and with that of other engineers with whom I have talked. I have known of several instances where overhead lines pass through transformers into underground cable systems, where cable punctures have resulted simultaneously with thunder storms along the overhead lines. This indicates a possible necessity for having lightning-arresters of some form on the secondaries as well as on the primaries of the transformers. I have noticed in the Taylor's Falls installation that there are such static dischargers on the secondary circuits.

It is also interesting to note that the tell-tale papers in shunt with the test choke-coils on the line have been punctured. This certainly indicates that choke-coils act as barriers to the progress of these lightning surges in spite of the fact that this has been disputed so many times. It is evident that choke-coils are a decided protection where they are installed.

In general, I believe that with steel construction adopted throughout a transmission line so as to eliminate the burning and shattering experienced in wooden construction, and with one or more guard-wires installed along the line and over the transmission wires, that most of the serious lightning troubles on overhead lines will be eliminated.

P. M. Lincoln: In Figs. 11 and 12, Mr. Vaughan shows a number of curves the ordinates of which purport to give the static stress upon the insulators. I am not convinced that they do represent stress on those insulators. The ordinates of these curves are taken as the diameters of holes which were punctured in the tell-tale papers, and from that diameter is deduced the stress upon the insulators. I doubt if the diameter of a puncture in the tell-tale paper is an indication of stress on the insulator; I think it an indication of the current that has passed through that tell-tale paper. The current may have come from a lightning stroke, but more likely it has come from the passage of the dynamic current.

J. F. Vaughan: The question of interpretation and graphic representation of these tell-tale papers is open to discussion. It has been given a good deal of thought in the preparation of the curves. The curves are drawn up to show graphically or pictorially the differences in stress on the insulators, spill-overs of static and dynamic discharges; and the scale assumed in plotting the curves is intentionally exaggerated in the lower ranges to facilitate comparison of the smaller punctures. The curves should be interpreted in the liberal spirit in which they were plotted; that is, as a general indication (as accurate as possible) of the relative activity of disturbances in each case.

P. H. Thomas: These papers differ from most lightning-arrester papers in that they are a simple record of practical operating results and not a compilation of theories. What is most needed in the study of the lightning problem is not so much theory and speculation as sufficient data and knowledge as to exactly how lightning affects a transmission line, so that an intelligent design can be made of protective apparatus, and so that the action of such apparatus can be properly judged. These papers go a long way toward showing the nature of the attack of lightning on the high-tension transmission line. Of course the data here recorded are not necessarily typical of all lines, but they indicate in a general way what may be expected to happen.

The interpretation of these punctures in the tell-tale papers is important. It will be found on examining the data that one storm occurred when no generator potential was on the line at all; in another case the potential went off in the early part of the storm. In these storms, then, at least during the major part of them, there was no actual generator potential on the line. The punctures in the tell-tale papers were just as severe during the times when there was no generator connected with the line as at any other time. Most of the punctures show, on examination, that the fibres of the paper are unburned even when large holes appear, showing them to be purely static discharges. In other words, the holes in the punctured papers are simple records of the static passing over the line.

I have not counted the total number of so-called spill-overs, but there must be hundreds of them. These are cases where a static discharge has passed over the wire to the pin from the surface of the insulators and not a capacity current to the pin. Only a small percentage of these spill-overs have injured insulators.

It is interesting to know that there has been very little disturbance of any serious character at the stations. Mr. Buck draws the conclusion that it is because the insulation of the station apparatus has been raised in relation to that of the line. It seems to me that the reason for the relative immunity of the stations is that the action is entirely local, the attack of the discharge being so sudden that it cannot pass more than a very short distance along the line. It is not of sufficient energy to cause any very great disturbance unless it should start an arc from the generator. It has been frequently assumed that the high potential on the line wire, due to lightning, is the release of a charge. This may be true, but I think the evidence points the other way. This is a matter which ought to be studied. The evidence suggests more strongly, it seems to me, the direct jumping to the line wire of electrical energy direct from the atmosphere and not the drawing of the charge from the ground.

V. E. Goodwin: The papers presented this evening are of special interest to me as I lived several years in Minneapolis and am quite familiar with the nature and severity of the lightning storms in that vicinity. I also inspected the Taylor's Falls system with Messrs. Vaughan and Neall during the preliminary testing of the line and protective devices. I was then of the opinion that it would be difficult to draw definite conclusions from the results they would obtain, as the system was so completely equipped that it would be impossible to differentiate the protective values of the various devices. I now believe that the papers presented to-night show conclusively that reliable data have at last been obtained on the effects of lightning on a transmission system and on the relative values of various types of overhead ground-wires.

The phenomenon regarding direct strokes of lightning on transmission lines mentioned by Mr. Vaughan has been reported on several other systems. One would naturally think that a line would be more subject to direct strokes after the wires are up than before. It seems probable that where the wires are up the charge dissipates over several insulators and poles and therefore does not splinter or burn the poles. I therefore question the ability of an investigator to determine from tell-tale papers whether a disturbance results from a direct or induced stroke of lightning.

The magnitude and intensity of many of the strokes indicated in these records give us a good idea as to what is required of a station lightning-arrester. The records indicate that the station arrester did not have sufficient discharge rate to relieve the line at those points, thus causing the horn arrester, which had a higher breakdown point, to discharge. In designing the latest types of arresters great care has been taken to avoid all series resistance and to increase the discharge rates. This feature has been thoroughly carried out in the aluminum type electrolytic arrester, by the use of large plate area and an electrolyte of very low specific resistance, thus giving low internal resistance and a maximum discharge ability.

It is interesting to note that many of the induced strokes on the Taylor's Falls line were highly concentrated and often of great intensity and volume. This is indicated by the storm of July 4, where one puncture 1.75 in. in diameter was recorded. The absolute protection of a line under such conditions becomes a very difficult problem. It is evident that one or two overhead ground-wires are of considerable assistance in shielding the line wires, but at best they can only be of partial protective value. The problem of a line-type lightning-arrester for this purpose involves the installation of several arresters per mile, and this, of course, is prohibitive in any transmission line of over 2300 volts. The only case where such arresters can economically be installed is at an exposed point, where experience indicates that the expense is warranted.

The Taylor's Falls tests indicate that during every storm a great many insulators spilled over without any resultant damage to the insulators or interruption to the service. I believe that the only means of entirely protecting an overhead power circuit lies in the development of an insulator which will not puncture, and, while having a fairly low spill-over, will not shatter. This perfection in the petticoat type of insulator is probably out of the question, but I believe it can be attained by a properly designed and proportioned insulator of the suspension or strain type. Such an insulator would be the equivalent of a line arrester at each pole or tower on the line.

E. E. F. Creighton: The two additional subjects I wish to discuss are the interpretation of tell-tale papers and the use of resistance type of horn arresters. The conditions which muddle the tell-tale records are: first, the impression of several static discharges on each paper before they are removed; secondly, the complete destruction of the static puncture holes by dynamic current. A fraction of an ampere of dynamic current for a half cycle of the generator wave is sufficient to destroy the static record. The authors were fortunate in obtaining records on an idle line. It may be suggested to those who are willing to aid in collecting data on this subject that the only data of great value in the study of lightning potential should be taken on an idle line, and furthermore should be collected on moving tapes by clockwork so as to separate the punctures due to each cloud discharge.

The value of the resistance type of horn arrester for discharging lightning increases as the value of series resistance decreases. On the other hand, the disturbance that one of these arresters may cause on the line increases as the series resistance is diminished. The menace resulting from a discharge through one of these arresters to ground may be either one of two effects, or both. First, the arrester may take sufficient current to overload the circuit-breaker. Opening switches under overload conditions should be avoided as much as possible, to say nothing of the interruption of service. Secondly, if the resistance is sufficient to prevent overloading, there may be a menace to the insulation by the operation of one phase only, especially on an insulated neutral system. It requires about one to two seconds at best for the arc to rise on the horns and go out. During this interval the arc varies from a short length to a very long length, and if there is a possibility of setting up a surge on the system this arc is most likely to produce the condition. On any particular system these arcs may occur repeatedly with impunity, whereas on another system the surge conditions will be such as to cause a destruction of apparatus on some other part of the system. To illustrate this two examples are cited:

On a 17,000-volt, 60-cycle, delta-connected system a single gap in series with enough resistance to limit the current to 0.5 ampere was connected between line and ground. Even with this high resistance all five of the arresters in the station on three feeders discharged continuously so long as the arc played across the gap to ground. A lightning-arrester of so limited a discharge would have little practical value, yet the surges caused by the discharge assumed dangerously high values.

As a second example, it is a common occurrence on cable systems to have several failures of cables after one has taken place, due probably to the surges set up during the first failure.

If one goes back over the history of the use of horn gaps with series resistance, he will find the hope always held out that an operator will finally obtain the right adjustment of resistance to give excellent protection without a resulting interruption of service. This has never been accomplished, and I think it can be shown that it never will be.

If we did not have the aluminum arrester it would be worth while working out the best conditions for the resistance horn-gap arrester. A comparison of the two will show the limitation of the resistance horn type and the uselessness of the development. At 60,000 volts every ampere of discharge through the series resistance of the horn gap represents, roughly, 60 kw. per phase, or 180 kw. If an arrester will not discharge 100 amperes, I think it will not take the usual run of heavy discharges. With this rated discharge the generator would be called upon to furnish 18,000 kw. On the other hand, if an aluminum arrester is used, the energy taken from the generator will be less than 20 kw. and the rate of discharge of lightning will be several hundred amperes at the same abnormal value of potential. The valve action of the aluminum arrester prevents almost entirely the flow of dynamic current at normal potentials and has a free discharge only at abnormal potentials. This information is sufficient to show the futility of using the resistance type of horn-gap arrester.

Furthermore, the current taken by the aluminum arrester from one phase to ground is leading, the same as the capacity current of the line or cable, and consequently one phase may arc continuously between line and ground without setting up high surges on the system. It should be noted that the aluminum arrester actually maintains the voltage and thus prevents grounding the line conductor.

President Stott: In listening to the discussion, I recall the experience of eleven years ago with the Niagara transmission lines. I am not certain whether this was the first line equipped with overhead ground-wire, but at all events it was so equipped when it started. After a few months' experience with the overhead ground-wires it was decided to take them down, as in the choice of two evils the lesser one seemed then to be the troubles due to lightning. This was due to poor material in the ground-wires themselves, as they were continually breaking and short-circuiting the lines. Now eleven years after, we hear that as the result of a most elaborate series of tests and investigations, the ground-wire gives the most certain protection. In a practical way there is every reason why it should. No one ever heard anywhere of an underground cable being struck by lightning. That means that if the ground itself is above the conductor the line is safe. We cannot possibly afford to put all transmission lines underground. A 60,000-volt underground transmission line 200 miles long is absolutely impossible from a financial or commercial standpoint; but instead of putting the wires underground, we can in effect put the ground above the wires. The most perfect protection will be got where we have the most perfect network of ground-wires above our conductors. I think everything said to-night points to that fact.

Now to avoid ordinary troubles there must be a high factor of safety in all apparatus. Troubles with underground cables are almost unknown outside of mechanical damage and faulty joints, and the reason is that those cables are made with an extremely high factor of safety; for instantaneous voltage it is five; for continuous service, two. Just as it is with a human being, if a man is in a weakened condition every few germs that come along will give him a new disease; but if he is strong enough they won't affect him at all. We have got to make our system germ-proof, as it were, and have a very large factor of safety on the insulators. That, and the ground-wire, I think, is going to be the solution of our overhead transmission work.

J. F. Vaughan: I am sorry not to hear more discussion on the interpretation of tell-tale papers, as there is plenty of material for discussion. It is rather surprising that with the necessarily crude methods of measurement used there are not more apparent inconsistencies in the results. For instance, the three wires grounding the three pole pins through individual tell-tale spark-gaps are not more than a few inches apart and are mounted on porcelain knobs only, which might be expected to allow disturbances of such intensity as have been indicated by the papers to break across from wire to wire. This fact brings out one point which has not been touched on, and that is the lack of pronounced phase-to-phase disturbance, indicating that the main stresses which are between wires and ground do not greatly differ in the three wires.

N. J. Neall: I wish to emphasize again the points which I have made about insulators. According to the theory which I have advanced in my paper, suspended-type insulators would be subjected by lightning to greater disturbance locally than any insulator so far used for lower voltages, because I am assuming that there is no special overhead protection at all, and am taking the broad case. If the transmission wire takes this lightning charge, the charge must get to the ground some way or other, and the only place at which it could do so would be presumably by way of the insulator support. The suspended type insulator has not come into the Taylor's Falls problem, and we have no data respecting it; but if insulators could be studied with reference to the equivalent spark-gap we would probably find certain explanations of the phenomenon at which we can now only guess. I think that is a point on which the Institute should have the fullest possible information, if not from a practical reason, certainly in connection with the advancement of the art, and, perhaps, indirectly, of the science.

V. D. Moody (by letter): In a paper presented at a recent meeting of the Institute,* Messrs. Rushmore and Dubois recommended for insulator protection steel rods with ends pointed, bolted to the vertical members of the towers and projecting above the highest point of the line. This method of protection was freely criticized, but my experience is that this type of arrester is highly valuable.

Several years ago this type of arrester was used on the Winnipeg hydroelectric installation at Winnipeg, Canada. The transmission line was 65 miles long, delivering about 20,000 h.p. at 60,000 volts, 60 cycles. From the power house to the substation duplicate transmission lines of No. 00 B. & S. hard-drawn cable, with a hemp centre, were run in duplicate on steel towers. This line crosses the Winnipeg River with a span of about 760 ft., on towers 72 ft. high, each weighing about 6 tons, with a sag in the line of about 23 ft. at 50 degrees. The standard towers are 40 ft. high, weighing about 2400 lb., spaced 500 ft. apart with a sag of about 14 ft. at 50 degrees. There are four railroad crossings. At Winnipeg, this line crosses the Red River with a 1100-ft. span, the towers are 105 ft. high with a line sag of 45 ft. at 50 degrees. These towers weigh 15 tons. The railway and river crossing towers are on concrete footings, and are grounded with a ground-plate. This transmission line has 10 complete transposition spirals and is paralleled by a telephone line of No. 8 B. & S. hard-drawn copper wire on porcelain insulators on the towers. The telephone line was transposed at each tower. The telephone line and transmission line insulators were made of the same kind of porcelain.

On all of these towers this steel-rod type of horn arrester was used. In operation it was found that the protection afforded was extremely valuable, as none of the high-tension insulators was punctured in several very severe lightning storms. In this country the storms are very severe in the summer months. In one instance five miles of telephone line was knocked down and insulators broken without breaking any of the line insulators, although the effects of the storm were felt in the sub-station by throwing out of synchronism, momentarily, the 800 kw. motor-generator sets.

This line has now been in operation since June 1906, and has never had a shutdown. As the storms have been severe, I feel assured that these arresters are doing good work, as this is the only protection on this line.

It appears to me, that this type of arrester with a ground-wire and multigap station arresters with choke-coils will afford protection that can be relied upon.

* TRANSACTIONS A. I. E. E., Vol. XXVI, page 425.