Engineering Features of the Boulder Dam-Los Angeles Lines

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Bureau of Power and Light
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Marking a new milestone in the history of the transmission of electric power, the 275 kv system that will transmit power from Boulder Dam to Los Angeles, Calif., embodies many novel engineering features. These features are discussed in this paper. The paper includes not only a description of the line and the terminal equipment and facilities, but also a discussion of the effects of the characteristics of each portion of the system on the performance of the system as a whole. The engineering studies and laboratory research on system stability, corona, high voltage impulses, lightning, conductor vibration, tower stresses, footing uplifts, and other factors are described, and the use of such data in the selection of line voltage, conductors, insulation, clamps, lightning protection, towers, and appropriate generating, transforming, and receiving end equipment is shown.

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THE Boulder Dam transmission system of the Bureau of Power and Light, Department of Water and Power, of the City of Los Angeles, Calif., will serve to transmit its allotment of power from Boulder Dam to Los Angeles, a distance of 266 miles, and consists of 2 60-cycle 3-phase circuits with a nominal line to line voltage of 275 kv. In the more or less built up section adjacent to Los Angeles, 40 miles of the line is carried on double circuit steel towers. The remainder of the line is carried on single circuit steel towers, with the conductors in horizontal configuration. Two sectionalizing switching stations are located at $^1/_3$ points.

Approximately 60 miles of the single circuit tower portion of line extends through mountainous territory, encountering 3 main mountain passes, at elevations of 4,862, 4,419 and 3,809 feet above sea level. Approximately 166 miles of the single circuit line is in desert territory of a hilly or flat topography, with a prevailing elevation of 2,000 to 3,000 feet. At least 225 miles of the line is subjected to the sparse and erratic rainfall associated with the desert. Such rainfall, at times, is of cloudburst proportions. The remainder of the line is in territory having the seasonal but somewhat limited rainfall experienced in the coastal plain of southern California. The desert section is subject to lightning storms at a frequency of 20 to 30 storm days per year.

The desire to achieve the utmost in high standards of continuous service, and the fact that this line will provide a relatively large portion of the total system power of the Bureau of Power and Light has made it necessary to regard reliability as the foremost consideration in the design of the line. A very liberal policy has been followed in conducting research to develop or verify and refine each step in the design of the line, and in establishing safety factors in order that the desired reliability might be assured. The newly developed features of the line, therefore, not only have a definite purpose, but have their performance well verified in advance by exhaustive investigation. The care in design has been carried on into the purchase and routine testing of the materials before they are incorporated into the line.

System Voltage and Equipment Characteristics

The earliest preliminary thought about this line centered on the use of 220 kv as the nominal rated voltage. At that time the state of the electrical art was such that the means of determining the dynamic stability or power limit of a transmission system had not been developed, and the proper method of determining the static power limit was a subject of discussion. It was realized that the most important factor in determining the voltage of the line was the power limit. In order definitely to obtain the required reliability, the ability of the system to withstand various types of disturbances without losing synchronism had to be determined. Such studies involve the terminal equipment and lay the basis for the selection of such equipment as well as line voltage. From a knowledge of the relative cost and the relative performance at each voltage, came the decision to use 275 kv.

In this work, methods of calculation were devised[1] that followed the fundamental theory set up in various papers on this subject[2,3,4]. Certain refinements were taken into account by setting up the circuits in terms of general circuit constants including all line characteristics and the exciting current and reactance characteristics of the terminal equipment. In addition, an approximate but fairly ac-

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[1] For all numbered references see bibliography at end of paper.

curate method was devised of taking into account the characteristics of the load, by having the power component of the portion of the load admittance that represented induction motor load to increase inversely as the square of the voltage during disturbances, thus more closely representing the action of such load in consuming constant power, and drawing increased current as the voltage drops during synchronizing action on the system. Such motor load was assumed to comprise 40 per cent of the total load. In making these studies, the problem was reduced to a 2 machine problem, and the method of calculation was one giving results directly without making use of the point to point method of calculation and plotting time-angle curves.

Power limits are affected by many factors subject to variation, such as mechanical and electrical characteristics of the synchronous apparatus at each end of the line, frequency, voltage, spacing of conductors, location, type and duration of fault, number of sectionalizing points and manner and time required in switching faulted sections, nature of load, voltage drop between ends of line, reactance of transformers, and many other less prominent variables. As the preliminary work progressed, certain preliminary conclusions and assumptions became quite obvious and narrowed down the field to be investigated. These may be stated as follows:

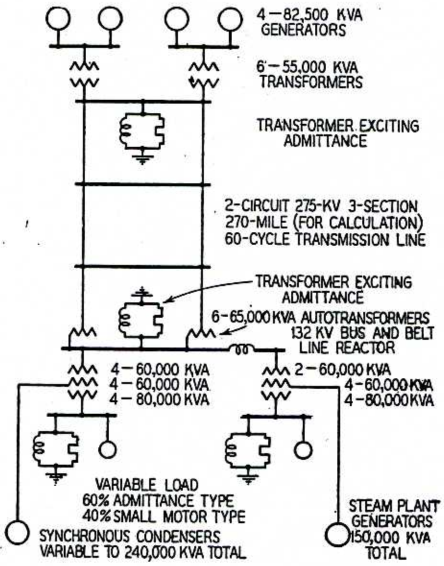
1. The power limit is increased appreciably as the reactance between the internal voltages of the synchronous machine groups is reduced.
2. Corollary to the above, low reactance generators with large inertia effects were found to increase the power limit more than 40,000 kw, which justified the assumption of using the most liberal design of generators obtainable.
3. Sudden increasing of the reactance, such as occurs when a faulted line section is switched out, reduces the power limit very materially; hence it is essential that results be obtained principally for this case.
4. Three line sections are necessary, as the increase in power limit over that obtained by using 2 line sections is worth many times the investment in an additional switching station.
5. Within practicable limits, changes of spacing, diameter, or resistance of the conductors have negligible effects on the power limit.
6. Because of the effects of the equipment, the power limit varies almost directly as the transmission voltage, for lines of this length.
7. The fastest possible switching is exceedingly desirable to increase the power limit.
8. For the system arrangement contemplated for these lines, a fault near the sending end bus and involving one section of line to be switched out generally reduced the power limit to the lowest value.
9. Excepting for fault durations of less than 0.1 second the power limits for 3-phase faults are so low that it would not be considered economical to design the system to remain in synchronism for such conditions.

The rating of the system, that is its reliable transmitting capacity, of necessity depends on the criteria set up as to the type of fault that the system successfully must handle. Since a 3 phase fault is of exceptional occurrence and would be still less likely with reasonably rapid switching, and since it produced relatively low power limits, it finally was decided that the system would be rated on the load it could carry and not lose synchronism when subjected to 2 conductor-to-ground faults at the most unfavorable location, when the fault was removed by switching out a section of line in 0.2 second. When this switching duration was set it was considerably more rapid than generally seemed possible of achievement. However, confidence in this possibility was rewarded by switches and relays finally being supplied that will limit the fault duration to less than 0.11 second.

A single line diagram of a typical system setup is given in figure 1. Every element shown in the diagram was subject to variation in the study, which makes the tentative list of assumptions too long to include. The 2 groups of synchronous machines at the receiving end were combined into one equivalent machine. The load kept its separate identity.

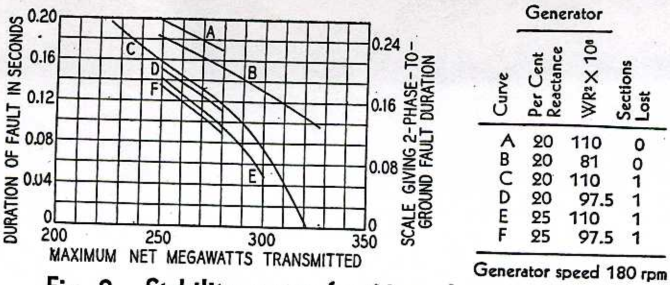
In accordance with preliminary system studies,[5] it was desirable to transmit a load of approximately 240,000 kw to one receiving station. The first stability studies at 220 kv, using 2 circuits and 300,000 kva of low reactance generators, gave a theoretical power limit of the order of only 150,000 kw. If the generator ratings had been reduced accordingly, the value would have been still lower and more unsatisfactory. Further studies indicated that where under certain circumstances 3 220 kv lines would have a theoretical power limit of 280,000 kw, 2 275 kv lines would have a power limit of 265,000 kw and would transmit power at a cost per peak kilowatt of approximately 17 per cent less. Although more power could be transmitted by using a higher voltage, such as 330 kv, the use of such a voltage would result in excessive costs, because of the large diameter of conductor required, and would not be as economical per peak kilowatt. Since the 275 kv lines were the most economical and fitted in best with the desirable size of receiving station already established, this voltage was selected.

Fig. 1. Typical one line diagram of Boulder Dam-Los Angeles transmission system as used in stability studies



Sending End Equipment

The present system of the Los Angeles Department of Water and Power operates on a frequency of 50



	Generator		
Curve	Per Cent Reactance	$WR^2 \times 10^6$	Sections Lost
A	20	110	0
B	20	81	0
C	20	110	1
D	20	97.5	1
E	25	110	1
F	25	97.5	1

Generator speed 180 rpm

Fig. 2. Stability curves for 60 cycle operation of system with a 3 phase fault at sending end

cycles per second. There were many reasons, from the standpoint of engineering and practical economics for both the system and the consumer, that made a change-over to 60 cycles attractive. If such a change were to be made, it obviously should be made at the time of bringing in such a large amount of new power. Other reasons, of a nonengineering nature, delayed the possibility of an early decision, so that much of the work had to be done for both frequencies and the earlier equipment specifications and purchases had to be made so as to permit the use of either frequency.

A typical set of stability curves for 60 cycle operation is shown in figure 2. All curves are for the condition where the fault is on a line section just out from the high voltage bus at the sending end. If no line sections are lost, the short circuit would be on the bus. All curves were calculated and drawn for the 3 phase fault condition as this saved considerable work in calculation and served for comparative purposes. In addition, a great many calculations for 2-phase-to-ground faults had indicated that for such a system as this, the permissible duration of a 2-phase-to-ground fault for the shorter switching times was 4/3 that of a 3 phase fault at the same load. The curves, therefore, were made to serve for 2-phase-to-ground faults by adding a new scale at the right-hand side of the graph, giving such approximate durations.

From the foregoing curves and other similar ones, were plotted the data given in figure 3, where the curves show power limits, in accordance with the criteria set up for line rating. For the particular system setup used, the inertia constant H used as abscissa is given by the relation[2]

$$H = \frac{4 \times 0.462 \times WR^2}{250{,}000}\left(\frac{\text{rpm}}{1{,}000}\right)^2 = 7.4\,\frac{WR^2}{1{,}000{,}000}\left(\frac{\text{rpm}}{1{,}000}\right)^2$$

where W is the weight of the rotating parts of one machine in pounds, R is the radius of gyration in feet, and rpm is the synchronous speed of the generator in revolutions per minute.

The lowest practicable transient reactance that could be obtained in designing a generator for straight 50 or 60 cycle use was about 21 per cent, while a generator suitable for operation at either frequency would have reactances of 21 and 17.5 per cent at 50 and 60 cycles, respectively, if the rating were held at the same value in both cases. The maximum value of moment of inertia (WR^2) that could be worked into the design was a function of the runaway speed of the water wheels, being larger for the lower speed. A tabulation of data for the 5 typical generators is given in table I.

An important point in the selection of the generators of table I is that the turbine used on the double speed machine has such dimensions that its maximum overspeed is lower than that of a single speed design with the same synchronous speed, which, together with the reduced reactance, gave a more favorable 60 cycle condition than a machine designed exclusively for 60 cycles. The frequency decision could not be settled at the time the generators were specified; however, as the most probable frequency would be 60 cycles, and as the power limit at 50 cycles was adequate, the double frequency machines fulfilled requirements very satisfactorily. As the switching time has been decreased from that shown in table I to 0.11 second, the power limits have been increased, still further. As these theoretical limits have no safety factor, the actual operating capacity has been fixed at 80 per cent of the theoretical figure to allow for imperfection of assumptions in calculation and to allow for general system hunting. Such rating is 235,000 kw.

In fixing the rating of the generators, one is faced with the fact that if the rating were made in exact accordance with the kilovoltamperes required for normal peak, the machines would be smaller than those of table I and no longer would permit the required power to be transmitted because of their higher reactance. Therefore, the method of obtaining low reactance consisted partly of using increased rating. This increased rating serves other functions, namely, stand-by capacity in the power plant and also for emergency operation, when because of failures in other power sources it is desirable to transmit larger amounts of power over this system, even at the risk of losing synchronism if a fault should happen. Such emergency rating is 300,000 kw delivered, requiring 4 82,500 kva generators for the 2 circuits.

The generators finally selected are 40-pole vertical water-wheel-driven machines, with main exciter and pilot exciter on the same shaft, and are rated 150/180 rpm, 13,800/16,500 volts, 50/60 cycles, 82,500 kw at unity power factor. They are provided with amortisseur windings and have the type of insulation designated as Class *B* on the armature and field. (Class *B* insulation consists of inorganic materials such as mica and asbestos in built-up form combined with binding substances.) At 50 and 60 cycles, respectively, the short circuit ratios are 2.28 and 2.74 and the transient reactances are not more than 21 and 17.5 per cent. The flywheel effect of each

Table I—Generator Characteristics and Power Limit for 5 Generators

Frequency, Cycles per Second	Per Cent Reactance	Speed, Rpm	Over-speed, Rpm	WR^2 Lb-(Ft)^2	H	Theoretical Power Limit/(*KW*) at 0.15 Sec
50	21	150	280	127×10^6	21.1	301,000
50	21	187.5	350	75	19.5	297,000
60	21	150	280	127	21.1	273,000
60	21	180	335	80	19.2	271,000
50/60	21/17.5	150/180	320	110	18.3/26.3	291,000/280,000

generator will be not less than 105,000,000 pounds at a radius of one foot. The load on the thrust bearing is of the order of $1^3/_4$ million pounds. The total weight of the generator is about 2,000,000 pounds. Because of the long time constant of such machines, and the rapid switching contemplated, there was no need for the highest possible rates of excitation, so the exciter response was set at 0.5. The over-all diameter is 40 feet and the over-all height above the generator floor line is 22 feet. The rating of the turbines under the minimum head of 420 feet is 90,000 horsepower, corresponding to a generator output of 65,000 kw, which with 4 machines provides for the normal reliable peak capacity of the line. However, as the head is increased larger outputs become available. For all heads in excess of 525 feet the turbine can deliver the full rating of the generator corresponding to an output of the turbine of 115,000 horsepower.

Two generators are connected to each transformer bank consisting of 3 55,000-kva water-cooled 287,500 Y/16,320-volt single-phase transformers. The high voltage windings are of the circular coil non-resonating type and are designed to withstand a $1^1/_2$x40 microsecond impulse voltage sufficient to flash over an 88 inch rod gap on the tail of the wave. The impedance is as low as practicable and will not exceed 10.75 per cent; the exciting current at normal voltage is 4.5 per cent and the full load efficiency is 99.31 per cent. The transformers each require a floor space 13 by 21 feet and their over-all height is 32 feet. The total weight of each transformer is 385,000 pounds of which 150,000 pounds is oil.

Receiving End Equipment

The generally accepted method of controlling transmission line voltage is to operate with fixed voltages at the sending and receiving ends. Voltage regulators for the generator hold fixed voltage either at the generator terminals or are compensated to the high voltage bus at the sending end. Synchronous condensers or other synchronous machines are required at the receiving end. The regulators for these machines usually are compensated to hold fixed voltage at the load bus or the incoming voltage bus, depending on system connections. The exact amount or points of compensation have not been decided. Such methods of operation are equivalent to operating on a fixed voltage ratio circle on a receiving end circle diagram for the transmission line and equipment between the constant voltage points. From such a circle diagram, and the known characteristics of the system load, it is possible to estimate the required condenser capacity for all loads. Such a set of curves for the Boulder Dam system is given in figure 4. The curves are for full 2 circuit operation and for operation with one section out, designated as $1^2/_3$ circuits. The controlling points are the lagging requirement at very light loads and the leading requirement for the emergency rating of 300,000 kw delivered. Normal synchronous condenser design produces machines that have a lagging rating of 40 to 60 per cent of their leading rating. It is best, therefore, to select the voltage ratio between the 2 ends of the line of such value that approximately this adjustment is obtained. In this system the voltage ratio of 1.05 approximately does this and also approximately adheres to the established voltage ratings of equipment where the maximum operating voltage is 115/110 of the nominal. This latter ratio of 287,500 to 275,000 volts between sending and receiving ends was adopted. On this basis approximately 240,000 kva leading is required to deliver 300,000 kw and 115,000 kva lagging is required at zero load. There is the possibility that when emergency loads are being carried the voltage ratio can be increased, and approximately 200,000 kva of condenser capacity will be sufficient. This is very close to the requirement necessary to transmit the normal peak of 240,000 kw over the system with one section of one line out of service. At 50 cycles the requirements were about the same for high loads, but about 20,000 kva less lagging capacity was required at zero load. The capacity used to permit of the emergency rating essentially gives sufficient capacity to have the equivalent of a spare machine during ordinary operation.

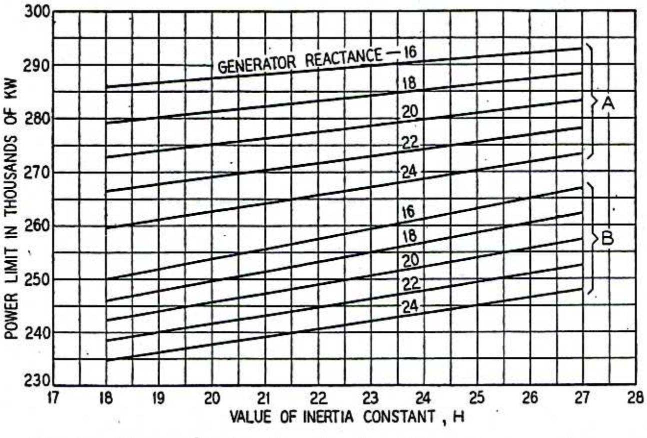


Fig. 3. Power limits of system for 60 cycle operation

A. Fault cleared in 0.15 second
B. Fault cleared in 0.20 second

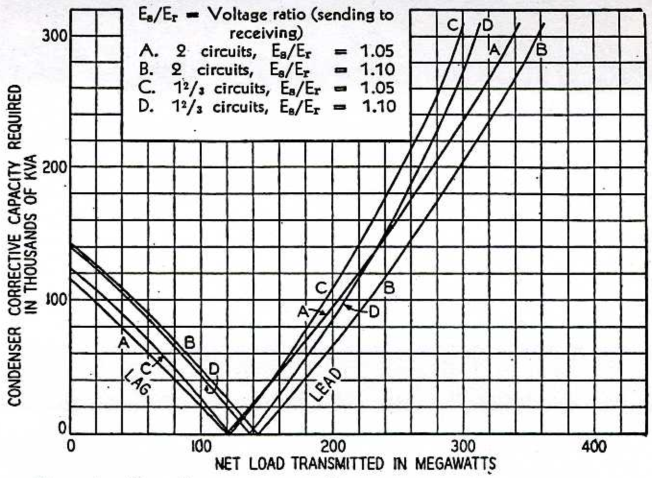


Fig. 4. Synchronous condenser corrective capacity required for operation at 60 cycles (transformers included)

The stability problem also entered into the selection of the proper equipment characteristics at the receiving end. For this purpose stability curves were plotted showing the effects of reactance of the autotransformers, reactance, and inertia of the condensers, location of fault, and fault duration. Some results were obtained without consideration of the auxiliary or stand-by steam plant.

The section of line at the receiving end included the same length of line as the other sections and, in addition, included the reactance of the autotransformers. Studies in connection with the generators had indicated that a sending end fault represented the worst operating condition. In studying the receiving end equipment, variations were made in such equipment and results obtained for faults at each of 3 locations, namely: sending end, losing adjacent line section; receiving end, losing receiving end line section; fault 180 miles ($^2/_3$ point) from generator, losing receiving end section. For any given setup, the sending end fault gave the lowest or controlling power limits or line ratings. The receiving end faults gave the highest power limits. The 180 mile fault gave limits slightly in excess of those for the sending end. For fault durations of the order of 0.1 second the power limits for the 180 mile fault were almost equal to those for sending end faults, and for quicker switching would be slightly less and thus establish the rating. For the switching times involved in this study, these results indicated that the proper correlation had been obtained in setting the electrical length or reactance of each section.

Decreasing the reactance of the autotransformers from 10 per cent to 7 per cent at 50 cycles increased the theoretical power limit 11,000 kw for sending end faults and about 15,000 kw for 180 mile faults, for the fault durations under consideration (0.14 and 0.11 second). For 60 cycles, decreasing such reactances from 12 to 8.4 per cent increased the power limits 14,000 and 20,000 kw, respectively, for the preceding 2 fault locations. Obviously such improvement is worth more than the increased cost of low reactance transformers so autotransformers of the lowest practicable reactance were purchased.

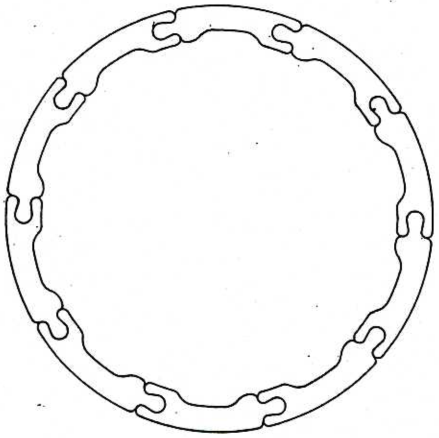


Fig. 5. Cross section of conductor selected

Area of cross section 512,000 circular mils
Wall thickness: maximum 115 mils; minimum 80 mils
Number of segments, 10

Two types of synchronous condensers were considered, one having a transient reactance of 35 per cent and a moment of inertia (*WR^2*) of 1,500,000 pounds at a radius of one foot, and the other having 50 per cent reactance and a moment of inertia of 1,250,000 pounds at a radius of one foot. In all cases, whether considered with or without auxiliary steam plant at the receiving end, it was found that the smaller high reactance machine gave the higher power limits. In either case the difference was small, being of the order of 3,000 kw. Under such circumstances, the lagging requirements controlled the selection of the condensers; and as the 50 per cent reactance machine satisfied these requirements, there was no object in purchasing more liberal equipment.

Within the range of the switching times considered, and for the final resulting system setup, the improvement in theoretical power limit is about 3,000 to 5,500 kw for each 0.01 second reduction in fault duration. On the basis of such improvement in performance, the selection of the most rapid switches, developed with an over-all switch and relay time of not more than $5^1/_2$ cycles, was made. With such switches the theoretical power limit in accordance with criteria previously referred to is 292,000 kw. A more detailed description of all the receiving equipment will be given in connection with the consideration of the receiving station.

DIAMETER OF CONDUCTOR

For the voltages under consideration for this line, the primary consideration in the choice of conductor diameter is corona loss. In general, the diameter that will give an economical value of corona loss will be large enough but the amount of material required to construct such a conductor is likely to be more than is needed for conducting the currents that will exist in such a line.

No corona loss data were available for cables larger than approximately 1.1 inches in diameter.[6] Such tests indicated that existing corona loss formulas did not give accurate results for cables of such large diameter, particularly in the low loss portion of the curve which is the part a designer is most interested in. Accordingly, tests were made at the Ryan high voltage laboratory at Stanford University on stranded cables with diameters of 1.125, 1.49, and 2.00 inches to study the effects of diameter, condition of surface, spacing, atmospheric conditions, effects of cleaning, and other factors that would be pertinent to the selection of conductors for voltages ranging from 220 to 330 kv.[7] Further data on effects of surface conditions, temperature, humidity, and barometric pressure were provided by graduate student investigations in the same laboratory.[8,9]

Such laboratory tests cannot be conducted under exactly the conditions that will be encountered along the line, that is, the temperatures and barometric pressures will be different, as well as other less well known variables such as dust, humidity, and surface conditions. Furthermore, unless a great many cables were tested, it is likely that none of the sizes tested would be the final choice. In order to make use of fewer tests and in order to be able to make the design fit the line conditions, it was desirable to derive a method of calculating losses that would agree with the tests and that could be used with some assurance for all the conditions anticipated along the line.[10]

A preliminary study of various designs of conductors was made to form the basis of an economic study to determine the proper conductor diameter to use. From data pertaining to the lighter designs, complete estimates of annual cost were made, after having determined the most economical combination of span and tension for each form and size of cable under consideration. The effects of conductor weight, strength, and diameter on tower and insulator costs were included, as well as those things directly pertinent to the conductor such as conductor cost, resistance, and corona losses. In this study the probable elevations and temperatures of the line were taken into account.

In the region of minimum cost, the annual cost of the conductor varies very gradually with the diameter. The corona tests had indicated that some uncertainties creep into the conditions that affect corona, so it is desirable to use some safety factor in the selection of the diameter. The economic choice in general comes near the knee of the corona loss curve. At such a point a small change in the uncontrollable and least known conditions makes large changes in the corona loss and could increase the annual cost possibly 30 per cent. Because of the relatively flat form of the cost curve, it was deemed advisable to be liberal by selecting a conductor diameter 0.1 inch larger than the theoretical but slightly uncertain diameter economy would dictate. From these studies the diameter of the conductor was fixed at 1.4 inches.

These preliminary corona and conductor studies provided appropriate information for making line estimates at various voltages when voltage selection was under way.

TYPE OF CONDUCTOR

Conductor studies had indicated that when all features of cost were considered, the most economical cross section of a copper conductor of 1.4 inches in diameter was of the order of 500,000 circular mils, and that the maximum tension should be 40 per cent of the ultimate strength. The main influences on these values were those involving mechanical loading.

Essentially 6 different designs of cable were offered to meet the requirements of the line conductor:

Type *A*. A copper conductor weighing 2.226 pounds per foot, made up of a 7 wire strand surrounded by 6 twisted I beams with a single layer of round wires over all, this outer layer containing 30 wires each 0.125 inch in diameter.

Type *B*. A copper conductor, weighing 2.545 pounds per foot, made up with an inner structure composed of a central tube surrounded by layers of smaller tubes, with a single outside layer of 37 solid round wires each 0.104 inch in diameter; a variation of this conductor having thinner walled tubing and weighing 2.387 pounds per foot also was considered.

Type *C*. A hollow copper conductor weighing 1.57 pounds per foot, made up of 10 interlocking segments forming a self-supporting tubular structure; a similar conductor of heavier section weighing 2.3 pounds per foot also was considered.

Type *D*. An aluminum conductor, steel reinforced, weighing 1.852 pounds per foot containing 66 aluminum wires 0.1355 inch in diameter and 19 steel wires 0.117 inch in diameter; a conductor weighing 1.44 pounds per foot similar to this, excepting that a hemp filler of 0.213 inch radial thickness is used between 19 0.086 inch steel wires and 50 0.1355 inch aluminum wires, also was considered.

Type *E*. A copper conductor weighing 2.667 pounds per foot, of standard single-twisted I-beam construction, having 2 layers containing 66 wires 0.1077 inch in diameter.

Type *F*. A hollow copper conductor, weighing 1.80 pounds per foot, made up of 12 segments, grooved to take an oval wire acting as a tongue between adjacent segments.

Typical cross sections of these various cables are shown in figure 1 of a paper entitled "Corona Losses From Conductors of 1.4 Inches in Diameter." [11]

In selecting the conductor, comprehensive and accurate estimates of annual costs were worked out for each type for various tensions and span lengths, so that comparisons would be made between the most economical uses of each type. The lighter conductors showed savings of the order of $12^1/_2$ per cent over the heavier types, partly due to conductor price and partly due to the higher cost of towers and supports for the heavier conductors.

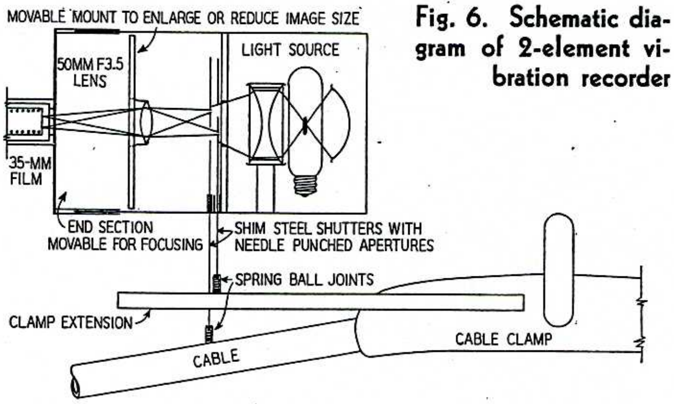


Fig. 6. Schematic diagram of 2-element vibration recorder

Comparative corona tests were made[11] and type *C*, the interlocked segmental type of hollow copper conductor, showed the lowest losses and preferable characteristics, although all conductors, as was anticipated, had low losses at the operating voltage, even with some allowance for elevations.

Because of the low weight for the diameter involved in all these cables, it was thought necessary to give due regard to the tendency for conductors to vibrate in light winds[12, 13, 14]. As a preliminary test to assist in the selection of conductors, a wind tunnel was used that provided an orifice 50 feet long and 2 feet high which was so baffled and controlled as to produce a quite uniform wind velocity across cables hung in front of the opening. In this manner the tendency of the cable to vibrate under the same type of forces and at the same tensions as in actual practice was simulated closely. Although from its diameter-weight relation, the light hollow copper cable might be expected to give greater amplitudes under such conditions, it actually gave the same amplitudes as the heaviest I beam type of conductor; this indicated a considerable degree of self-damping, a fact that was confirmed by later tests.

These data together with the successful operation of similar cables in Germany, led to the selection of the cable as previously described under the designation "type *C*"; a cross section of this cable is shown in figure 5. The copper area is 512,000 circular mils. As a permanent lubrication between segments, graphite is introduced between the surfaces of the interlocking tongue and groove. The exterior of the cable is washed and cleaned thoroughly as was indicated to be necessary from the corona tests. The ultimate guaranteed tensile strength is 21,600 pounds.

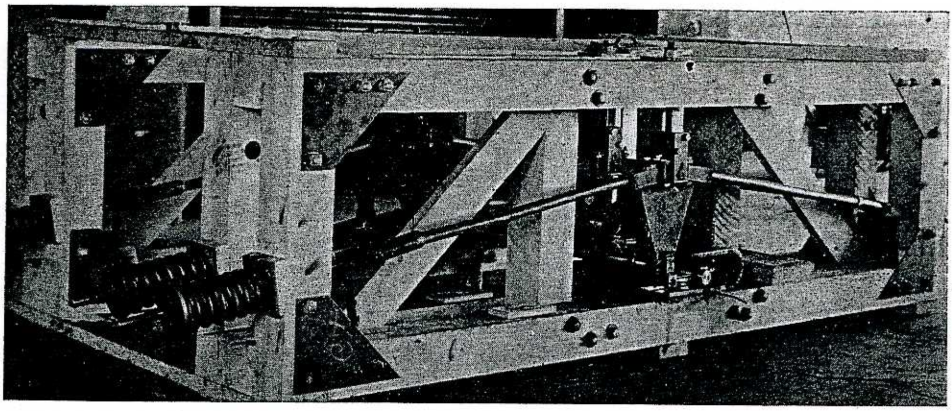


Fig. 7. Cable testing frame for studying bending properties of conductor

Vibration Studies for Clamp Development

Having selected the cable, the next procedure was to determine accurately all the vibration characteristics of the cable, in order to ascertain what features had to be incorporated into the design of the clamps to be used therewith so that the possibility of fatigue failures would be eliminated. It had been decided to follow this program irrespective of what type of cable had been purchased for the line, as it was believed that the large diameter entered into a new range of stress relationships that had a bearing on fatigue failures.

The wind tunnel tests were continued, to introduce refinements and perfection of technique and to study the effects of variation in tension. As a standard of comparison, tests were made also on the 1.00-inch double-layer I-beam type of conductor used by the Pacific Gas and Electric Company, for which a considerable amount of field data was available.[12] It was not found possible to obtain as large amplitudes as found in the field, possibly because of the absorption of energy at the ends being large with respect to that imposed by the wind on such short lengths of cable.

The tendency of the cable to vibrate in conformance with recent theory as regards frequency and loop lengths was established. Where the wind frequency was not exactly resonant with possible loop frequencies, beat note effects were observed due to the nearest possible loop frequencies. There was a marked increase in vibration amplitude at any given wind velocity or air eddy frequency as the conductor tension was increased.

Because the tunnel tests apparently did not produce as high amplitudes as would be obtained under actual operating conditions, it was decided to make measurements on actual full length spans with natural wind. A site near one of the construction camps was selected as being most favorable for producing such vibration. The country is of even topography for many miles either side of the line and the prevailing winds are at right angles to the line. Standard suspension towers (3) were used to support 2 full spans; 100 feet beyond these towers temporary poles were erected for dead end connections. The recording devices were installed at the middle tower. Records of vibration were obtained for 2 values of normal tension, 4,350 and 6,500 pounds.

For obtaining the vibration records 2 photographic recorders were used. One recorder having a single element records the movement of the conductor 6 feet from the center of the suspension clamp, indicates time in 5 second intervals, and shows the direction and velocity of the wind. The other recorder has 2 elements and records simultaneously the movement of both the conductor and the suspension clamp, at a point $15^1/_4$ inches from the center of the clamp; 5 second intervals also are recorded. The purpose of this record is to show the relative bending between the cable and clamp.

Records are taken on standard moving picture film, run at a normal speed of one foot per minute, with the additional provision that the 2 element recorder automatically makes a 5 foot record at 10 times normal speed every 15 minutes of normal operation. The recorders are mounted on a platform which replaces the insulator string and is pivoted to move similarly in the wind. The alignment between cable, clamp, and recorder accurately is preserved for all wind conditions. A schematic sketch of the installation is shown on figure 6. In addition to the parts shown, the installation is equipped with an initiating device that permits the recorder to be shut down except when the vibration exceeds a predetermined amplitude.

The principal conclusions that might be drawn from these records are as follows:

1. The conductor vibration is extremely variable and complex showing considerable beat note phenomena or superposition of loop lengths.

2. With few exceptions, vibration of importance occurs at very low wind velocities, less than 6 or 7 miles per hour.

3. The portion of the total time that the cable has appreciable vibration is of the order of 3 to 5 per cent for the lower tension and 12 per cent for the higher tension.

4. The maximum angle of cable movement at a node point is 0.27 degree for the lower tension and 0.49 degree for the higher tension.

5. The maximum angle of relative bending between cable and clamp, when the phase relations are such that the cable is moving the same direction on each side of the clamp, is 0.033 degree for the lower tension and 0.132 degree for the higher tension.

In order to study the bending properties of the cable, tests were made using the rack shown in figure 7. For this test the cables were run over simple radius clamps of various radii from 28 to 42 inches. A keeper was bolted down to clamp the cable in place and the clamp was oscillated by the eccentric and connecting rod shown in figure 7. As the samples were short, care was taken to equalize the tension on each segment.

The essential conclusion drawn from this test is that for any radius longer than 28 inches, the conductor will have an indefinitely long life when the relative movement between the conductor and clamp does not exceed an angle of 0.4 degree, while at double this angle the life of the cable is very short. The actual relative bending encountered on the line is only about $^1/_{12}$ of that which the rack tests indicated would give long life.

In another set of tests, various suspension clamps were set up in a normal position between spans one per cent different in length. These spans were vibrated by means of 2 eccentrics with the same percentage difference in their frequencies. This successively subjected the clamp to in-phase and out-of-phase vibration at the 2 ends. A recorder, similar in principal to that shown on figure 6, was used to measure the relative movement of the cable and clamp. It was found that for those clamps that provided for trunnion action at or near the center line of the cable, the relative bending between cable and clamp was about 80 per cent of that obtained with clamps pivoted or hung approximately 2 inches above the center line of the cable.

Clamp Design

As a result of various facts ascertained from the cable vibration studies and detailed analysis, a suspension clamp of novel design was evolved, known as the free-center type, shown in figure 8. It consists of an outer housing or shell supported by knife edge trunnions on strap hangers. The shell in turn provides knife edge support for 2 saddles in which the cable rides. These knife edges are $^1/_2$ the cable spiraling pitch apart. The malleable cast shell is of a form that will avoid formation of corona. The saddles are die cast of bronze to avoid corrosion and to give a supporting surface free from pits, projections, and blemishes in which the curvatures could be controlled accurately within very small tolerances. Attached to the cable and normally free from the clamp is a center clamping piece consisting of a double conical wedge adjacent to the cable, which fits into the 2 halves of the clamping piece. In the event of a cable breaking, the central clamping piece engages bosses at the center of the shell, whereupon the conical wedge exerts clamping action on the cable and develops strengths in excess of 8,700 pounds.

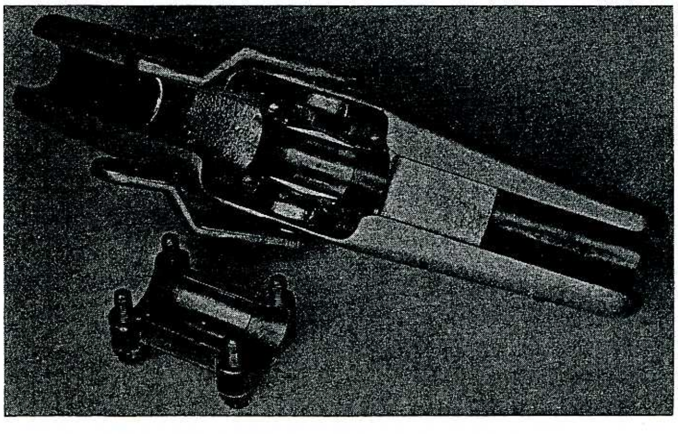


Fig. 8. Free-center suspension clamp

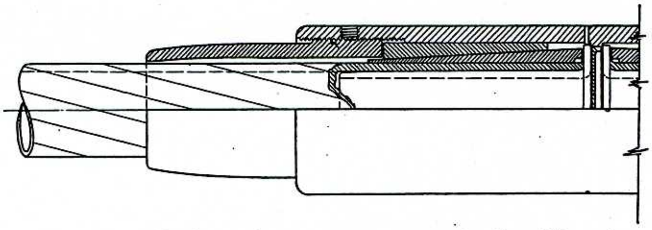


Fig. 9. Cable splicing connector (only $^1/_2$ of connector is shown)

With this type of suspension clamp, the bending of the cable resulting from vibration is not localized at one point, but is distributed essentially on nearly uniform curvature over a full pitch length, thus avoiding any concentration of bending stress on any one segment or single place in the cable. At points where the bending is taking place there are no superposed stresses due to clamping action.

All principal dimensions of the clamp parts were determined by special tests including such things as location of trunnion points, saddle pivots, curvature of saddles in both directions, length of saddles, and dimensions of parts in the center wedge system.

Clamp Life Tests

During the progress of the design of the clamp and after the final design, life tests of this clamp together with other types of clamps were made and are still in progress. Such tests were made by driving the cables on both sides of the suspension clamp by means of an eccentric attached to the cables approximately 6 feet from the clamp. In order to produce maximum bending for a given deflection of the cable and to avoid any trunnion action that would reduce the bending, the cables on each side of the clamp were driven in the same direction simultaneously. In this manner, without using unusual speeds or amplitudes, the fatigue failures could be tested with the kind of maximum bending that occurs for only a part of the total time of vibration in actual service where considerable trunnion action takes place.

By means of such tests, refinements were made in the free-center clamp. The superiority of this type of support over more conventional types of clamps was demonstrated. There is every assurance that can be afforded by laboratory testing and field investigation that the line should be free from any difficulties arising from fatigue failures.

CONNECTORS AND STRAIN CLAMPS

In accordance with the specifications for the conductor, a suitable means of splicing had to be furnished with each length together with extra connectors for making field splices. The type of splice provided with the hollow conductor is that shown in figure 9. It consists of an inner supporting tube inside the conductor, and a double split wedge assembly that grips the conductor tighter as the pull is increased. The pulls are transferred to an outer sleeve by the threaded members at the ends. The radial wedge pressures also are borne by the outer sleeve. Refinements have been introduced in the wedges so that the intensity of grip is increased as the inner edge of the wedge is approached; also the outer threaded members are so shaped as to limit the bending of the cable that can occur at the wedge entrance so that vibration cannot cause a concentration of stresses at such a point. The connectors are made of high strength bronze, so as to be free from corrosion, and have accurate smooth surfaces and sufficient strength with light weight. The light weight is essential in order to avoid large bending stresses while the vibrating cable is accelerating the connector.

The dead end connector is similar to the splicing connector except that one half of the connector is replaced by a screw clevis fitting, shown in figure 10 (part *A*). A similar fitting with a single wedge (part *B*) is used for the jumper loop connecting the 2 dead ends on opposite sides of the tower arm. The jumper loop clamp and the strain clamp are interconnected by flexible copper braid of 307,000 circular mils, as a shunt around the mechanical interconnection provided by the yoke.

INSULATION AND LIGHTNING PROTECTION

For purposes of insulation design, the line is divided into 2 main sections as regards its exposure. The section from Cajon Pass to Boulder Dam (a distance in excess of 200 miles), which is on single circuit towers, can be considered as the lightning section, with lightning storm days probably not exceeding 30 per year. The insulation scheme for this section is based almost entirely upon lightning considerations. From Cajon Pass to the receiving station, the remaining section of the line 40 miles of which is on double circuit towers, the lightning storm frequency is of the order of 5 storm days per year. This section will be subject to troubles from insulator leakage that arise from dust accumulated during a long dry season followed by fog and rains, with the accompanying noise and flashing over of single units, at times involving the possibility of string flashovers at normal voltages or switching surge voltages.

Engineers of the Los Angeles Department of Water and Power have profited very considerably from a study of the results obtained from lightning research being carried on by various power companies and electrical manufacturing companies [15–22]. Consideration of the data obtained from such studies made it almost self-evident that in order to limit the number of flashovers per year to a small value compatible with the reliability desired for this line, 2 overhead ground wires per tower line should be used and probably some type of buried ground wire or counterpoise system as well, in lieu of trying to establish any other satisfactory form of tower footing grounds in such dry desert territory.

Studies indicated that lightning can be expected to strike with about equal frequency the transmission towers and the overhead ground wires. The danger of flashover of the insulator string is greatest when lightning strikes the tower. The danger of flashover between a ground wire and a conductor is greatest when lightning strikes the ground wire at the center of the span. Spacings at these points should be co-ordinated to withstand the same lightning streamer voltage.

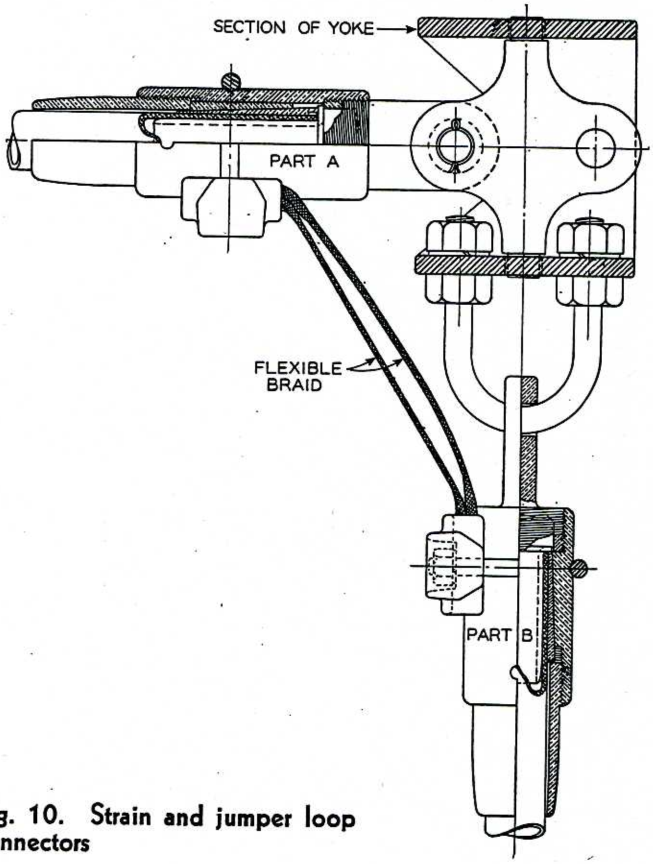


Fig. 10. Strain and jumper loop connectors

In the selection of the insulator string length on a lightning basis, the voltage of the line has small influence; however, to hold the danger of a power arc following lightning flashover within limits prescribed by existing practice, it was deemed advisable to increase the string length in proportion to the voltage over the present trend in 220-kv line insulation. This gave a length of the order of 120 inches. This same string length was confirmed for the section affected by dirt and fog.

The dirt and fog problem was studied at the Ryan high voltage laboratory, where a wind tunnel was arranged so that controlled wind would carry dust and fog alternately past insulators while voltage was applied to them. The object of this test was to find insulator shapes that would be superior for the purpose and to determine the desirable number of units to use to reduce trouble from this source. These studies indicated a distinct advantage in using relatively long strings of closely coupled insulator units, such as 10 inch units with 5 inch spacing.

In selecting the insulator units for the single circuit tower section, the cost of the insulator units and the increased cost of towers necessitated by those units requiring longer strings to develop the same impulse flashovers were taken into account. It was found most economical to use suspension insulator units 10 inches in diameter, with a hanging distance or pitch of 5 inches; 24 such units constitute a standard suspension string for both the single and double circuit tower sections. For suspension strings carrying heavier loads because of horizontal or vertical line angles, 22 suspension insulator units $10\frac{1}{2}$ inches in diameter with 6 inch pitch are used. For dead end positions on the single circuit towers, double strings of 22 $10\frac{1}{2}$ inch units with 6 inch pitch are used. For dead end positions on the double circuit towers where the maximum pulls were reduced by the type of loading assumed, double strings of 24 10 inch units with 5 inch pitch are used. The insulators are of resilient pin construction. The light duty insulators have a mechanical and electrical ultimate strength of 11,000 pounds, while the heavier duty insulators have a similar strength of 15,000 pounds.

Clearances

In establishing clearance distances from the conductor or other parts at line potential to the tower, it was desirable that arcs be confined between arcing horns, which are to be provided at each end of the insulator strings, rather than between conductor and tower. However, it was realized that this ideal would not be economical to achieve at the highest wind velocities assumed in the mechanical design of the line. The highest wind velocities would endure for such a small part of the life of the line that it was thought reasonable to have an impaired clearance under such circumstances. At the time it was necessary to set clearances for tower design purposes, the question of arcing horns had not been investigated completely so a fairly liberal size was chosen, 30 inches in diameter in the plane of swing (suspension type) placed one foot above the conductor.

For all wind pressures up to 4 pounds per square foot (about 40 miles per hour) a full clearance of 11 feet to the tower is maintained, which is about 10 per cent in excess of the point-to-plane arcing distance equal to the insulator flashover. The conductor then is placed at its extreme position under a wind pressure of 12 pounds per square foot. At this position a clearance of 7 feet is maintained. The outer boundaries of the figures described by these radii constitute the clearance diagram. The 7 foot flashover distance corresponds to approximately $4\frac{1}{2}$ times normal voltage, which is considered to be protection against switching surge flashovers. The same fundamental clearance diagram assumptions are applied to each type of tower. These clearance diagrams resulted in a horizontal spacing of 32.5 feet for single circuit towers, and a horizontal spacing of 40.5 feet and a vertical spacing of 24.5 feet for double circuit towers.

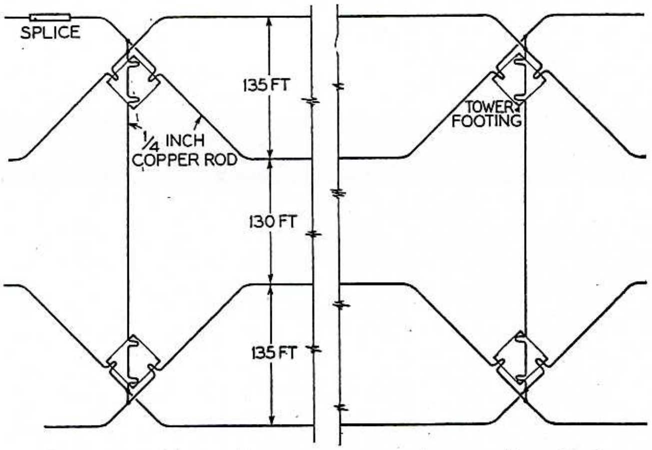


Fig. 11. Typical counterpoise layout for single circuit tower section of line

Overhead Ground Wires

For the single circuit tower section, each tower line is protected by 2 overhead ground wires of $\frac{1}{2}$-inch 7-strand galvanized wire with a guaranteed ultimate strength of 18,800 pounds. At the towers the ground wires have a horizontal separation of 50 feet and are 32 feet above the main conductors, while at the center of the span they are 40 feet above the conductors. Two wires are used because of the advantages resulting from the decreased surge impedance, the increased coupling factor to the conductors, a more balanced relation to each conductor, and, most important, because of the more complete and reliable shielding of the conductors from lightning streamers, without going to unreasonable heights. Surge calculations indicated that co-ordination of flashover across an insulator string caused by a stroke hitting a tower, and a similar flashover caused by a stroke hitting a ground wire at mid-span, required that the spacing between conductor and ground wire be 40 feet. Economical tower design then led to the location of the ground wire attachment at the tower about 32 feet above the conductor. It was thought that such height should give very reliable shielding. Too high ground wire pulls at such heights were quite uneconomical.

Steel wire of a size that will meet the mechanical requirements of the line has more than adequate conductivity from the standpoint of lightning protection. Investigations in other similar desert areas had indicated that over very long periods of time the corrosion of such wire was negligible. With this in mind the material having the lowest cost, steel, is used in this section. On the double circuit tower section there is more likelihood of corrosion occurring, because of moisture and fog conditions in the coastal plain section. For this reason, copper covered steel wire is used; this wire consists of 7 strands, is 7/16 inch in diameter, and has a strength of 18,500 pounds and 30 per cent conductivity. Two ground wires are used, mounted in the same vertical plane as the conductors, and at heights above the conductors similar to those of the steel wire on the single circuit towers.

Fig. 12. Typical suspension insulator assembly

Buried Counterpoise

Successful operating results achieved by a few power companies as a result of very limited installation of counterpoise at exposed positions,[20] made it attractive to consider the extensive use of the counterpoise for this line, where grounding conditions are particularly severe. A large part of the desert soil is gravel, sand, or both, with the water table in general measured in hundreds of feet below the surface and with an annual rainfall of the order of 3 inches. In such high resistant earth, the counterpoise serves to provide a low impedance conducting system to permit the lightning discharge to terminate at the opposite charges on the surface of the earth under the cloud area. As an outcome of the studies, the counterpoise was installed in the single circuit tower sections as shown on figure 11, giving 2 continuous counterpoise wires for each tower line with cross ties at each tower between circuits. The 45 degree spreading at the towers was adopted to obtain the low surge impedance advantages of the radial type of counterpoise, and the continuity of the counterpoise eliminated the possibility of end reflections from such points of discontinuity in the purely radial counterpoise. The continuity also has advantages in permitting the fault currents to be large enough to avoid too much difficulty in relaying the line at points distant from power sources. The particular pattern adopted also facilitated the laying of the counterpoise by means of a specially devised plow and counterpoise laying machine.

Table II—Effect of Tower Footing Impedance on Lightning Streamer Crest and Flashovers

Tower Footings Impedance, Ohms	Lightning Streamer Crest, Volts	No. Flashovers per Year per 100 Miles of Circuit
17	18,500,000	0.5
21	16,000,000	0.75
27	13,500,000	1.1
38	9,000,000	2.9

The wire used for the counterpoise is 1/4-inch diameter black rolled copper rod. This diameter was adopted as representing the smallest size that might be expected to withstand corrosion for the life of the line and be mechanically strong enough to withstand the stresses involved in laying the wire. The softness of the rolled copper was also an advantage in handling.

From test data that were available[21] some judgment could be formed of the value of the counterpoise. Theoretical values of surge impedance required the use of a large dielectric constant for the soil in order to agree with the tests. By using such a constant and making allowance for corona effects caused by the higher voltage on such wires resulting from natural lightning, estimates of surge impedance were made. All factors entering into the calculation of surge impedance of counterpoise systems are not fully understood, and no method of calculation has met with universal approval. However, this does not deprive one of the advantages of making comparisons in terms of definite relative figures, even though the actual accuracy of such figures is subject to limited doubt. Taking into account the surge impedances of the lightning stroke, ground wires, and counterpoise system, and the coupling effects between the ground system and the main conductors, the crest voltages of the oncoming lightning wave in the streamer were calculated for various tower footing or counterpoise surge impedances as shown in table II. In this table are included also the numbers of flashovers per year per 100 miles of circuit for a region having 30 lightning storm days per year.[19] For comparison with these values, the surge impedances of various combinations of continuous counterpoise wires were estimated as follows:

1 tower line, 1 counterpoise wire	38 to 50 ohms
2 tower lines, 1 counterpoise wire each, cross-connected	27 to 40 ohms
1 tower line, 2 counterpoise wires	21 to 30 ohms
2 tower lines, 2 counterpoise wires each, cross-connected	17 to 25 ohms

Considerations of reliability and relatively low cost of counterpoise compared with other methods of obtaining equal protection, that is, by use of additional insulators, dictated a choice of 2 counterpoise wires per tower line, cross-connected in the single circuit tower section. In the double circuit tower section, the lightning storm frequency is much lower so the double counterpoise for a single tower line will give excellent performance there.

In connecting the counterpoise wires to the towers, it was considered inadvisable to attach the copper directly to the towers because of the possibility of electrolytic action between the copper and steel corroding the tower footing steel. Consequently, attachment is made through a spark gap that is essentially 2 concentric bronze cylinders with a $^1/_{16}$ inch air gap. A very small percentage of any fault potential will be capable of arcing over the gap and bring the counterpoise into action.

TRANSPOSITIONS

A complete transposition "barrel" is arranged within the sending end section and the middle section of the line. Transposition towers are, therefore, approximately 30 miles apart. Another complete "barrel" is arranged in the single circuit tower portion of the line beyond the second switching station. The double circuit portion of the line, because of communication line interferences, has 3 complete transposition "barrels" of 13, 4, and 23 miles.

HARDWARE

Aside from the suspension and dead end clamps that were discussed in connection with the conductor, the 2 main items of hardware to be considered are the arcing protectors and the dead end yokes. The principal functions of the arcing protectors is to avoid cascading of the insulators and burning of the conductors.

The arcing horns adopted for suspension type insulator strings consist of a twisted and bent $^3/_8$x$1^1/_4$ inch strap arcing horn at the top or grounded end of the string and a "figure 8" horn of bent $1^1/_4$ inch pipe at the bottom of the string as illustrated in figure 12. For the dead end assemblies, each yoke carries on its top side an arcing horn made of bent $1^1/_4$-inch pipe, as illustrated in figure 13.

These particular forms of arcing horns were developed in the high voltage laboratory of the Ohio Brass Company with the assistance and co-operation of the engineers of that company. Impulse voltage tests were conducted on these devices for the purpose of determining the maximum separation, with the most favorable location of each horn tip, that could be obtained and have all arcs form between the horns and not cascade over the insulators. Similar tests also were conducted at an earlier date at the high voltage laboratory of the General Electric Company on the oval ring type of shield. Both types of shields as finally developed by these tests gave satisfactory performance in both flashover and protection from cascading. The greater tower clearances and the economy of the simpler horn types led to their adoption.

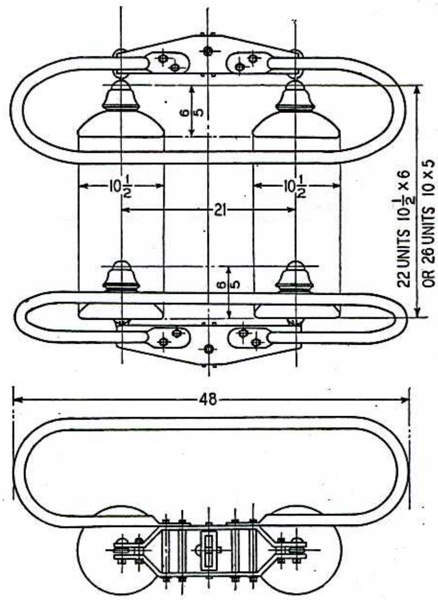


Fig. 13. Typical strain insulator assembly

All dimensions are n inches; string engths show diameter and spacing of individual units

In the yokes, which also are illustrated in figure 13, 2 new features of design have been incorporated: approximately a 50 per cent increase over standard practice in the distance between strings, and a short offset distance between the pin for the strain clamp and pins for the ball and socket fittings to the insulators. The distance between strings was set at 21 inches to try to avoid the possibility of cross-flashing of strings because of the poor voltage distribution that occurs under dirt and moisture conditions. The short coupling distance mentioned is to obtain a long natural period of vibration in the vertical plane, so that the yoke will not be set in harmonic vibration within the range of vibrations existing on the conductor and thus introduce special bending forces at the entrance of the cable into the dead end clamps.

The width of opening of the yoke is to accommodate the dead end clamp in the position it will take if one string of insulators should break. The central inner clevis of the yoke, to which is attached the dead end clamp, has on its opposite side another clevis opening to which can be attached a strain bar with turnbuckle arrangements connecting to a similar clevis at the other yoke, so that tension can be removed from the insulators and the whole insulator and yoke assembly removed for maintenance work without affecting the conductor. The yoke members are of $^1/_2$ inch steel plates 5 inches wide at the center, and the complete yoke has an ultimate strength of 30,000 pounds.

The jumper loop at the dead ends is hung from a U bolt underneath the yoke. Its suspension is independent of the main conductor so that its swing angle will not be influenced by the wind movements of the main conductor and thus require more clearance space. The jumper loop is stiffened by the insertion of a 20 foot length of $^3/_4$ inch (iron pipe size) extra heavy copper tubing, so that it can be bent and held to the proper form to give clearance under the tower arm. This added weight reduces the swing of the loop caused by wind. The electrical connection is made by means of the braid previously described.

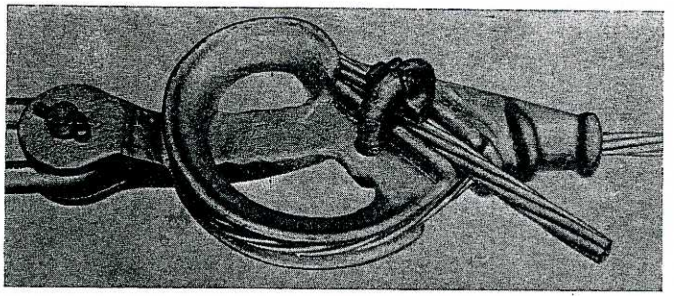


Fig. 14. Ground wire strain clamp

Special clevises and attachments were designed so as to keep the string lengths to a minimum.

At all suspension towers, the ground wire is supported on standard trunnion type suspension clamps. At all towers of special strength, the ground wire is connected by means of a special strain clamp illustrated in figure 14. This clamp is designed to have an ultimate strength of 20,000 pounds, and is a modification of existing types of clamps in order to develop increased strength. This type of clamp was selected primarily in order to have a clamp that would have a high natural frequency of oscillation, so that it would follow the natural vibration frequencies of the ground wire without causing large relative bending between clamp and cable at the entrance.

SINGLE CIRCUIT TOWERS

A diagram of a typical standard suspension tower is shown in figure 15. Exclusive of the footing steel, this tower weighs 18,100 pounds. It is designed for use on 1,000 foot spans and has a height to the cross arm of 90 feet. Its over-all height is 109 feet. It may be modified by leg extensions in 10 foot intervals up to 40 feet, none of which need be equal. Where very short towers are desired, the portion of the tower below the "waistline" is omitted. The tower is of the narrow waisted type with a rotated base, that is, the base is rotated 45 degrees with respect to direction of the line. The types of towers are standard suspension, angle suspension for vertical and horizontal angles that can be taken on the heavy duty suspension insulator strings, strain towers for all large angles and other points where such construction is required, and transposition towers which accomplish the transposition of conductors at one tower. All towers are of the same general appearance and have the same system of lower leg extensions.

The total number of single circuit towers in 225.3 miles, of double circuit line is 2,422, producing an average span of 984 feet. The longest span is 1,811 feet and the shortest 431 feet.

All single circuit towers are designed for the loadings imposed by $^1/_2$ inch radial thickness of ice on the conductor, with a wind pressure of 8 pounds per square foot of projected area at 10 degrees Fahrenheit. Under such circumstances the stress in the conductor is 40 per cent of its ultimate strength, or 8,700 pounds. The height of the towers is such as to give a minimum center span clearance to the surface of the ground of 27 feet at a conductor temperature of 150 degrees Fahrenheit with no wind. The normal tension at 60 degrees is 4,370 pounds. Under similar loadings the maximum ground wire tension is 5,000 pounds, with a normal tension at 60 degrees of 1,800 pounds.

Table III—Tower Design Stresses

	Stresses in Pounds per Square Inch	
	Structural Steel Grade	High Elastic Steel Grade
Axial tension on net section	20,000	22,500
Axial compression on gross section for L/R ratios of 60 to 150	20,000–85 L/R	25,350–110 L/R
Axial compression on gross section for L/R ratios of 150 to 200	15,500–55 L/R	17,400– 57 L/R
Maximum compressive stress	15,000	18,750

Suspension towers are designed to withstand 1 broken conductor and 1 broken ground wire simultaneously under maximum tension in the same span on the same side of the tower. Angle suspension towers, used where small horizontal or relatively large vertical angles are encountered, are designed to withstand under maximum load 3 broken conductors and 2 broken ground wires on the same side of the tower. Strain towers, used at large horizontal angles and other points of special nature requiring dead end construction, also are designed to withstand 3 broken conductors and 2 broken ground wires on one side of the tower. The towers are designed also for the torques imposed by the worst case of other combinations of the specified broken wires. The wind load on the towers was specified as 20 pounds per square foot on $1^1/_2$ times the net projected area of one face of the tower.

The towers are built largely of steel having a high elastic limit. The schedule of design stresses is given in table III. The slenderness ratio (L/R) was not in excess of 135 for leg members and 200 for web members. (The slenderness ratio of a compression member is the ratio of its unsupported length to its radius of gyration.)

In response to the specifications, several types of towers were offered embodying conventional designs, narrow waisted type, and narrow waisted type with rotated base. The latter design was slightly lighter in weight, had advantages from the standpoint of smaller footing reactions, and was less costly—hence its selection.

DOUBLE CIRCUIT TOWERS

A diagram of a typical double circuit suspension tower is shown in figure 16. Its height to the bottom crossarm is 75 feet, and its over-all height 144 feet. It weighs 23,000 lbs. This tower with extensions in multiples of 10 feet, is used on normal spans of the order of 850 feet in the populous territory adjacent to the City of Los Angeles, where the minimum clearance to the ground is maintained at 45 feet. The tower is of the conventional double circuit type, and has the same general classification of towers as the single circuit type. The total number of double circuit towers in 40.8 miles is 257, giving an average span of 839 feet. The longest span is 1,620 feet and the shortest 331 feet.

Double circuit towers are designed for a maximum pull of 8,700 pounds. The wind loading on the conductor at maximum tension is assumed at 12 pounds per square foot of projected area, with no ice and a temperature of 25 degrees Fahrenheit. The broken wire assumptions are 1 conductor and 1 ground wire broken for suspension towers, 3 conductors and 2 ground wires broken for angle suspension towers, and all 6 conductors and 2 ground wires broken for the strain towers. The basis of design is the same as for the single circuit towers.

FOOTINGS

All towers are provided with reinforced concrete footings of the pad and pedestal type, set in an undercut excavation so as to develop uplifts in largely undisturbed soil. A series of footing stubs of different lengths, capable of further limited length adjustment, were designed to take care of various depths of footings to meet conditions imposed by differences in soil, slope of the ground, and soil erosion. The footings were designed for bearing, uplift, shear, bending caused by shear, and punching. The uplifts are computed on a 30 degree cone basis. In connection with the footing design, full sized footings were set in various types of soil and pulled to failure. Those in uniform soil indicated quite close agreement with the 30 degree cone theory. Attempts to fasten appropriate anchor bolts in hard rock did not give satisfactory test results, so none of the towers have such footings. The selection of the type and dimensions of footing for a given location depended on examinations of the character of the site as excavation was in progress.

A typical footing for a single circuit suspension tower is 7 feet deep and has a diameter at the base of 4 feet. The reinforcing steel and the footing stub were put together and tack welded, so as to constitute one complete unit that could be placed in the holes and held in place by the template. Steel forms were used for the concrete, and in many cases were designed to be adjustable as to depth. The aggregate was ob-

Fig. 15 (below). Standard single circuit suspension tower

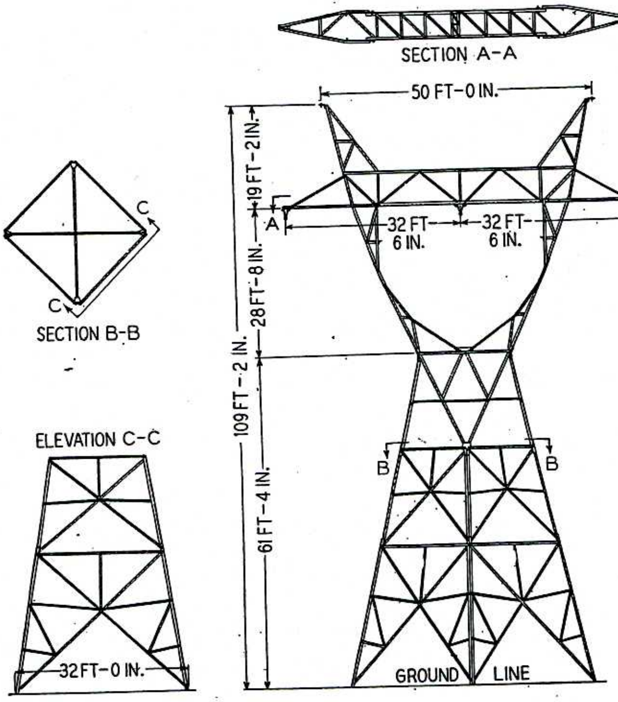
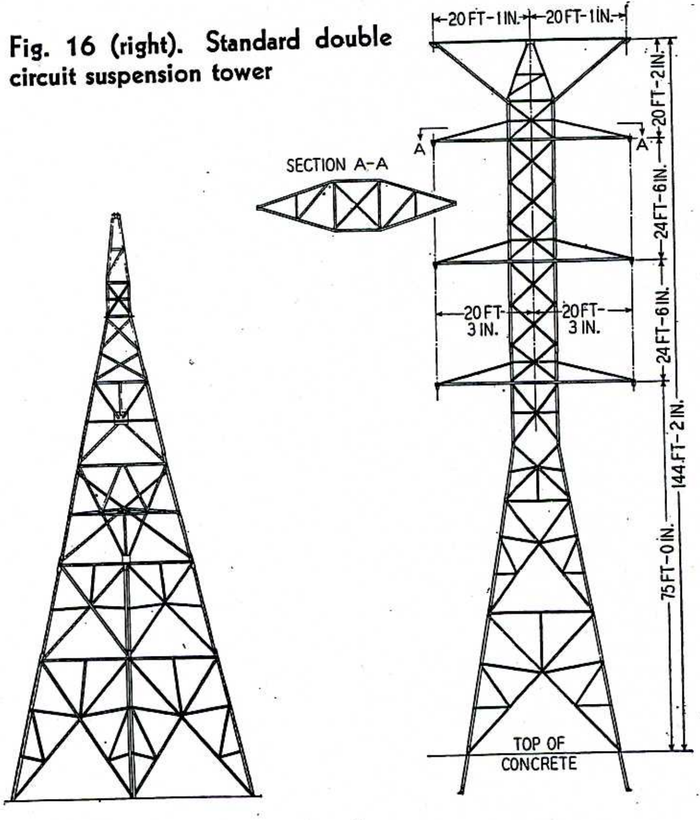


Fig. 16 (right). Standard double circuit suspension tower



tained from several favorable locations along the line. The quality of the concrete was maintained by checks on sample test pieces. A waterproofing compound was applied to the concrete preliminary to backfill.

TOWER LOCATION

Selection of right of way for this line was facilitated considerably by aerial observation and aerial mapping, which together with field observation made an accurate ground work upon which to proceed with the running of center lines and profiles.

In anticipation of the large amount of span, sag, and tension data that would be necessary for stringing the conductors and laying out the line on the profiles, an improved method of calculation was devised that was entirely analytical, adhered to catenary formulas, and readily could be reduced to a calculation form. For most of the tower locations a template was used that gave the center span sags for maximum hot day conditions for various spans. Within the ordinary span lengths, this curve did not depart very far from the true complete catenary curve for any one span. When especially long spans were studied, special templates would be made for the precise condition. For the single circuit tower section spans were held as near 1,000 feet as was desirable with due consideration to the topography.

Office analysis and layout was followed by a field check to verify that such a location and tower height was satisfactory from the standpoint of footings, safety from erosion by cloudburst, satisfactory from the standpoint of wire clearances to the ground, and other factors. Preliminary recommendations would be made for footings, unequal leg extensions, excavations, and other features, or pertinent data would be brought back to the office for further economic study of such matters. After final locations were chosen, the footings would be located, and detailed elevations of the ground at each leg would be given so that a proper selection of footing stubs could be made. The judgment on footings would be rectified or confirmed as excavation progressed.

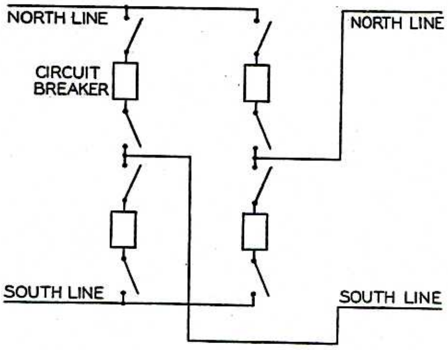


Fig. 17. One line diagram of intermediate switching station

SWITCHING STATIONS

As was mentioned in connection with the stability studies, 2 intermediate switching stations are used for line sectionalizing, so as to switch out faulted line sections with the least possible disturbance to the continuity of power flow. These stations are located at almost exact $^{1}/_{3}$ points. The arrangement of oil circuit breakers and disconnecting switches is indicated in figure 17. This arrangement gives the required amount of flexibility for switching and maintenance with a minimum number of circuit breakers.

Switching stations are of the conventional outdoor, latticed column and girder type, occupying an area of 550x580 feet. The busses are supported with strain and suspension insulator strings and are constructed of cable similar to that used for the line.

Of special interest in these stations are the recently developed high speed impulse type of circuit breakers, the first and largest of their type ever built for commercial purposes.[23] Each breaker is rated at 287 kv, 1,200 amperes, and will interrupt up to 5,000 amperes. The over-all time of breaker action from energizing trip to extinguishing of the arc is not more than 3 cycles. The breakers have 8 contacts in series, housed within tubular horizontal members. These contacts are operated by springs, which are wound up by a motor driven mechanism; when the breaker is open the springs automatically are put in position to take care of the next closing and opening cycle. The extinguishing of the arc is accomplished by forcing a jet of oil across each contact at a pressure of 100 pounds per square inch.

As installed, the switch will be 27 feet high and will occupy a space of 22x54 feet. The amount of oil required is only 2,600 gallons for a complete 3 pole switch, of which only 210 gallons is exposed to arcing.

Although this circuit breaker constitutes a radically new development, every feature of its operation has been investigated and tested to the satisfaction of all parties concerned, such tests including 60 cycle and impulse voltage flashover, interrupting capacity, voltage distribution while opening, and mechanical life. On each side of the circuit breakers, motor-operated vertical-break disconnecting switches are installed.

For lightning protection, the station framework and all equipment are connected to a ground mat that is an extension of the counterpoise system. The overhead ground wires do not connect to the station framework, but are carried to isolated towers connected to the counterpoise system. These towers are 150 feet high and support the ground wires sufficiently high above the station to shield the structure from direct strokes.

RECEIVING STATIONS

Figure 18 shows a perspective sketch of receiving station *B*, the terminal of the Boulder Dam line. The station occupies an area of 1,600 x 677 feet. The central structure is the 132 kv switch rack, while the 4 similar structures at the 4 corners are the 33 kv racks. The operating room, repair shops, station auxiliaries, and storage rooms are housed within the concrete building in the foreground. Adjacent to the 132 kv rack are 2 banks of autotransformers, each bank of which is connected directly to a transmission

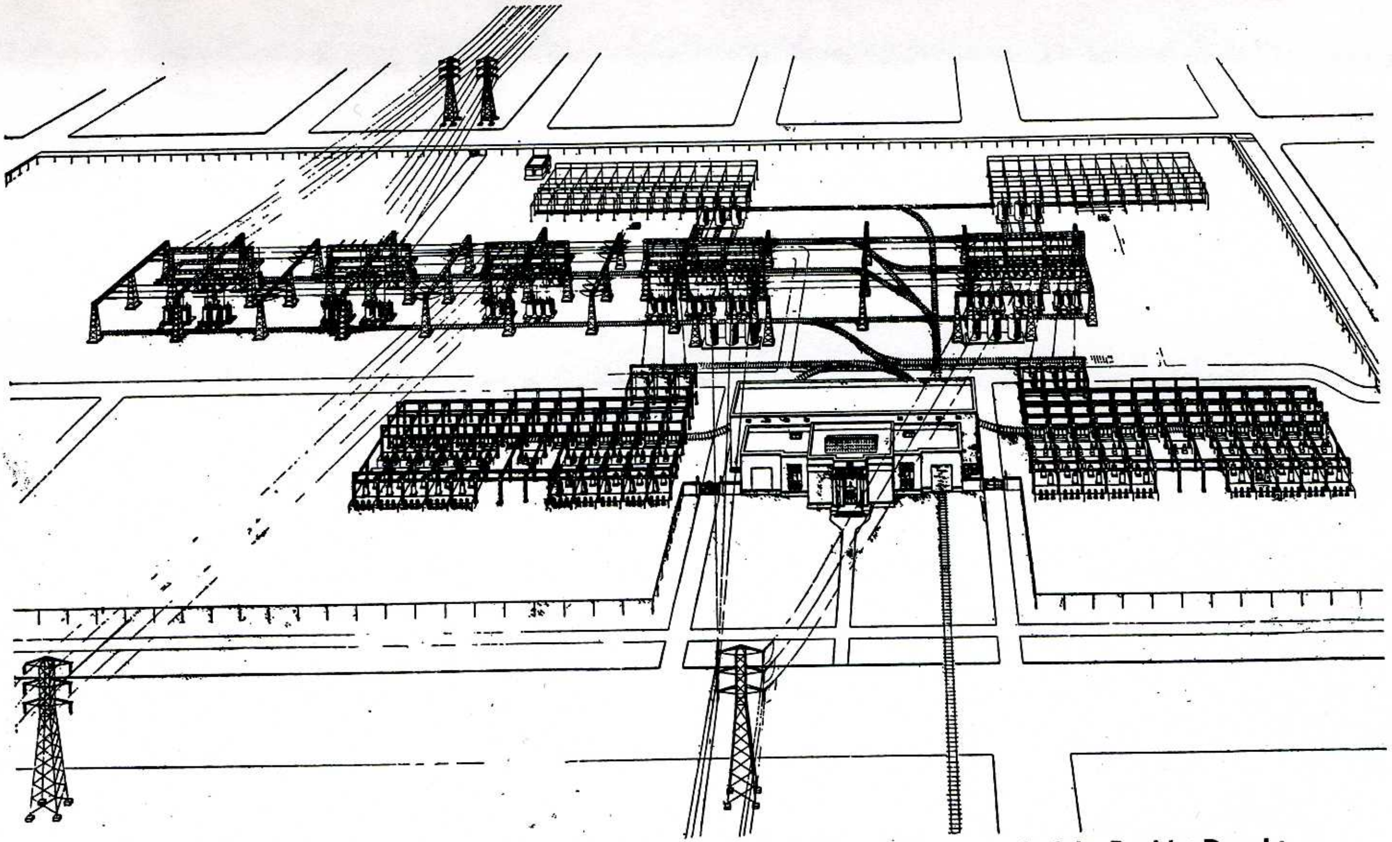


Fig. 18. Receiving Station B of the Los Angeles Bureau of Power and Light, terminal of the Boulder Dam Lines

circuit and serves to transform the voltage to 132 kv, thus eliminating the use of 287 kv circuit breakers at this station. Under the system of operation proposed for the lines, each of these transformer banks was required to have a self-cooled capacity under normal conditions of 120,000 kw. After carrying that load continuously, they were required to be capable of carrying 240,000 kw for 2 hours using forced air cooling when the other receiving end line section was out. They also had to be capable of carrying 150,000 kw continuously with forced air cooling to provide for the emergency rating of the line. In meeting these requirements, the actual ratings obtained for each single phase autotransformer were: 48,750 kw without blowers, 65,000 kw continuous with blowers, 80,000 kw for 2 hours with blowers. A 13,200 volt tertiary winding of 16,000 kva is provided for delta connection for circulating exciting current harmonics. These transformers have an impedance of 8.4 per cent at 65,000 kva, which is the lowest practicable impedance for the voltages involved. At this same load they have an efficiency of 99.47 per cent and a normal exciting current of 2.75 per cent. They are the largest autotransformers ever built to date.

Since these autotransformers are operated as parts of the lines, and their continuity of service is highly important, they will be protected on the 275 kv side with autovalve lightning arresters, which so far are the highest voltage arresters ever furnished commercially.

These autotransformers are connected to the 132 kv bus by means of 4 138-kv 1,200-ampere oil circuit breakers of the impulse type having the same speed and interrupting capacity as the circuit breakers in the switching stations. Four series breaks per pole are used at this lower voltage. The remaining 132 kv oil circuit breakers, which operate on the various double-circuit belt-line interconnections to 3 other receiving stations and on the 132/34.5 kv transformer banks, are of the conventional tank type and have a speed of 5 cycles and an interrupting capacity of 2,500,000 kva. Each of the 33 kv bus sections is supplied by a bank of 3 winding transformers. The bank rating on the secondary or 34.5 kv winding is 80,000 kva, which load is approximately at 0.75 to 0.80 power factor. The tertiary windings have a rating of 60,000 kva at 13,200 volts and are designed to be connected to the synchronous condensers, which furnish correction so that the primary windings operate at or near unity power factor with a rating of 60,000 kva. These transformer banks are connected star-star with a delta tertiary connection. At 70,000 kva these transformers have a primary to secondary impedance of 10.8 per cent. They have an efficiency at full load of 98.82 per cent.

For the initial installation, only 2 33 kv bus sections will be placed in operation at this point. A pair of "belt" transmission lines to station *D* will serve to extend the 132 kv bus to that similar receiving station, which will have 2 more similar transformer banks.

Full final details regarding the synchronous condenser installation cannot be given at this time, as they are dependent on stand-by steam plant arrangements which still are being studied. A typical synchronous condenser will be of the hydrogen-cooled outdoor type and will have a rating of 60,000 kva leading, 36,000 kva lagging, at 600 rpm and 13,200 volts.

Relay and Communication System

Carrier frequencies will be imposed on the line for 4 distinct purposes: relaying, supervisory control of switching stations, telephone communication between stations, and telephone communication to patrolmen's automobiles in the vicinity of the line.

The carrier current relay system is of the lockout type. When given a fault signal from a ground relay or an overcurrent relay, directional element relays will check the direction of power flow. If the direction is normal at the 2 ends of a phase conductor of the circuit, a lockout action will prevent the switches on that section from tripping. Suitable filters are provided in the lines on each side of the station to isolate the various frequencies. The time of operation of this relay system is less than 3 cycles.

In addition to the carrier relaying system, conventional cross-balanced relays will be used, in which the current in a given phase of one circuit is balanced against the similar current in the other circuit at a given station. For most troubles, this relay system will be slightly more rapid than the other, except where the fault is near a station and cascade action of switching takes place.

Telephone communication will be provided over a separate wired line as well as over the carrier system. Patrolmen's cars will be provided with radio receiving sets tuned to the carrier frequency so that they can be given instructions when on the transmission line road, which is in the vicinity of the line for its entire length.

Conclusion

It is believed that this line not only has established a new voltage step in the transmission of electric power on the North American continent, but also has served to stimulate advances in the art and science of electric power transmission and related electrical fields. It is a milestone of current progress. In a project of this magnitude, it is unavoidable, or perhaps incidental, that many features are notable for their size, or capacity; but the ideal of the designers will have been realized if the system delivers the required power with the reliability and continuity of service that it seems reasonable at this time to expect.

Appendix—Statistical Data of Boulder Dam–Los Angeles Transmission System

Line

Number of 3-phase 60-cycle circuits	2
Line-to-line kilovolts, receiving end	275
Line-to-line kilovolts, sending end	287.5
Reliable operating capacity, kilowatts	235,000–240,000
Emergency capacity, kilowatts	300,000
Approximate full load loss, including transformers and synchronous condensers, per cent	8
Length of single circuit tower section, miles	225.3
Length of double circuit tower section, miles	40.8
Total length of double circuit line, miles	266.1
Length of sending end section, miles	91.7
Length of middle section, miles	90.8
Length of single circuit tower portion of receiving end section, miles	42.8
Length of double circuit tower portion of receiving end section, miles	40.8

Conductor

	Diameter, inches	1.40
	Type	segmental hollow copper
	Total circular mils	512,000
	Number of segments	10
	Spiral pitch, inches	28
	Weight per foot, pounds	1.57
	Ultimate strength, pounds	21,600
Single circuit	Maximum line tension, pounds	8,700
	Normal tension at 60 degrees Fahrenheit, pounds	4,370
Double circuit	Maximum line tension, pounds	6,400
	Normal tension at 60 degrees Fahrenheit, pounds	4,750
	Splice	Bronze sleeve with double wedge grip
	Installation	Pulling in under tension controlled by 8 foot capstan and brake
	Total pounds used, approximately	13,455,000

Overhead Ground Wire

	Number per tower line	2
Single circuit towers	Material	½ inch galvanized steel, stranded
	Weight per foot, pounds	0.517
	Ultimate strength, pounds	18,800
	Maximum tension	5,000
	Normal tension	1,800
	Total pounds used, approximately	2,461,000
Double circuit towers	Material	0.4395 inch copper covered steel, stranded
	Weight per foot, pounds	0.421
	Ultimate strength, pounds	18,500
	Maximum tension, pounds	2,500
	Normal tension, pounds	1,600
	Total pounds used, approximately	181,000
Counterpoise	Material	¼ inch rolled black copper rod
	Weight per foot, pounds	0.205
	Total pounds used, approximate	1,300,000
	Depth, feet	not more than 3
	Method of installation	by plow
	Method of attachment	4 spark gaps per tower

Span

Single circuit towers	Normal span, feet	1,000
	Average span, feet	984
	Maximum span, feet	1,811
	Minimum span, feet	431
	Normal sag, feet (1,000 foot span)	45
	Sag at 150 degrees Fahrenheit, feet (1,000 foot span)	48.5
Double circuit towers	Normal span, feet	850
	Average span, feet	839
	Maximum span, feet	1,620
	Minimum span, feet	331
	Normal sag, feet (850 foot span)	30
	Sag at 130 degrees Fahrenheit, feet (850 foot span)	33.5

Insulation

Light duty suspension unit	Size, inches	10 x 5*
	Strength, pounds	11,000
Heavier duty suspension unit	Size, inches	10½ x 6*
	Strength, pounds	15,000
Standard suspension insulator string		24–(10 x 5)
Standard angle suspension insulator string		22–(10½ x 6)
Heavy duty strain insulator string		double 22–(10½ x 6)
Light duty strain insulator string		double 26–(10 x 5)

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* Diameter of unit by spacing between units.

Clearances

Up to 4 pounds per square foot wind, feet	11
At 12 pounds per square foot wind, feet	7
Suspension horn arcing distance, inches	110
Angle suspension arcing horn distance, inches	121
Heavy duty strain arcing horn distance, inches, approximate	117
Light duty strain arcing horn distance, inches, approximate	115
Minimum vertical distance to surface of ground:	
desert and mountain sections, 150 degrees Fahrenheit, feet	27[†]
coastal plain section, 130 degrees Fahrenheit, feet	45[‡]

[†] Some inaccessible locations 22.5 feet.
[‡] Some nonagricultural hilly locations 40 feet.

Hardware

Conductor	Strain clamp	Bronze sleeve, double wedge grip
	Suspension clamp	Free center, double saddle type
	Lower arcing horn	Figure "8"—$1\frac{1}{4}$ inch pipe
	Upper arcing horn	Steel strap—$\frac{3}{8}$ x $1\frac{1}{2}$ inches
	Strain string arcing horns	$1\frac{1}{4}$ inch pipe ovals above yokes
	Yokes, low frequency vibration	21 inch string spacing
Ground wire	Strain clamp	Special 315 degree snubbing type
	Suspension clamp	Standard trunnion type

Single Circuit Towers

Loading		$\frac{1}{2}$ inch ice, 8 pounds per square foot wind
Suspension type	Broken wire assumptions	1 conductor, 1 ground wire
	Conductor spacing, feet	32.5
	Crossarm height, standard tower, feet	90
	Ground wire spacing, feet	50
	Ground wire height, standard tower, feet	109
	Extensions, feet	10, 20, 30, 40
	Tower base, feet	32 x 32
	Weight, pounds	18,100
Angle suspension	Broken wire assumptions	3 conductors, 2 ground wires
	Horizontal line angles, degrees	0 to 10
	Weight of 10 degree tower, pounds	25,400
Strain type	Broken wire assumptions	3 conductors, 2 ground wires
	Horizontal line angles, degrees	0 to 50
	Weight of 50 degree tower, pounds	27,925

Double Circuit Towers

Loading		no ice, 12 pounds per square foot wind
Suspension type	Broken wire assumptions	1 conductor, 1 ground wire
	Conductor spacing: Vertical, feet	24.5
	Conductor spacing: Horizontal, feet	40.5
	Lower crossarm height, standard tower, feet	75
	Ground wire spacing, feet	40.5
	Ground wire height, standard tower, feet	144
	Extensions, feet	10, 20, 30, 40
	Tower base, feet	32 x 32
	Weight, pounds	23,050
Angle suspension	Broken wire assumptions	3 conductors, 2 ground wires
	Horizontal line angles, degrees	0 to 10
	Weight of 10 degree tower, pounds	38,300
Strain type	Broken wire assumptions	6 conductors, 2 ground wires
	Horizontal line angles, degrees	0 to 90
	Weight of 50 degree tower, pounds	41,150

Standard Footings

Type		reinforced concrete, pad and pedestal
Diameter and depth	Single circuit suspension tower, feet	4 x 7
	Single circuit 10 degree angle tower, feet	5 x 7 (side) 6.5 x 9.5 (long)
	Single circuit 50 degree strain tower, feet	7 x 9.5
	Double circuit suspension tower, feet	4.25 x 8
	Double circuit 10 degree angle tower, feet	7 x 10.5[*]
	Double circuit 50 degree strain tower, feet	8.5 x 12[*]

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[*] Preliminary and approximate.

Generators

Number used on 2 circuits	4
Kilovolt amperes each at unity power factor	82,500
Voltage	13,800/16,500
Number of poles	40
Speed, revolutions per minute	150/180
Short circuit ratio	2.28/2.74
Direct axis transient reactance, per cent	21/17.5
Moment of inertia (WR^2) each	not less than 105,000,000
Total weight, pounds, approximate	2,000,000
Outside diameter, feet	40
Type of insulation	Class *B*
Excitation	nominal 250 volts, main and pilot exciter direct connected
Exciter response	0.50

Sending End Transformers

Number used on 2 circuits (2 banks)	6
Type	Water cooled, outdoor
Rating of each, kilovoltamperes	55,000
Voltage	287,500Y/16,320 delta
Frequency, cycles per second	60
Impedance, per cent	not more than 10.73
Exciting current at normal voltage, per cent	4.5
Full load efficiency, per cent	99.31
Three-quarter load efficiency, per cent	99.33
Total weight per unit, pounds	385,000
Floor space and height, feet	13 x 20 x 32

Receiving End Autotransformers

Number used on 2 circuits	6
Type	forced air cooled
Rating of each, kilovoltamperes	48,750, no blowers; 65,000, blowers; 80,000, 2 hours, blowers
Tertiary winding rating, kilovoltamperes	16,000
Voltage	275,000Y/132,000Y/13,200
Frequency	60
Impedance, primary to secondary, per cent on 65,000 kilovoltamperes	8.4
Exciting current at normal voltage, per cent	2.75
Full load efficiency at 48,750 kva, per cent	99.487
Full load efficiency at 65,000 kva, per cent	99.466
Full load efficiency at 80,000 kva, per cent	99.422
Total weight per unit, pounds	332,000
Floor space and height, feet	$11\frac{1}{2}$ x $23\frac{1}{2}$ x 36

Three Winding Transformers

Number used for 2 circuits		12
Type		forced air cooled outdoor type
Kilovoltamperes each		primary 60,000, secondary 80,000, tertiary 60,000
Voltage		76,200/20,000/13,200 delta (132,200Y/34,500Y/13,200)
Frequency, cycles per second		60
Impedance	Primary to secondary (23,333 kva), per cent	10.8
	Primary to tertiary	12.3
	Secondary to tertiary	3.3
Exciting current, normal voltage, per cent		2.75
Full load efficiency, per cent		98.988

Synchronous Condensers

Kilovoltamperes, each	60,000 lead/36,000 lag
Voltage	13,200
Number of poles	12
Speed in revolutions per minute	600
Direct axis transient reactance, per cent	45
Moment of inertia (WR^2) each, pound-feet^2	1,250,000
Type of insulation	Class *B*
Excitation	motor generator, main and pilot exciter, 250 volts
Exciter response	0.5

Oil Circuit Breakers for Switching Stations

Type	porcelain clad, impulse
Voltage class, kilovolts	287.5
Interrupting capacity, kilovoltamperes	2,500,000
Normal current rating, amperes	1,200
Speed of operation, cycles	3
Weight, pounds	113,300
Floor space and height, feet	22 x 54 x 27
Gallons of oil	2,600

Oil Circuit Breakers for Receiving Stations

Type	porcelain clad, impulse
Voltage class, kilovolts	138
Interrupting capacity, kilovoltamperes	2,500,000
Normal current rating, amperes	1,200
Speed of operation, cycles	3
Weight, pounds	51,000

Floor space and height, feet	20 x 22 x 22
Gallons of oil	750

Oil Circuit Breakers for Receiving Stations

Type	tank
Voltage class, kilovolts	138
Interrupting capacity, kilovoltamperes	2,500,000 (convertible to 4,000,000)
Normal current rating, amperes	1,200
Speed of operation, cycles	5
Weight, pounds	100,000
Floor space and height, feet	8 x 26 x 17
Gallons of oil	7,380

Lightning Arresters

Voltage class, kilovolts	287.5
Kilovolts, line to ground	235.0
Mounting	suspension
Crest voltage at 1,500 ampere discharge, kilovolts	825
Impulse voltage breakdown, kilovolts	800
Over-all height, feet	33

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