T H E S I S

on

Long Distance Electric Power Transmission.

Submitted to the Faculty

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As transmission voltages, actual or proposed, become higher and higher and transmission distances reach out farther and farther, it is interesting and profitable to inquire into the probable maximum distance to which power will be commercially transmitted. As with most engineering enterprises, the limitations will come through economic conditions, and the greatest distance to which power will be commercially transmitted, is the greatest distance to which it can be economically transmitted.

The elements which, in the broadest sense, limit the distance to which power can be economically transmitted are two:-the cost of power at the generating station, and the price which can be obtained for the delivered power. The difference between these two elements must cover the cost of transmission, the interest on the investments and the profits. The cost of transmission comprises the loss of power in transmission, the cost of operating and the cost of maintenance and repairs. The value of the sum total of the interest which must be paid upon the investment, and the minimum profit which is considered satisfactory, will have much weight in determining the limiting distance of transmission. The less this sum is the farther power can be transmitted; a low interest rate and a low rate of dividends will, therefore be conducive to a long transmission. In considering in a general way the manner in which the investments in a transmission plant, and the annual charges and expenses in connection with the plant, vary with different voltages, outputs, and distance of transmission. For a given voltage, drop, and distance of transmission the cost of all the apparatus and equipment except the line conductors will increase more slowly than the output of the plant. That is, the greater the output of the plant the less cost per K.W. of all the equipment, except the line conductors. Since the interest charges and the charges for depreciation and repair, are dependent on the investment, the greater the output of the plant the less will be the quantities going to make up the annual cost per K.W. of transmitted power. Since the weight of the line conductors will vary directly as the amount of power transmitted, those elements of the annual cost per K.W. depending upon the line conductors will be practically constant for all amounts of power transmitted and cannot be materially reduced by increasing the amount of power transmitted. With the same voltage, economic drop, and output, the elements of annual cost per K.W. due to the line structure (Pole Line) will increase directly as the distance. On the other hand the weight of the line conductors increases as the distance, and the elements of annual cost per K.W. due to the weight of the line conductors will increase as the distance, no matter what the output. This shows that all the elements in the annual cost per K.W. for transmitting power, except those depending upon the line conductors, may be continually reduced by increasing the amount of power to be transmitted. As the first cost of line conductors can be be reduced only by increasing the voltage of transmission and there is a limit to which such increase can be carried, it follows that--"The limiting distance to which power can be economically transmitted will depend, finally upon the cost of the line conductors and upon this alone."

However it shall not be forgotten that the history of electric power transmission in the past shows that it is unsafe to prophesy the commercial limiting distance of transmission. In the early days of the development of the incandescent lamp it was demonstrated mathematically that it would be commercially impracticable to transmit electric power to such lamps more than a few hundred feet. The proposition was valid at that time, but only for the conditions then existing. The three-wire system and the 100-volt lamp upset both the assumptions and the conclusions. The practical men carried power to lamps distant several thousand feet from the generator. Then the transformer became known and it was demonstrated that it would be commercially impossible to transmit power more than a few miles distant. But improvements in construction invalidated the assumptions of the proposition also, and the practical men have now succeeded in carrying power commercially to a distance of two hundred and thirty miles in California at a pressure of about 60,000 volts.

The greater percent of our large cities today depend for their lighting, transportation, water supply, and operation of their industries, upon the electric power transmitted over considerable distances. This transmission service is compelled to be continuous, for any interruption, however small, of the power service, so inconveniences the public as to be conspicuous. The public opinion that long-distance power transmissionsare unreliable, is a very great drawback to its development. Although continuous service may not be possible, many of the troubles that have been experienced can now be either eliminated or greatly reduced. The most important causes of interruption of service, where wooden poles and cross-arms are used, are short circuiting of lines, by branches of trees, or by large birds getting across them; the burning of the wooden insulators pins, and cross-arms; burning, often, of the poles at the ground, from forest and prairie fires, lightning damaging the apparatus connected in the circuit and sometimes destroying the poles. The deterioration of a line requires its replacement in from five to twenty -five years and the replacement of a pole can only be accomplished by shutting off of the service, or by taking a very great risk of accidental interruptions, which may be more serious than the shutting off of the service while the repair is made.

Many of these drawbacks can be overcome by the use of steel towers and long spans, in the place of the wooden pole line. In the tower construction short circuits are by far the most common difficulty and these can be greatly reduced by putting the wires so far apart that they are unlikely to be bridged across. Burning of the pins and tower is entirely eliminated where metal is used. Larger and better insulators can be used on towers than on poles, and being fewer of them lessens the chance of their failure. Each metal tower is itself a lightning arrester and as they are the highest point in the line they materially assist in its discharge and being a conductor cannot be injured by lightning. Steel towers can also be figured exactly to meet safely any strain that they may be subjected to, and can generally be located where there is no danger of washouts by water. The deterioration of a well constructed galvanized steel tower is very slight, as it has been proven by marine and windmill service, and the almost negligible as far as the pins are concerned and also the cross-arms. Then any part of a steel tower may be removed and replaced without the interruption of the service. By far the greatest gain in the steel tower and long spans over the wooden pole line, is the reduction of the number of parts. If one tower takes the place of six or eight or more poles, the trouble will be reduced in nearly a direct ratio, the inspection and repair of the line will be much simplified and the cost of maintenance greatly diminished.

Steel towers are rapidly coming into use for the support of electric transmission line that deliver large units of energy at high voltages on long distances of transmission. The cost of a tower compared with that of wooden poles depends on the locality of the transmission line. Where the right kind of timber exists wooden poles are cheaper, but where wooden poles have to be transported long distances the tower is much cheaper. In order to have long life of a pole a creosoted wood only could be used and this still increases the expense. The fewer insulators and pins and the ease of transportation and erection are in favor of the tower , they can be packed in light bundles suitable for muleback transportation and quickly put together even in the most inaccessible places. Even where tower construction is greater in cost it is often justifiable by the greater certainty of operation which it insures and the less cost of maintenance.

Steel towers are used in the seventy-five-mile transmission line of 24,000 H.P. at 60,000 volts, from Niagara Falls to Toronto and on an eighty-mile line in northern New York, at a voltage of 60,000. In the older lines now using pole line construction are the one hundred and forty-seven mile line carrying 13000 H.P.

from Electra station to San Francisco, California at 66600 volts and the one hundred and forty-two mile line carrying 15000 H.P. from Colgate power house to Oaklan, California at 60000 volts. In the operation of these and many others of high voltage transmissions on pole line, during various parts of the last decade some difficulty has been met with, butnothing serious enough to prevent satisfactory service. Nevertheless it is now being urged that certain impediments that are now met with in transmission, would be greatly reduced by the use of steel towers, and that probably the first and total cost would be less with steel than with wood. The argument for steel in the matter of cost is that while a tower requires a larger investment than a pole, yet the smaller number of towers as compared with that of poles, may reduce the entire outlay for the former about that of the latter, and also the maintenance and depreciation charges of steel supports will make their final cost no greater than that of wooden poles.

The cost of a steel tower support will vary according to its weight about 3 to 3½cts. per pound. The steel towers used between Niagara Falls and Lockport, each tower carried a single three -phase transmission circuit, has three legs and built of tubing that tapers from 2½ inches to smaller sizes and is braced at frequent intervals. The height of each of these towers is 49 feet and weight 2800 lbs., at 3¢ per pound they would each cost $84.00. For the transmission line in northern New York, towers 45 ft. high, carrying two, three phase systems and weighing 3000 pounds, the price for each was from $100 to $125. On the line from Niagara to Toronto, towers 40 ft. high, weighing 2360 pounds cost $70.80 each.

With these examples of cost of steel towers, a fair idea may be gotten of the relative cost of wooden poles. Cedar poles, or other desirable wood, 35 ft. long with 8 inch top, fitted with one or two cross arms, cost about $5.00. This size of pole has been much used on the long high-voltage transmission systems that involves large power units and uses heavy conductors. Poles of this size were used between Niagara Falls and Buffalo; Colgate power-house and Oakland; and between Canon Ferry and Butte. With steel towers 400 ft. apart, and poles 100 ft. apart, 4 of the latter must be used to one of the former. At $5 per pole this requires an investment of $20 in poles as compared with at least from $45 to $100 in steel towers. To reach the same result when towers carry two circuits, it would take two pole lines and this would bring the cost up to $40. This cost of the towers and poles includes nothing for erection. Each tower has at least three legs and more, commonly four, and owing to the height of the tower and the long spans they support, the legs are generally set in cement and concrete, thus the same amount of holes will be dug as with pole line, and considering the cost of the concrete footings, the cost of erecting the towers is probably greater than that of the poles. With wooden poles about four times as many pins and insulators are required, as with steel towers. The cost of insulators and steel pins for 50,000 to 60,000 volts is about $1.50, so that the saving per tower reaches not more than $15.50. In the labor of erecting there may be a small advantage in favor of the tower, but the weight of the long spans probably offsets to a large extent any gain of time due to fewer supports. An approximate conclusion from the above data seem to be that a line of steel tower will cost about 1.5 times as much as a line of wooden poles to support the same number of conductors the same distance. Wooden poles of good quality have been known to last ten or fifteen years, it is doubtful whether steel towers will show enough longer life to offset their first cost. The strongest argument in favor of steel tower for transmission of electric energy, is that these towers give a much more greater reliability of continuous service than do wooden poles. For the great majority of power transmission, however, it seems probable that wooden poles or structures will long continue to be much cheaper and more practicable as a form of support. Another advantage of steel towers over wooden poles or structures is that the former will not burn and are probably not subjected to destruction by lightning. Where a long line passes over a territory where there is much brush, timber or long grass, the fact that the steel towers will not burn may make them more desirable. In tropical countries where insects rapidly destroy wooden poles, the use of steel towers may be very desirable even at greater first cost. Steel towers are much used in Guanajuato, Mexico.

Long distance transmission lines should follow as near a straight line as possible, or direct routes from generating plant to point of distribution. The number of poles, cross-arms, or towers, insulators, increase directly as the length of the line, and the weight of conductors increases with the square of the length of line, other factors and pressure of line, remaining the same. The material deviated from a straight line must be paid for at a much higher rate.

General transmission lines follow the public streets or highways, in order that consumers may be reached, but the saving of the cost of a private right-of-way and ease of access are the main considerations which tend to keep transmission lines on streets or highways. The cost of a private right-of-way may be very important and should be compared with the additional cost of transmission lines erected on streets and highways. All of these considerations seem to point towards a tendency to locate transmission lines on private right-of-way, where large power is to be transmitted at high voltage. These private right-of-ways range from fifty to several hun dred feet in width, for in timber all trees large enough to reach the wires are cut.

In many cases of transmission at very high voltages two independent transmission lines are erected, each carrying one or two circuits; that mode of transmission has been followed out in the transmission line from Niagara Falls to Buffalo, Canon Ferry to Butte, Welland to Hamilton, and Colgate to Oakland. Such double transmission lines are generally located on the same right-of-way. The main reason for the use of two pole lines instead of one are the probability that an arc started on one circuit would be transmitted to the other circuit of the same poles, thus the greater safety and ease of repairs is obtained when each circuit is transmitted on separate transmission lines. The use of one circuit of larger wire instead of two circuits of smaller wire has the advantage of greater mechanical strength in each conductor, saves the cost of one pole line and the erection of the second circuit. With voltages above 40 to 50,000 on long transmission lines there is a large loss of energy by leakage directly through the air from wire to wire. To keep this loss within desirable limits it may be necessary to give each wire of a circuit a greater distance from the others of the same circuit than can readily be had if all the wires of the circuit are mounted on the same pole line. If there is only one three-wire circuit to be provided for three lines of poles or two lines with a long cross-arm between them, may be set with any reasonable desired distance between the pole lines, so that the leakage from one wire to another through the air may be reduced to a very small quantity.

Distance from pole to pole in the same transmission line varies somewhat with the size, number and material of the conductors to be carried. The ordinary construction in a straight line, is to place the poles from 100 to 110 feet apart, or about fifty poles to the mile. On curves and corners the poles should be put much nearer together, depending on the sharpness of the curve. In the two 142 mile line from Colgate to Oakland, the poles are placed 132 feet apart, one line of poles carries three copper wires and the other three aluminum wires. As aluminum wire has only one-half the weight of copper wire for the same conductivity, the distance between poles carrying aluminum wire may be made greater than that where copper wire is used. Where bodies of water must be crossed by overhead transmission a verylong span with special supports for the wires will be necessary. In the Colgate-Oakland transmission line where the line crossed the Carquinez Straits, a point where the water way is 3200 ft. wide, it was necessary to have the lowest part of the cables 200 feet above the water surface, in order that large vessels could pass underneath.

To secure the necessary elevation for the cables a steel tower was erected on each bank of the Strait, at such a point that the distance between the points of the cable supports of the towers was 4427 feet. As the bank rises rapidly from the water level, one steel tower was given a height of 65 ft. and the other 225 ft. Between these two towers four steel cables were suspended, each cable being made up of nineteen strands of galvanized steel wire, having an outside diameter of seven-eighths inches and weighing 7080 pounds for the span. The breaking strain of each cable is 98000 pounds and its electric conductivity equal to that of a No. 2 copper wire. The cables are supported on the towers by steel rollers, and the pull on each cable amounting to twelve tons is taken care of some distance behind each tower by an anchor where each cable terminated. Each anchor consists of a large block of cement, deeply imbedded in the ground, with anchor bolts running through it. Each cable is secured to its anchorage through a series of strain insulators, and the regular line cables of copper and aluminum are connected with the steel cables just outside the insulators. This span is the longest and highest which has ever been erected for transmission of electrical energy of high voltages.

The metals used for line conductors in long distance transmission are copper, aluminum, iron and bronze, but copper is the standard metal used for this purpose. An ideal conductor for transmission lines should be one that has the greatest electrical conductivity, greates t tensil strength, a high melting point, small coefficient of expansion, hardness and great resistance to oxidation. No one metal has all of these properties to the highest degree, but copper is the best, being high in electrical conductivity which is by far the most important factor in a line conductor. In ordinary line construction tensil strength of wire is of secondary importance compared with electrical conductivity, but where long spans have to be made, as the 4427 ft. span in the Colgate-Oakland line mentioned, tensil strength is of the first importance. Steel wire wasused in this construction, having a tensil strength, depending on the quality, as high as 350000 lbs. per sq. inch, while ordinary copper wire has only a tensil strength of about 50000 lbs. per sq. inch.

The most necessary property of a transmission wire is, conductivity, copper excels all other metals in this except silver. Taking the conductivity of copper as 100, bronze ranges from 45 to 90, aluminum 60, iron 14 and steel about 11. It is not desirable to use copper wire smallerthan No. 4B&S , for transmission lines, because of the lack of tensil strength of smaller sizes. When conducting smaller than that of No. 4 is ample, iron wire will give the required conductivity witha much greater tensil strength. Thus it is evident that a much greater cost per pound can be paid for copper wire than for any other metal, for the same conductivity of wire. For a line of given cost and length,copper wire has the least cross-sectional area, and tensil strength, with the greatest conductivity and non-oxidation effect.

Long distant transmission lines are in nearly all cases run with bare wire, supported by poles and insulators. Where very high voltages are employed no insulation that could be put on the wires would make it safe to handle and the cost of such insulation would add materially to the cost of the line. The practice is to run transmission wires above all others and depend upon the insulators and supports for insulation. When an alternating current passes through a wire it tends to concentrate itself in the outer layers of the wire leaving the center idle. This unequal distribution of the current increases with the frequency of the current, thus the resistance of a wire for alternating current is a little greater than that for direct current, but it seldom amounts to more than one percent.

The maximum practical limit of pressure on transmission lines has been frequently stated as fized at certain voltages, but this limit has more than once been extended with good results. At the present time no considerable difficulty should be experienced with 100,000 volts, and there is no good reason to fix the limit at that figure. The problems of insulations are being understood, but there is a large field for development yet. The capacity and surface effects of line insulators have received but little attention and many failures are due to this fact. The form and material of the insulator have not had enough attention paid to them. A desirable insulator for high tension is not merely a piece of glass or porcelain arranged to shed rain and of a sufficient thickness to resist puncture. A material that has promises of becoming used for high insulation is prepared paper. There are many different forms of the glass and porcelain insulator and from actual tests of porcelain, Brown glaze, 92000 volts has been put on the insulator for some time, without a breakdown. Glass insulators have been tested up to 91,800 volts.

Defective insulators may be divided into two classes, those that the line voltage will puncture, and those that permit an excessive amount of current to pass over their surface to the pins and cross-arms. When an insulator is punctured and broken, the pin, cross-arm, and pole, to which it is attached, are liable to be burned up. If the leakage of the current over the surface of the insulator is large, not only may the loss of energy on the line where the insulator is used be serious but this energy follows the pin and cross-arm in the path from wire to wire and gradually chars the former or both so that they are ultimately set on fire or break through lack of mechanical strength. The discharge over the face of an insulator may be so large in amount as to have a disruptive character and thus to be readily visible. More frequently this surface leakage is of the invisible and silent sort, nevertheless it may be sufficient in amount to char and set fire to the insulator pin and cross-arm.

All insulators whether glass or porcelain, should be tested electrically to determine their ability to resist puncture and to hold back the surface leakage of current, before they are put to practical use on high tension lines. Experience has shown that inspection alone cannot be depended upon to detect defective glass insulators. Electrical testing of insulators serves well today to determine the voltage to which they may be subjected in practical use with little danger of puncture and disrupture of passage of current through their substance. It is also possible to determine the voltage which will cause a disruptive discharge of current over their surface when the outer part of the insulator is either wet or dry. This is as far as the electrical tests are usually carried but it seems desirable that such tests should also determine the amount of silent, invisible leakage over the surface of insulator, at the voltage which their currents are supposed to carry. The voltage employed to test insulators should vary in amount according to the purpose for which any particular test is made. Glass and porcelain like many other solid insulators will withstand a voltage for a few minutes that will cause a puncture if continued indefinitely. In this respect these insulators are unlike air which allows a disruptive discharge at once when the voltage to which it is exposed reaches an amount that the air cannot permanently withstand. Because of this property of glass and porcelain insulators, it is necessary in making a puncture test to employ a voltage much higher than that to which they are to be permanently exposed. In good practice it it thought desirable to test insulators for puncture at least to twice the voltage of the circuit which they will be required to permanently support on transmission lines.

There is a difference of opinion as to the proper duration of a puncturing test, the practice in some cases being to continue the test for only one minute on the insulator, while in other cases the time runs up to five minutes or more. As a rule the higher the testing voltage compared with that under which the insulator will be regularly used, the shorter should be the period of test. Test with insulators are usually made with alternating current and the formof the voltage curve is important especially where the test is made to determine what voltage will arc over the surface of the insulator from the line wire to the pin. The square root of the mean square for two curves of alternating voltage, or mean effective voltage, as read by the voltmeter, may be the same though the maximum voltage of the two curves differ widely. In tests for puncture of insulators, the average alternating voltage applied is more important than the maximum voltage that is shown by the highest point of the pressure curve, because of the influence of the time element with glass and porcelain insulators. On the other hand when the test is to determine the voltage at which current will arc over the surface of insulator from line wire to pin, the maximum value of the pressure curve should be taken into consideration because air has no time element, but permits a disruptive discharge under a merely instantaneous voltage.

An insulator that resists a puncture test may fail badly, when subjected to a test as to the voltage that will arc over its surface from line wire to the pin. This arc-over test should be made with the outer surface of the insulator both wet and dry. For the purpose of this test the insulator should be mounted on an iron pin, that has been covered with tinfoil. The voltage that will arc over the surface of the insulator from line wire to the pin, depends on the condition of the surface of the insulator and of the air. In light air, such as is found at high elevations, an arc will jump a greater distance than in dry air at sea level. A fog will increase the distance that a given voltage will arc between the line wire and insulator pin, and heavy rain still lengthens this arcing distance. An insulator should be given an arc-over test under conditions that are approximately the most severe to be met with in practice. These conditions can perhaps be fairly represented by a down pour of water that amounts to a depth of one inch in five minutes for each square inch of plane included in by the edges of the largest petticoat of the insulator, when the direction of the falling water makes an angle of 45° with that plane. Under the severest conditions mentioned, the arc-over test voltage from line wire to the pin, should be somewhat greater at least than that of the normal voltage of the circuit, where the insulator is to be used. When the outside surface of the insulator is wet as during a moderate rain it seems that the under dry surface of the insulator and the distance through air from the lower wet edge of the insulator to the pin or cross-arm, make up most of of the insulation that prevents arcing over from the wire to the pin and cross-arm.

The design of the insulator pin for the support of the insulator is a most important factor in high tension and long distance transmission. The bending strains due to the weights of degree of tension and the directions of line wires, plus those resulting from wind-pressure and ice forming on the wires, are the most important causes that lead to the mechanical failure of insulator pins.

Considering the unbalanced components of these forces at right angles to the axis of the pin, which alone produce bending, each pin may be considered at a beam of circular cross-section secured at one end and loaded at the other. For this purpose the secured end of the beam is to be taken as the point where the pin enters the cross-arms and the loaded end the point where the line wire is attached to the insulator. The distance between these two points is considered as the length of the beam. The maximum strain in the outside fibers of the pin measured in pounds per square inch of cross-section, represented by S may be found from the formula $S = \frac{PX}{.0982D^3}$, where P is the pull of the wire in pounds, D the diameter of pin at cross-arm; X the distance in inches from the point where D is taken to where the wire is attached to the insulator. The cross-section of the pin just at the top of its hole in the cross-arm is thus subjected to the greatest strains, because this cross-section is more distant from the line wire than any other that is exposed to the bending strain. It is at this weakest point and smallest cross-section that the pin usually breaks. This break comes just below the shoulder that is turned on each pin to keep it from slipping down through the hole in the cross-arm. If the shoulder on the pin made a tight fit all around down through the cross-arm, the strength of the pin to resist the bending strain would thereby be increased. By giving a pin a suitable taper from its shoulder at the cross-arm to its top, the strain per square inch in the outside fibers of the pin may be made constant for every cross-section throughout its length above the cross-arm, whatever the length may be.

The weight of conductors varies inversely with the square of the line pressure, the power, length and loss being constant. Whatever the total lin pressure, the weight of conductors varies inversely with the percentage of loss. The case of maximum loss and minimum weight of conductor is that in which all the transmitted energy is expended in heating the line wires. Such a case would never be met with in practice, because the object of power transmission is to perform some useful work. Minimum loss is zero and the corresponding weight of conductors being infinite, but these conditions cannot be attained in practice. Between these extremes of minimum and of infinite weight of conductors, comes every practical transmission with a line loss greater than zero and less than 100%.

A system of transmission may operate with either constant volts or constant amperes on the line conductors but in a practical case constancy of both these factors is seldom or never to be had. This is because the product of the line volts and amperes represents accurately in a constant-current system, the amount of power transmitted. In an actual transmission system the load, that is the demand for power, is subjected to more or less variation at different times of the day and the line volts or amperes or both must vary with it. Most electrical transmissions are carried out with nearly constant line voltage, mostly alternating and the line current in such cases varies directly with the power transmitted, except as to certain results of inductance on the alternating lines. As the line resistance is constant, save for slight variations of temperatures, the rate of energy loss on a constant-pressure line varies with the square of the number of amperes flowing, and the percentage of the loss with any load varies directly as the number of amperes.

Energy transmitted over long distances must sometimes pass through conductors that are underground. In some cases it is a question of relative advantage merely where portions of the transmission lines go underwater or over head. Where the transmitted energy must enter a substation in the heart of a large city, it not infrequently goes by way of underground conductors without regard to the voltage employed. In some cities the transmission line may be carried overhead, provided that their voltage is within some moderate figure, but not otherwise. Here it becomes a question whether transmission lines at high voltages shall be carried underground or whether transforming stations shall be established out side of the restricted area, and then low pressure lines brought into the business section overhead or underground as desired. Where a transmission line crosses a steam railway track it may be required to go underground, whether the voltage is reduced or not. The distance across a body of water in the path of a transmission line may be great enough that a span is impossible and a cable under the water therefore is necessary. Such a cable may work at the regular line voltage, or transforming stations may be established on each side of the body of water. Even where it is possible to span a body of water with a transmission line, the cost of the span and of its supports may be great enough that a sub-marine cable is more desirable. A moderate increase in the length of a transmission line in order to avoid the use of a submarine cable is almost advisable, but where rivers are in the path of the line it generally is impossible to avoid crossing them either overhead or underneath. Sometimes an existing bridge may be utilized to support a transmission line, but more frequent the choice lies between an overhead span and a submarine cable. The principal advantage of an overhead line at high voltages is its comparatively small first cost, which is only a fraction of that of an underground submarine cable.

In the business portions of many cities a transmission line must go underground, whether its voltage is high or low. Under these conditions it may be desired to transmit energy to a substation for distribution within the area where conductors must go underground or to transmit energy from a generating station there, located to outside points. If the transmitted energy is reduced in pressure before reaching such a substation a transforming station must be provided, and this will allow the underground cables to operate at moderate voltage. For such a case the advantage as to insulation at the lower voltage should be compared with the additional weight of conductors in the cable and the cost of the transforming apparatus and station. If the voltage at which current is delivered from the transforming stations does not correspond to the required voltage of distribution at the substation, the necessary equipment of step-up transformers is doubled in capacity by lowering voltage of the transmitted energy where it passes from the overhead line to the underground cables. The saving effect in capacity of transformers and in weight of cables by continuing the full transmission voltage right up to the substation; whence distribution takes place furnishes a strong motive to work underground cables at the pressure of the overhead transmission line of which they form a continuation.

Where a river or body of water has to be crossed by a transmission line, either of three plans may be followed: The over-head line may be continued across the water, either by a single span or by two or more spans supported by one or more piers, built for that purpose in the water. The overhead line may connect directly with the submarine cable, at the full voltage of the line. Or third expedient, a submarine cable may be laid and connected to step-down transformers on the other bank of water to be crossed. The overhead lines connecting with these transformers can obviously be operated at any desired voltage, and this is true also of the cable. Even though the distance across the body of water is not so great that a transmission line cannot be carried in a single span, the cost of such a span may be very large.

The standard structure of high voltage cables for either underground or submarine work includes a continuous metallic sheath outside of each conductor, or of each group of conductors that goes to make up a circuit. As most transmissions are now carried out with three-phase current, the three conductors corresponding to the three-phase circuit, are usually contained in a single cable and covered by a single sheath. If a single-phase or a two -phase circuit is transmitted, each cable should contain the two conductors, that go to make up a circuit. In work with alternating current the use of only one conductor per cable should be avoided because of the loss of energy that results from the current induced in the metallic sheath of such cables. Where two, three, or more conductors that form a complete circuit for alternating current are included in a single metallic sheath, the inductive effect of currents in the several conductors tend on neutralizing each other and the waste of energy in the sheaths is in a large part avoided. To neutralize more completely the tendency to local currents in the metallic sheath, the several insulated conductors of an alternating current are sometimes twisted together, after being separately insulated from each other, before the sheath is put on. Underground and submarine cables for operation at high voltage are generally covered with a continuous lead sheath and sometimes with a spiral layer of galvanized iron wire . For high voltage work underground, the lead covering is generally preferred without iron wire, but in submarine work cables of both sorts are used. The lead sheath of a cable being continuous completely protects the insulation from contact with gases or liquids. As ducts of either tile, wood, or iron form a good mechanical protection for cables, the rather small strength of the lead sheath, is not a serious objection in conduit work. Submarine cables on the other hand, depend on their outer covering for mechanical protection and may be exposed to forces that would rapidly cut through a lead sheath. Cables for operation under water should be covered with a layer of galvanized iron wire outside of the lead sheath. These wires are laid closely about the cable in spiral form and are usually between 0.12 and 0.25 inches in diameter each, depending on the size of the cable and its location.

Underground conduits cannot be relied upon to exclude moisture and acids of the soil from the cable which they contain, and either of these agents may lead to destructive results. If cables insulated with rubber, but without a protecting cover outside of it, are laid in underground conduits, the rubber is apt to be readily destroyed by the fluids and gases that find their way into the conduits. If a plain lead cable is employed the acids of the soil attack it, and if stray electric currents from an electric railway find the lead a convenient conductor it is rapidly eaten away when they flow out of it. To avoid both of these results, the underground cable should have a lead sheath, and this sheath may be protected by an outside layer of hemp treated with asphaltum. Rubber, paper and cotton are extensively used as insulation for underground and submarine cables, but the three are not usually employed together. As a rule the insulation is applied separately to each conductor, and then an additional layer of insulation may be located about the group of conductors that go to make up the cable. Where rubber insulation is used, a lead sheath may or may not be added, but where the insulation depends upon cotton or paper the outer covering of lead is absolutely necessary to keep out the moisture. The thickness of insulation for each conductor and of that about the group of conductors in a cable should vary according to the voltage in operation.

Underground cables in which the separate conductors are covered with cotton braid treated with an insulating compound, and then the group of conductors going to make up the cable enclosed in a lead sheath, are extensively used in Austria and Germany. For cables that operate at 10,000 to 12,000 volts the radial thickness of cotton insulation on each conductor is said to be about three-sixteenths of an inch, and these cables are tested up to 25,000 volts by placing all of the cable except its ends in water, and then connecting one end of the 25,000 volt circuit to the water and the other to the end of the cable. A test on a paper insulated cable shows its charging current to be 1.1 ampers at 25000 volts for each mile of its length. For a cable with rubber insulation, the charging current was found to be nearly twice as much as when paper insulation was used. When overhead transmission lines join underground or overhead lines join submarine cables, either with or without the intervention of transformers, lightning arresters should be provided to intercept discharges of this sort that come over the overhead wires. If an underground or submarine cable connects two portions of an overhead line, lightning arresters should be provided at each end of the cable. One advantage of a high rather than a low voltage on underground cables, where power is to be transmitted at any given rate, lies in the fact that the amperes flowing at a fault in the cable determine the destructive effect at that point, rather than the voltage of transmission.

Ozone seems to destroy the insulating properties of rubber very rapidly, and as it is well known that the silent electric discharge from the conductors at high voltages develops ozone, care should be taken to protect rubber from this action. This is especially true at the end of cables where connections are made with switches or other apparatus and the rubber insulation is exposed. To protect the rubber at such points, it is the practice to solder a brass cable head, or terminal bell to the lead sheath near its end, this head having a diameter of perhaps twice that of the lead sheath and then to fill this space about the cable conductors with an insulating compound. As insulating material, whether rubber, cotton, or paper may be impared or destroyed by heat, it is necessary that the temperature of underground cables under full load be kept within safe limits. Rubber insulation can probably be raised to 125° or 150°. Fahrenheit without injury, and paper and cotton may fall a little higher. For a given size and make of a leaded cable the rise in temperature of its conductors above that of the surrounding air, for a given loss in watts per foot of cable, may be determined by computation or experiment. The next step is to find out how much the temperature of the air in the conduits where the cable is used, will rise above the temperature of the earth in which the conduits are laid, with the given watts loss per foot of cable.

Lightning in various forms is the greatest danger to which transmission systems are exposed, and it attacks their most valuable points, that is, insulation. One danger to lightning is that it will puncture the line insulators and shatter or set fire to the poles. The greater danger is that the lightning discharge will pass along the transmission wires to stations or substations and there break down the insulation of the generators, motors, or transformers. Damage by lightning may be prevented by either of two ways, that is, by shielding the transmission line so completely that no form of lightning charge or discharge can reach it, or by providing so easy a path from the line conductors to the earth, that lightning reaching these points will follow the intended path rather than any other. In practice the shielding effect is sought by grounded guard wires and the easy path for the discharge takes the form of lightning arresters, but neither of these devices are entirely satisfactory.

Aerial transmission lines are exposed to direct discharges of lightning, to electromagnetic charges due to lightning discharges near by and to electrostatic charges that are brought about by contact with or induction from electrically charged bodies of air. It is evidently impractical to provide a shield that will free overhead lines from all of these influences.

Grounded guard wires near to and parallel with the long aerial circuits should tend to discharge any electrostatic pressure existing in the surrounding air, and materially to reduce the probability that a direct discharge of lightning will choose the highly insulated circuit for its path to earth. Lightning arresters may conduct direct and induced lightning discharges to earth, without damage to transmission lines, so that both arresters and guard wires may be used logically in the same system.

Wide differences of opinion exist as to the general desirability of grounded guard wires on transmission lines, both because of their undoubted disadvantage and because of the degree of protection that they afford is uncertain. The most noted defect of guard wires depend largely on the kind of wire used and the method of its erection. Galvanized iron wire with barbs every few inches has been more generally used as guard wires along transmission lines than any other sort. Sometimes a single guard wire of this sort has been used on a pole line carrying transmission circuits, the common location of the single guard wire is at the extreme top of the pole. Other forms are to have two guard wires located at the ends of the upper cross-arm outside of the power wires. Much variation in practice also exists as to the grounded connections of guard wires such connections being made at every pole in some systems and much less frequent in other systems. At the present time, knowledge of the laws governing the various manifestations of energy that are known as lightning discharges are imperfect, and the most reliable rules for the use of guard wires along transmission lines are those derived from practical experience.

Transformers are almost always necessary in long electric systems of transmission, because the line voltage is greater than that of generators or at least that of distribution. As transformers at either generating or receiving station represents an increase of investment without corresponding increase of working capacity, and also an additional loss in operation, it is desirable to avoid their use as far as it is practicable. In short, transmissions over distances less than fifteen miles it is generally better to avoid the use of transformers at generating stations and in some of these cases where the transmission is only two or three miles, it is even more economical to omit transformers at substations. Thus, where energy is to be transmitted two miles and then applied to large motors in factories, or distributed at 2500 volts the cost of bare copper wire for the three-phase transmission line will be only about $6.00 per kilowatt of line capacity at 2500 volts, with copper at 15¢ per pound, and a loss of 5% at full load. The average loss in such a line will probably be as small as that in one set of transformers and a line of higher voltage. Furthermore the first cost of the 2500 volt gemerators and line without transformers will be less than that of generators and line of higher voltage with some step-down transformers at the substation. As generators developing differences of potential up to 13500 volts are now regularly manufactured, it is quite common to omit step-up transformers at the main stations of rather short transmission systems.

Another solution of the problem is to provide one transformer for each three-phase generator, one transformer being wound with three sets of coils, sothat the entire output of the generator can be sent into it. With the three-phase transformers each generator and its transformer form an independent unit that can be connected to the line at pleasure, thus tending to keep the transformers at full load. As the regulation of transformers on over loads is not as good as that of generators, it seems good practice to give each group of transformers a somewhat greater capacity than that of generators. Usually the number of groups of transformers at a two-phase or three-phase generating station is made greater than the number of transmissions circuits supplied by the station. When this is not the case it is commonly desirable in any event to have as many groups of step-up transformers as there are transmission circuits, so that each circuit may be operated with transformers that are independent of the other circuits.

At substations it is also desirable to have a group of transformers for each transmission circuit andit may be necessary to subdivide the transformer capacity still further in order to keep them in operation at nearly full load, or to provide a group of them for each kind of service, or for each distribution circuit. All the transformers at the substation should have a total capacity equal to a little more than the output of the generators whose energy they are to receive, minus the loss of the step-up transformers and the line.

As transformers can be wound for any desirable ratio of voltage in their primary and secondary coils, a generator capacity that will allow the most economical construction can be selected where step-up transformers are employed. In general it may be said that the greater the capacity of the generator, the higher should be its voltage and that of the primary coils of step-up transformers for economical construction. At substations the requirementsof distribution must obviously fix the secondary voltage of transformers. The weight and cost of transformers depend in part on the frequency of the alternating current employed, transformers being higher and cheaper the greater the number of cycles completed per second by their current, other factors remaining constant. In spite of this fact the tendency during later years is to decrease the frequency, because the lower frequencies present marked advantage as to inductive effect in transmission systems, the distribution of power through induction motors, the construction and operation of rotary converters and the construction of generators. Instead of the 133 cycle per second that were the most common in alternating systems when long transmissions first became important, 60 cycles per second are now common, although practice is constantly extending the frequency to as low as 25 and 12 cycles per second.

Electrical transmissions over long distances in America have been mainly carried out with alternating, current, while in Europe on the other hand continuous current is widely used. So radical a difference in practice seems to indicate that neither system is lacking in superiority. A fundamental feature of long transmissions is the high voltage necessary for economy in conductors, and this is attained by entirely different methods in the two systems. In dynamos of several hundreds of kilowatts capacity the pressure of continuous current has thus far not been pushed above 4000 volts, because of the danger of sparking and flashing at the commutator. Where 10000 volts or more are required on a transmission line of continuous current, a number of dynamos are connected in series so that the voltage of each is added to that of the other. This way the voltage of each generator may be as low as is thought desirable without limiting the total line pressure. There is no apparent limit to the number of continuous current dynamos that may be operated in series, or to the voltage that may thus be obtained, When occasion requires 20 to 30 or more dynamos to be operated in series, giving 50000 to 75000 volts on the line, machines of the continuous current type may be used. No matter how many of these dynamos are operated in series the electric strain on the insulation of the windings of each dynamo remains practically constant because the iron frame of each dynamo is insulated in a most substantial manner from the ground. The electric strain on the insulation of the windings of each dynamo in series is thus limited to the voltage generated by that dynamo. There is no practical limit to the thickness or strength of the insulation that may be interposed between the frame of each unit and the earth and hence no limit to the line voltage as far as dynamo insulation is conderned.

It is impracticable to operate alternating generators in series so as to add their voltages, and the pressure available in transmission with alternating current must be that of a single dynamo, or must be obtained by the use of transformers. The voltage of an alternating current dynamo may be carried much higher than with continuous current dynamos of very large capacity, and in many cases a pressure of 13500 volts are now supplied to transmission lines by alternating current dynamos while 4000 volts is about as high as can be obtained with continuous current dynamos. The height to which the voltage of single alternating dynamos will be carried no one can say, but it seems probable that the practical limit will prove to be much less than the voltage now employed in some transmission systems. To the voltage that may be supplied by transmission there is no practical limit now in sight.

Line construction for the continuous current transmissions is of the simplest character apart from the necessity of high insulation. Only two wires are necessary and they may be of any desired cross-section, and need not be transposed. On these wires the maximum voltage for which insulation must be provided is the nominal voltage of the system. It is possible under these conditions to build a single transmission line and two conductors of such size and strngth and at sucha distance apart that a high degree of reliability is attained against the break of wires and arcing between them. Compared with a continuous current transmission, one with alternating current often requires more poles and is quite certain to require more cross-arms, pins, insulators, and labor of construction. For a given effective voltage of transmission it is harder to insulate an alternating than a continuous current line. In the first place the maximum voltage of the alternating line evén with a true sine wave of pressure is 1.4 times the nominal effective voltage. Then comes the matter of resonance, which may carry the maximum voltage of an alternating circuit up to several times its normal amount, if the period of electrical vibrations for that particular circuit should correspond to the frequency of the generator that operates it. In a transmission line of continuous current on the other hand, if the prevailing practice of a constant current and varying line pressure is followed, the insulation is subjected to the highest voltage only at times of maximum load on the system.

The following is a practical problem of power transmission and shows how the different elements of a transmission line may be obtained. We may assume that a three-phase 100 mile transmission line delivers 10000 k.w. at a voltage of 100000 to the receivers. The allowable line drop to be 5%; the frequency 25 cycles; powerfactor .85 and the spacing of wires 10 feet apart.

We have:---

$$\text{Power per wire} = \frac{\text{total power}}{\text{no. of wires}} = \frac{10000}{3} = 3333.3 \text{ K.W.}$$

$$\text{Voltage between one wire and neutral} = \frac{\text{total volts}}{\sqrt{3}}$$

$$= \frac{100000}{1.732} = 57,736.7 \text{ volts.}$$

$$\text{Energy delivered by each leg} = \frac{10000 + (.5 \times 10000)}{3}$$

$$= 3500 \text{ K.W.}$$

$$\text{Apparent delivered energy} = \frac{3500}{.85} = 4117.6 \text{ K. W.}$$

$$= 4,117,600 \text{ watts.}$$

$$\text{Current in each leg} = \frac{\text{Watts}}{\text{volts}} = \frac{4117600}{57736.7}$$

$$= 71.1 \text{ amperes.}$$

$$\text{IR drop in each leg} = 5\% \times 57736.7 = 2886.8 \text{ volts.}$$

$$\text{Resistance of each leg} = \frac{\text{volts}}{\text{amperes}} = \frac{2886.8}{71.1}$$

$$= 40.6 \text{ ohms.}$$

$$\text{Resistance of each leg per 1000 ft.} = \frac{40.6}{5.28 \times 100}$$

$$= .077 \text{ ohms.}$$

This resistance corresponds to # 00, copper wire, hard drawn, whose resistance .079 ohms per 1000 feet.

Resistance of one-phase of # 00 wire= .079 x 100 x 5.28

= 41.7 ohms.

Resistance of line then is 41.7 x 3 = 125.1 ohms.

Capacity of line in microfarads = $C = \frac{.00776 \times L}{2 \log_{10} \frac{d}{r}}$

L = length of line in miles.

D = Distance between wires in inches.

r = Radius of wire in inches.

Then $C = \frac{.0776 \times 100}{2 \log_{10} \frac{120}{.1824}} = 1.42$ microfarads.

Charging current per wire, per leg = $I_c = \frac{E \times C \times 2 \pi \times F.}{\sqrt{3} \times 10^6}$

E = volts between wires.

F = frequency.

C= capacity in microfarads.

Then $I_c = \frac{100000 \times 1.42 \times 2 \times 3.14 \times 25}{\sqrt{3} \times 10^6.} = 12.87$ amps. per wire.

Inductance for one mile of wire per leg is

L (in Henrys) = $(80.5 + 740 \log. \frac{d}{r})^{10-6}$ =

$(80.5 + 740 \log \frac{120}{.1824})^{10-6}$

L = .001267 henrys per leg per mile of wire.

Inductance per phase is 100 x .0012 = .1267.

" " " of whole line is .1267 x $\sqrt{3}$ = .2193 henrys.

" " " per phase per mile = .0012 x $\sqrt{3}$ = .002193 henrys.

" " " in ohms is $2 \pi FL$ = 2 x 3.14 x 180 x .1267

= 79.567 ohms.

In a transmission line inductance and capacity are not concentrated at any one point, but distributed through out the line. To explain the phenomena of such a line by concentrated inductance and capacity is as futile as to try to explain the motion of an elastic string by the mechanism of concentrated mass and elasticity. The motion of the string is wave motion as is also the movement of electricity in a transmission line. The various formulas and assumptions may be regarded, therefore, as approximations, more or less exact. The engineer desires a formula that is accurate and easy to apply. The exact equation of transmission line has been known for a long time, but it has been in a form not easy to apply.

The exact equation is of the nature of a Hyperbolic Function:

$$E_g = E_1 \cosh\sqrt{yz} + \frac{I_1 \sinh\sqrt{yz}}{\sqrt{yz}}$$

$$I_g = I_1 \cosh\sqrt{yz} + \frac{E_1 \sinh\sqrt{yz}}{\sqrt{yz}}$$

E_g and I_g are the voltages and current at generating end.

E_1 and I_1 " " " " " " " " the loaded end.

$Z = r + j\,2\pi f\,l$ or the line impedance.

$Y = g + j\,2\pi + C$, where g is the leakage conductance and C is the capacity of the whole line. Cosh and sinh are functions of the comples variable $\sqrt{yz}$ and are defined by the equations:

$$\cosh\sqrt{yz} = \frac{e^{+\sqrt{yz}} + e^{-\sqrt{yz}}}{2} \;;$$

$$\sinh\sqrt{yz} = \frac{e^{+\sqrt{yz}} \quad e^{-\sqrt{yz}}}{2} \;.$$

In order to solve a numerical problem it is necessary to first evaluate the $\sqrt{yz}$ andthen to determine the hyperbolic functions, either from double interpolation from a table of such functions of a complex variable or else to expand the functions into a trigonometric form. Mc. Laurin's therom in calculus furnishes us with a much simpler method of expanding a function in ascending powers of the independent variable, and will give us a desirable formula.

Mr. Mc Laurins therom states that

$$f(x) = f'(o)x + f''(o)\frac{x^2}{\underline{/2}} + \ldots$$

Now $\frac{d \cosh x}{dx} = \frac{d}{dx}\left(\frac{e^x + e^{-x}}{2}\right) = \frac{e^{+x} - e^{-x}}{2} = \sinh x.$

$\frac{d \sinh x}{Dx} = \frac{d}{dx}\left(\frac{e^x + e^{-x}}{2}\right) = \frac{e^{+x} \mp e^{-x}}{2} = \cosh x.$

Also cosh (o) = 1 and sinh (o) = 0

Then $\cosh\sqrt{yz} = 1 + \frac{yz}{\underline{/2}} + \frac{y^2z^2}{\underline{/4}} + \text{---------}.$

$\sinh\sqrt{yz} = \sqrt{yz}\,\left(1 + \frac{yz}{\underline{/3}} + \frac{y^2z^2}{\underline{/5}} + - - -\right)$

By substituting in the equations of E_g and I_g we get that

$E_g = E_1\left(1 + \frac{yz}{\underline{/2}} + \frac{y^2z^2}{\underline{/4}} + \text{---}\right) + I_1Z\left(1 + \frac{yz}{\underline{/3}} + \frac{y^2z^2}{\underline{/5}} + \text{--}\right)$

$I_g = I_1\left(1 + \frac{yz}{\underline{/2}} + \frac{y^2z^2}{\underline{/4}} + \text{---}\right) + E_1Y\left(1 + \frac{yz}{\underline{/3}} + \frac{y^2z^2}{\underline{/5}} + ??\right).$

From Dr. Steinmetz's "Alternating Current Phenomena", we get that the capacity concentrated in the middle of the line is

$$E_g = E_1 \left(1 + \frac{yz}{2}\right) + I_1 Z \left(1 + \frac{zy}{4}\right)$$

$$I_g = I_1 \left(1 + \frac{yz}{2}\right) + E_1 Y.$$

for capacity concentrated two-thirds and one-sixth at each end.

$$E_g = E_1 \left(1 + \frac{yz}{2} + \frac{y^2z^2}{36}\right) + I_1 Z \left(1 + \frac{yz}{6}\right)$$

$$I_g = I_1 \left(1 + \frac{yz}{2} + \frac{y^2z^2}{36}\right) + E_1 y \left(1 + \frac{5yz}{36} + \frac{y^2z^2}{216.}\right)$$

From tables in numerous handbooks we have that

$Z = 65.65 + j\,93.45$

$yz = -0.0664 + j0.0452$

$y^2z^2 = 0.0024 - j\,0.003.$

Also we have that

$$\frac{E^i}{\sqrt{3}} = \frac{E_1}{\sqrt{3}} + I_e(Z)\left(1 - \frac{yz}{3} + \frac{y^2z^2}{15} + \ldots\right)$$

Whence by substituting,

$$\frac{E^i}{\sqrt{3}} = \frac{100000}{\sqrt{3}} + 71.1\,(65.60 + j\,93.45)(1 + .0221 - j.0151 + .0003 - j.0004)$$

$$E^i = 100000 + \sqrt{3}\,(71.1)(65.60 + j93.45)(1.0224 - j.0155)$$

$$= 100000 + 123.003\,(68.52 + j\,94.53)$$

$$= 100000 + 8070 + 107.8 = 108177.8$$

$$\text{Regulation} = \frac{108177.8 - 100000}{100000} = 8.17\%$$

Total Cost of Line.

Cost of conductors erected, on average of 20¢ per lb. ,

is 647 x 3 x 100 x .20------- $40,820.00

Cost of steel towers erected and with insulators averaging

$125 a piece, putting 8 to mile is

$125 x 8 x 100-------------$100,000.00

Total cost of line is $140,820.00

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