SOME OPERATING FEATURES OF A 100000 VOLT TRANSMISSION

A THESIS PRESENTED TO THE FACULTY OF THE GRADUATE SCHOOL OF THE UNIVERSITY OF KANSAS

FOR THE DEGREE OF

ELECTRICAL ENGINEER

BY

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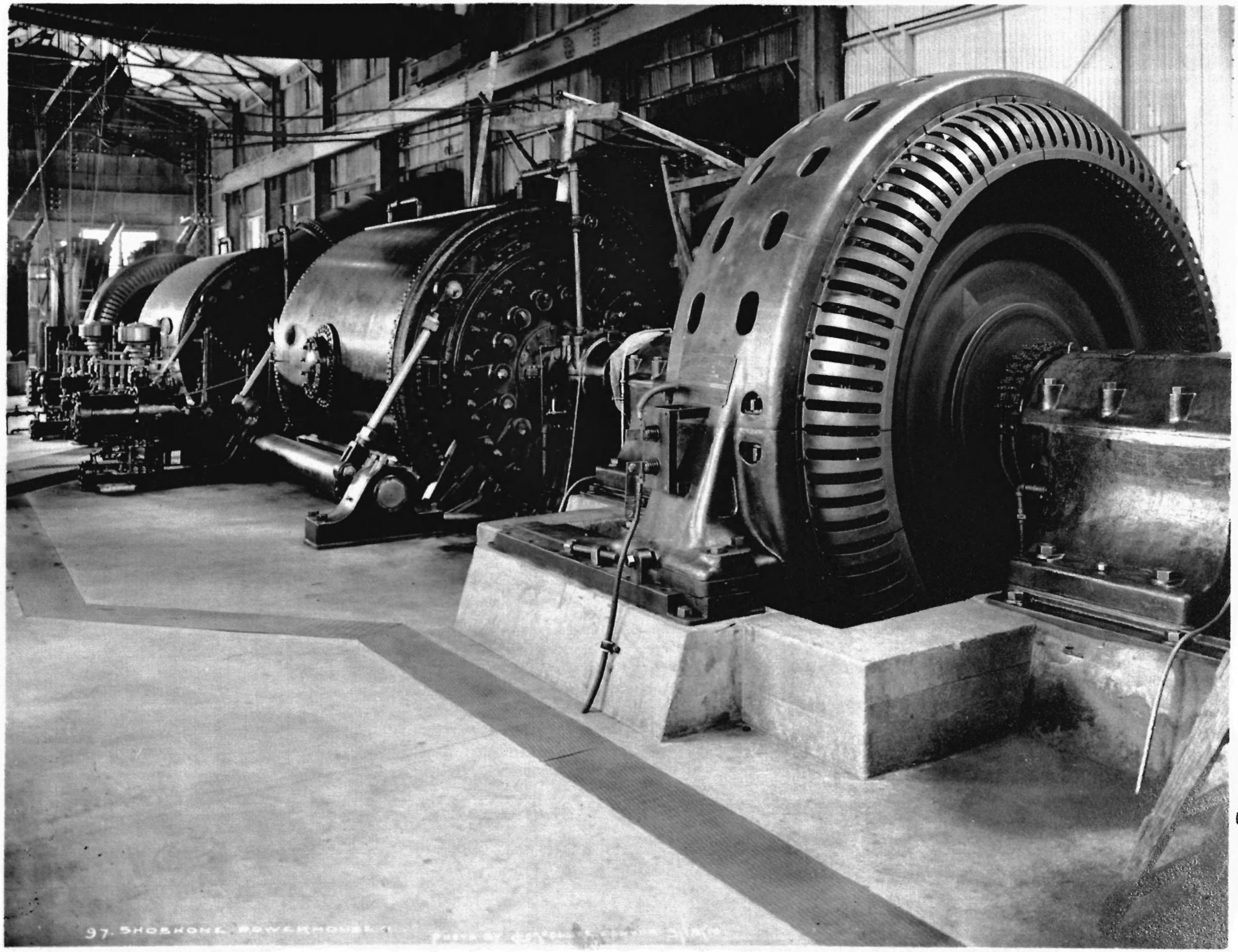

Fig. 1.

THE PURPOSE OF THE THESIS.

It is the purpose of this thesis to state, discuss as clearly as possible, and form conclusions upon some of the most important operating features, principally difficulties, of a long high tension transmission line.

The data available at the present time is scattering and, to a great extent, has been determined under widely different conditions. As far as the writer knows, no attempt has been made to date to collect the most important parts of this data and publish a volume commercially valuable to future projects. In other words, the high tension phenomena appearing as effecting the operation of such lines are not understood to such an extent that sound rules can be ennunciated for the best practice to follow. Special appeal has been made to operating companies to collect and preserve all data or observations upon operating features or difficulties even though, at the present time, some of it may seem unimportant.

Excellent articles along this line have appeared in the Proceedings of The American Institute of Electrical Engineers and should therefore be considered our most valuable sources of information. The line discussed in this article is one subjected to the most rigorous operating difficulties. By considering the features of such a line operating under the extremes of service, the broadest conceptions should be formed. What features are discussed here, should be especially valuable to a student desiring a general knowledge of high tension operating difficulties and conditions, eliminating thereby to secure it a laborious search thru our present scattered and in most cases highly specialized articles.

I would like to show as conclusively as possible that the three following points are absolutely necessary for the best operating conditions of high tension transmission.

1. The line must be designed and erected with great mechanical strength.

2. The most efficient apparatus available for protection from lightning and other surges must be installed.

3. The transformer should be designed with high insulation strength especially at the end turns.

THE IMPORTANCE of the SUBJECT.

The utilization of long distance high tension transmission is in its infancy. The present total development of our water power is very small compared to the total amount available within economical limits, considering the present cheap cost of power from steam; and is still smaller when compared to what will be economically available in the distant future when, as a result of the inevitable diminishment of our coal deposits, the cost of power from steam increases greatly.

[1] The total stationary power used in the Unites States

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1. Rome G. Brown. May 1913. Harvard Review.

is estimated at over 30,000,000 H P. The total developed water power is about 6,000,000 H P of which three fourths is commercial power or power produced for sale.

The amount of water power now economically capable of development is not less than 25,000,000 H P. The total potential water power available is estimated at 200,000,000 H P. The present annual coal consumption in the United States is over 500,000,000 tons and at the present rate of consumption, the anthracite will be exhausted at the end of the present century. The known supply of bituminous coal at the present rate of consumption, is sufficient to last six or seven centuries, but its cost to the consumer gradually increases as the supply decreases.

The present maximum limits of voltage and distance of transmission are no doubt small compared to what we can safely predict for the future. This branch of electrical engineering has become so broad and important that specialists in it are in demand. Those young engineers who were so fortunate in associating themselves a dozen years ago with our pioneer companies using high tension are now (many of them) foremost in their line. It has been only in the last few years, say six, that rigid and comprehensive tests have been made jointly by our large electrical manufacturing companies and our operating companies for the purpose of ascertaining as near as possible the best practice to follow in dealing with the most important features of such systems.

INTRODUCTORY DESCRIPTION of the LINE.

The Central Colorado Power Company was organized in 1906. The original capitalization was for $15,000,000, but the present system represents an outlay of approximately $20,000,000. It may be interesting to say here that the company went in to receivership early in 1913 and in June 1913 the present holdings were bought up for $7,000,000. Small sales of power due to unusual interruptions was the cause. The state tax assessment for 1913 on this corporation, now known as the Colorado Power Company is $3,432,000, based doubtless upon its earning capacity.

Two hydrostations are now in operation. The base load station is located at Shoshone Colorado seven miles east of Glenwood Springs on the Grand River western slope. This station contains two horizontal reaction type water wheels of 9000 H P each, operating under a head of 147 feet pressure 67 pounds. The peak load station is located at Boulder Colorado on Middle Boulder Creek 4 miles above the city. A storage reservoir has been built here of 525,000,000 cubic feet or 12000 acre ft. This station contains two 10500 H. P. Pelton impulse wheels operating under a head of 1850 feet or a pressure of 840 pounds. The normal load capacity of each station is only 10000 K. W. but each station has found

Fig. 2.

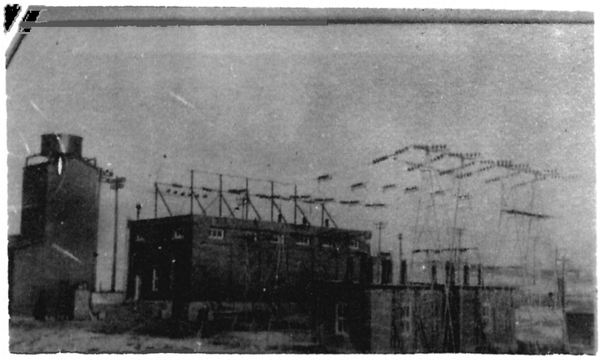


Fig. 3. Denver Sub.

it necessary at times to carry a 30 minute peak of 13500 K W. All station and substation equipment has been furnished by the General Electric Company.

A small emergency steam turbine plant of 3000 K W capacity is located at Leadville Colo. Four substations are now in operation, Leadville 4500 K W, Dillon 1200 K W, Idaho Springs 1500 K W and Denver. The Denver Substation contains six 2500 K W transformers so that 7500 K W may be received from either generating station.

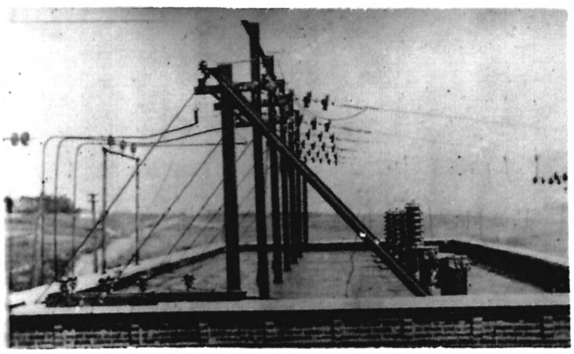


Fig. 4. Denver Sub. Superstructure.

The transmission line from Shoshone to Denver has been in operation since July 1909 and the line from Boulder to Denver was first used in the fall of the same year for power transmission from Denver to Boulder to supply the Northern Colorado Power Co. and for construction work on the Boulder power house.

The remarkable features of this transmission line as a whole are:-

1. The high voltage. 2. The extreme length.

3. The high altitude to which the line is carried.

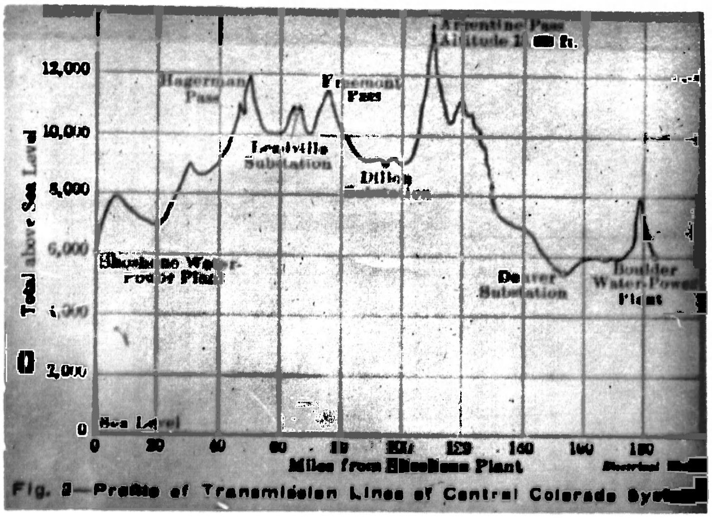
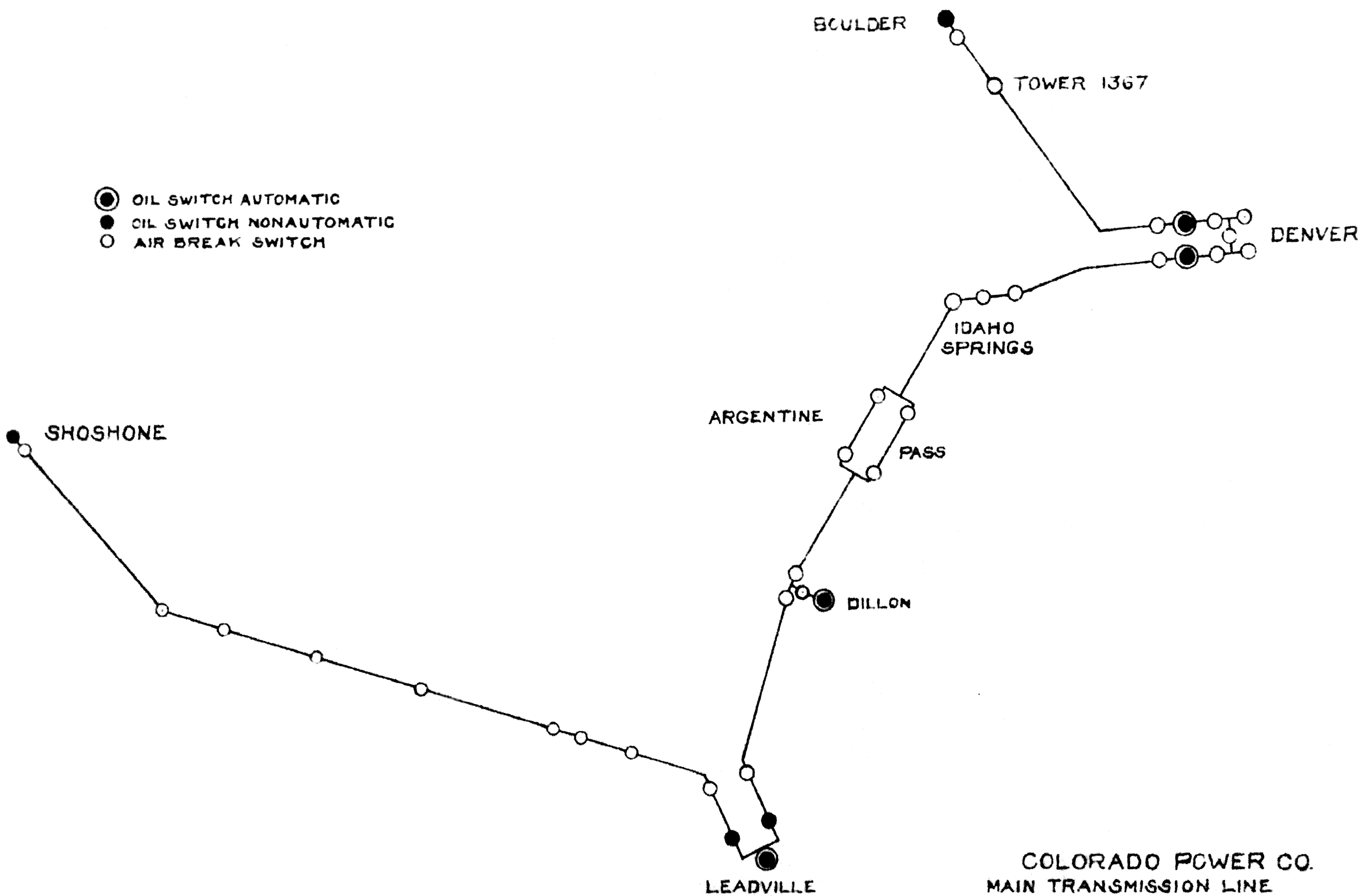


Fig. 5. Profile of Transmission Line.

4. The severity of climatic conditions of the country.

The power is generated at 4200 volts and stepped up to 100000 volts. At the substations, the main secondary feeders are supplied at13200 volts. The distance from Shoshone to Denver measured along the line is 153.5 miles, while from Denver to Boulder 27.6 miles are added. When the Boulder plant is not generating power, it motors a unit on the line and the total distance of transmission from Shoshone to Boulder becomes 181 miles. In the vicinity of Boulder, an average load of 1000 K W is carried.

The accompanying plan page8b is interesting in that it shows the relative positions of the various stations. The curve at the top of this page shows a profile of the entire length of the line. Three different ranges of mountains on the continental divide are crossed. Hagerman pass altitude 12000 ft., Freemont Pass altitude 11600 ft., and Argentine Pass the highest at an altitude of 13628 ft. This makes the



COLORADO POWER CO.
MAIN TRANSMISSION LINE
OCT. 1909

system as a whole the highest in the world as to altitude. No part of the line is lower than 5280 feet and the average altitude is 9000 feet.

To insure continuity of service in case of breakdown, a duplicate emergency line three miles long is provided over the most dangerous part of Argentine Pass. In case of trouble, this section can be cut in with knife switches. On these high passes, the conductor used is 1/2 and 5/8 inch steel cable.

The steel tower used is of the Milliken type as shown in the accompanying photos. The average height is 45 feet and the average number to the mile is seven making the average span 750 feet. The longest span used is 2900 feet and several are about 2000 feet. The conductors on the Shoshone line consist of 6 strand hemp center No. 0 B&S hard drawn copper. Those on the Boulder line are similar but of No. 1 B&S. They are suspended from a single cross arm by means of vertical strings of General Electric disc type insulators. Four 10 1/2 inch discs are used in series each capable of withstanding 90000 volts. The conductors are spaced at 124 1/2 inches in the same horizontal plane. As a protection from lightning, two grounded guard wires were originally installed midway between the copper conductors. These were of 1/4 inch Siemens-Martin steel pulled taut as possible.

MECHANICAL WEAKNESS of the LINE.

The transmission line is the weakest link in all extensive hydro systems. The transmission line of the Colorado Power Company, considering the nature and conditions of its field, is exceptionally weak. Fully 50 %, to be conservative, of its interruptions can be traced to mechanical weaknesses. Undoubtedly, the greatest defect is that the spans are too long. It is evident that too much "office engineering" was done by the men who designed the line. Conditions were not studied thoroughly and the proper factor of safety chosen. The result has been that an unusually large number of arcing shorts, arcing grounds and permanent grounds have occurred. It was thought that the three conductors would swing parallel but such an ideal condition has not been obtained in the long spans.

"At Argentine Pass, five desolate canyons unite their blasts to produce wind velocities unbelievable. The only wind guage ever installed on the pass to indicate these velocities pointed to 165 miles per hour and was then itself blown away. A specially prepared board 12 inches square suspended by a 50# spring balance was next experimented with in order to get a basis for wind pressure calculations but the wind quickly wrecked this apparatus too, straining the pointer far past the end of the scale. To what limits the actual wind velocities attain in the pass, therefore can only be guessed. Line patrolmen on the summit during storms have had to lash themselves to the steel work of the towers to prevent being blown away.

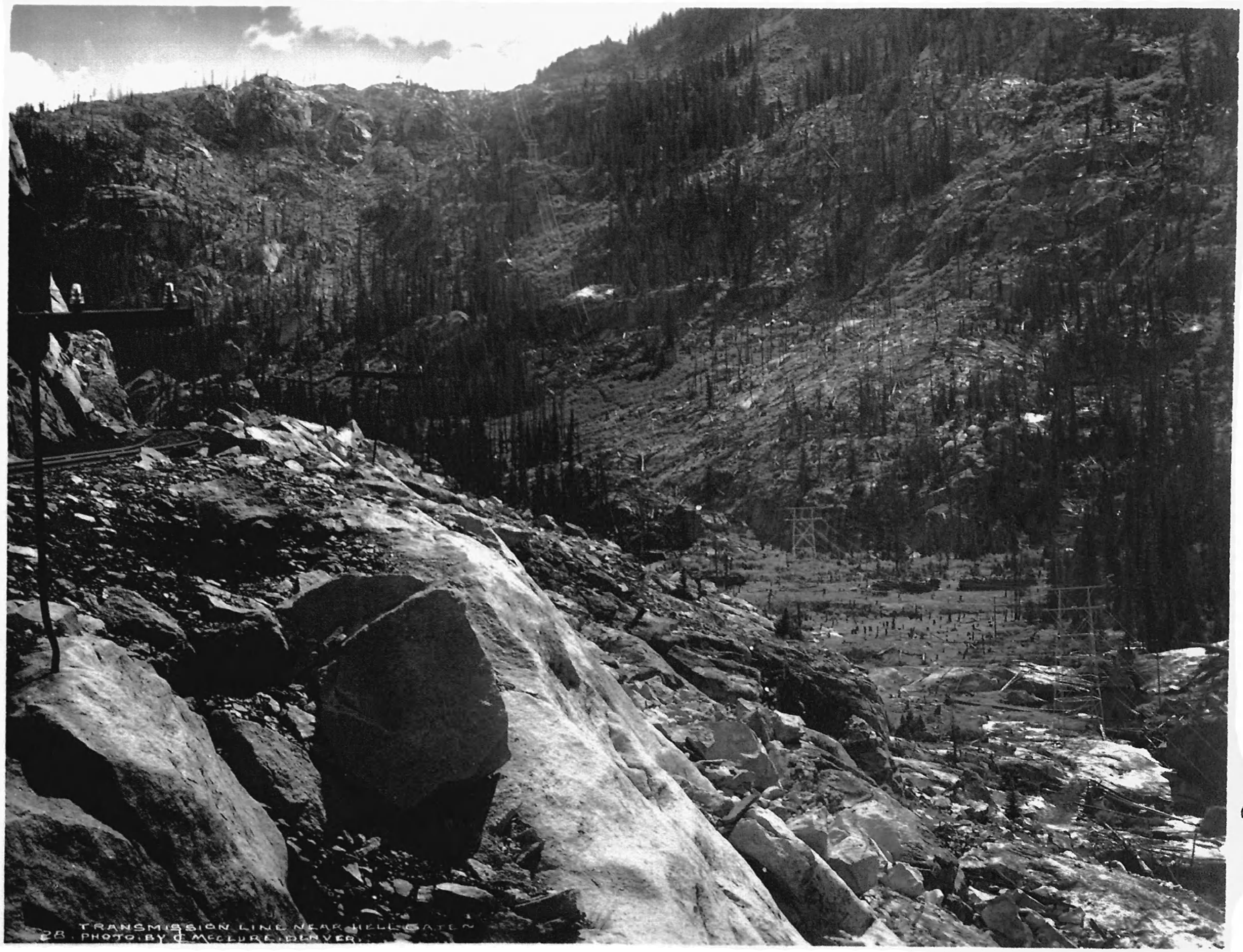

TRANSMISSION LINE NEAR HELL GATE
28. PHOTO. BY C McCLURE. DENVER.

Fig. 6.

One man's dog was actually picked up by the wind and blown far out over the side of the mountain not to be seen again. The winds which prevail on the pass are not steady in direction but are known to reverse almost instantly from one to another of the canyons so that towers must be braced and guyed from all directions."

This would explain therefore why the strands would not swing parallel in such places. These peculiar winds exert a remarkable lifting effort on the wires blowing them sometimes upward as well as sidewise so that the main conductors have been found actually looped over the ground wires.

Let us obtain a figure for the approximate pressure due to wind velocity. From the formula $P = .0025\ V^2$ (Standard Hand Book), we readily calculate for a wind velocity of 170 miles per hour that the pressure per square foot would be 72 pounds. Taking the diameter of the conductor as 3/8 inches, the pressure per linear foot would be 2 1/4 pounds. The weight of the conductor itself is only .32 pounds per foot. Of course the conductor would be whipped around easily. The resulting swinging arcs and grounds are very detrimental to the line operation. Destructive surges would be set up with results as explained later. Of course, actual shorts or grounds would result in a conductor burning in two and dropping to the earth. As one remedy for this, the ground wires have been removed from the whole

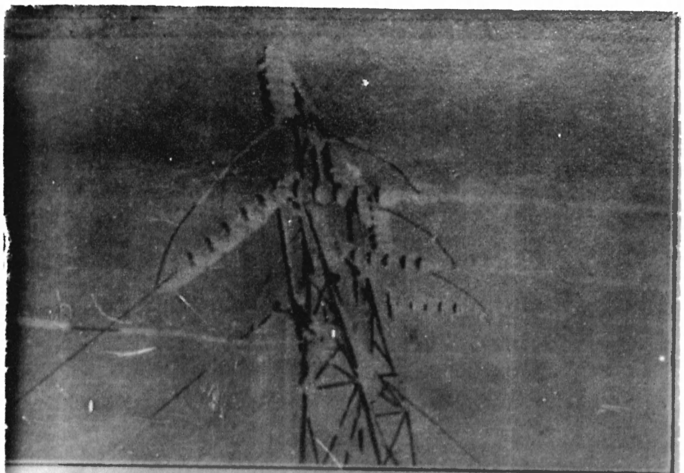


Fig. 3—Sleet on the Crest Tower of Argentine Pass, Elevation 13,628 ft.

Fig. 7.

system except on very short spans and at points where lightning protection seems imperative and even at such places the ground wires are being elevated four feet above the cross arms. Considering the extreme conditions, the tensile strength of this hard drawn No. 0 wire is very low 4560 pounds.

To the normal span strain must be added not only the component due to wind velocity, but also in many cases a vertical stress due to sleet or ice load. The sleet storms on the mountain passes are unusually severe. The photo on this page shows but a mild case of ice coating.

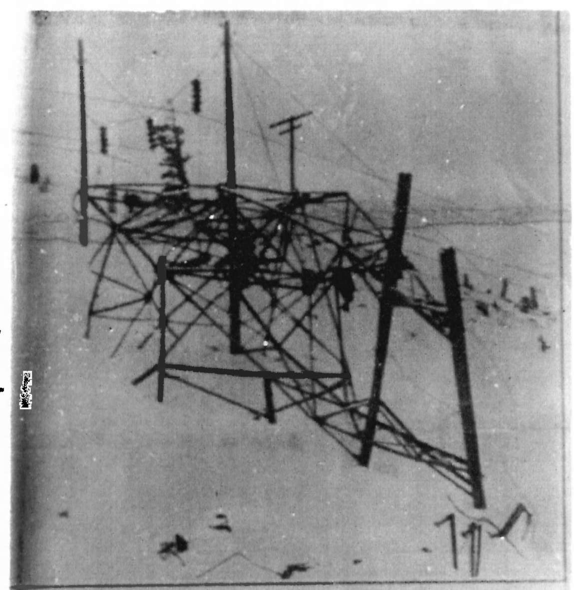


Fig. 7—Tower Crushed by Snowslide and Emergency Repair Construction.

Fig. 8.

After some storms, as much as two pounds of ice has been scraped from a single foot of conductor. A few cases are on record of a coating of ice six inches in diameter. I have talked to one patrolman who asserted he has met such a condition. This figures something over ten pounds of ice to a foot. Two pounds to the foot occurs frequently.

Under this combination of cold, sleet, and wind, the mechanical stresses set up in these conductors and supporting towers are almost unbelievable, but actually true. Several towers have been buckled and demolished during storms by sheer winds striking the conductors, without the presence of ice. As one remedy, the company is rapidly displacing the hard drawn copper in the most exposed places with special steel conductor copper coated. Also in many dangerous places, extra towers are being added.

EFFECTS of HIGH ALTITUDE.

There are three electrostatic conditions very peculiar to this line due primarily to the high altitude.

1. The presence of a large static charge on the line even when not energized.

2. The lowering of the dielectric strength of the air.

3. The lowering of the critical voltage with reference to the corona point.

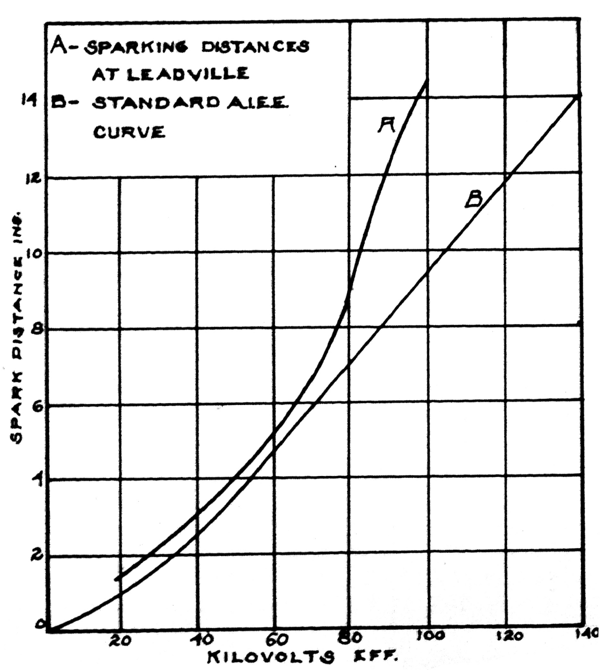
The later two points are very undesirable and play an important part in the operation of the line. In regard to the first point, I am not going to advance any theories to prove that it is detrimental to good operation. It is a very interesting phenomena however not met with on lines at lower altitudes and one that is never lost sight of by the employees who have occasion to come into direct touch with the line. In this connection, let me mention a similar fact. On Pike's Peak during days when the weather conditions are favorable, small metallic objects such as pick heads become charged with static to such an extent that, when touched, a slight discharge occurs. This fact should show that a metallic conductor a hundred or more miles long would also become charged with static induced perhaps by direct contact or even closeness to to the clouds. At all times, a very heavy charge is present and at certain times an extra-ordinary static charge is present upon these highly insulated conductors. Sparks two inches long have been drawn from the disconnected line. These are sufficient to cause severe shocks and burns to the flesh. During repair work on the line, the conductors must be grounded thoroughly as closely as possible to the workmen. After discharge, the charge in a few seconds is built up to the original value.

LOWERING of the DIELECTRIC STRENGTH.

It is an experimental fact that the dielectric strength of air is proportional to the absolute pressure. Hence at high altitudes there would be a greater tendency for the air to break down for a certain distance under an applied potential.

During May 1910 when the general line test was being made, this point was verified by direct test at Leadville Colorado. The curve below shows the results obtained as compared with the Standard A. I. E. E. curve.

SPARKING DISTANCES INS.



These values are for sharp needle points and the data was obtained upon three different days. The altitude at Leadville is 10500 feet. The barometric pressure during this test averaged 20.15 inches or 512 millimeters.

A noticeable feature of the curve is that, at higher voltages, an extreme departure occurs between the two curves. The normal sparking distance for 100000 volts we have considered as 9.6 inches but at Leadville it is 14.5 inches or an increase of 50%. The question is then, "What are the effects of this decrease in dielectric strength?" I can suggest two effects.

First the horn gaps must be set at a greater sparking distance. No definite rules can be laid down for a gap setting. The 100000 volt gaps are set on this system at from 12 to 15 inches. Even considering the fact that an aluminum arrester offers a large resistance to a discharge, I would think that this is too large a setting. To back up this conclusion, I will state that in June 1913 I saw a lightning surge come into the Boulder station, and, after passing through a comparatively large choke coil, jump from the high tension bus over a string of 5- 90000 volt insulators shattering them and, followed by the dynamic current, arc into the steel roof trusses for about 10 seconds.

The second effect of the decreased dielectric strength is that more frequent swinging shorts and grounds will occur. There are a large number of such undesirable disturbances on this line. If the decrease in the dielectric strength of air was 40% on the average, we could safely predict a correspondingly large increase of such disturbances. I base my guess in this way. I would assume that the danger zone for an arc is 8 to 10 inches at lower altitudes. If 100 shorts or grounds occurred under this condition, it would surely be true that 150 disturbances would occur if the danger zone was increased to from 10 to 12 inches other conditions remaining the same. So many wires swinging into the danger zone make this comparison evident.

LOWERING of the CRITICAL VOLTAGE.

A very important factor in the design of a high voltage transmission line is to keep the voltage low enough that the loss from corona is as low as possible. The corona effect upon conductors at high potential is the appearance at the surface of the conductor of a pale violet light. It is accompanied by copious ionization which lowers the dielectric strength of the air and results in an increase in the leakage current into the air and over the insulators.

At a certain critical voltage which depends chiefly upon the absolute temperature, barometric pressure, radius of conductor and spacing, the visible corona appears and the line losses then begin to increase much faster than in proportion to the voltage. As shown on page 45 curve 19, the curve is logarithmic. This critical voltage is proportional to the first power of the barometric pressure. The variation in critical voltage is shown by the following formula by Prof. Ryan (Ryan, Norris, and Hoxie. Elec. Mach.)

$$E_{max} = \frac{17.94h}{T} 350000(r + .07)\log \frac{1}{r}$$

where h is the barometric pressure in inches and the other constants as usually represented.

The lines of the Colorado Power Company are operating nearer their critical voltage than other lines using higher voltages at lower altitudes. A study of the line loss curves shown later will prove this.

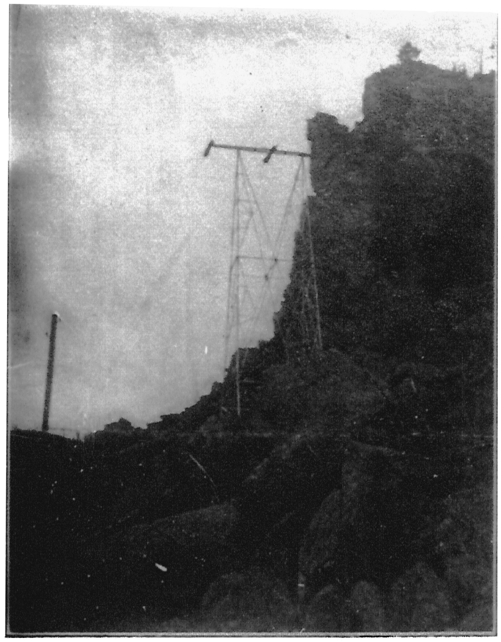


Fig. —Standard Transmission Tower, Showing Character of Country Traversed

Fig. 9.

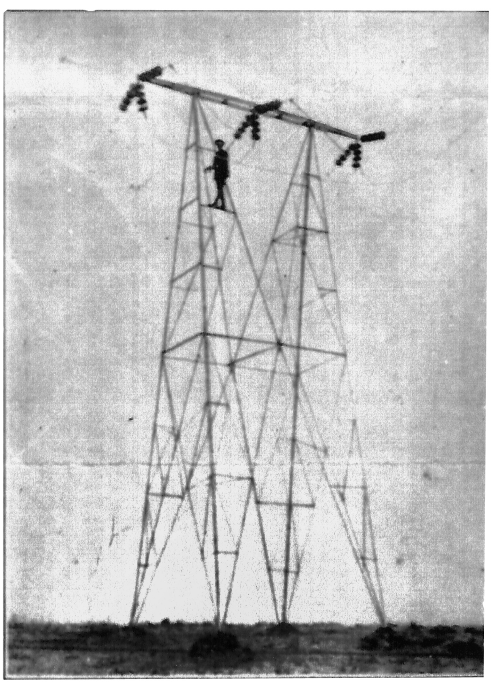


Fig. ‘—Emergency Breaker-Switch Tower

Fig. 10

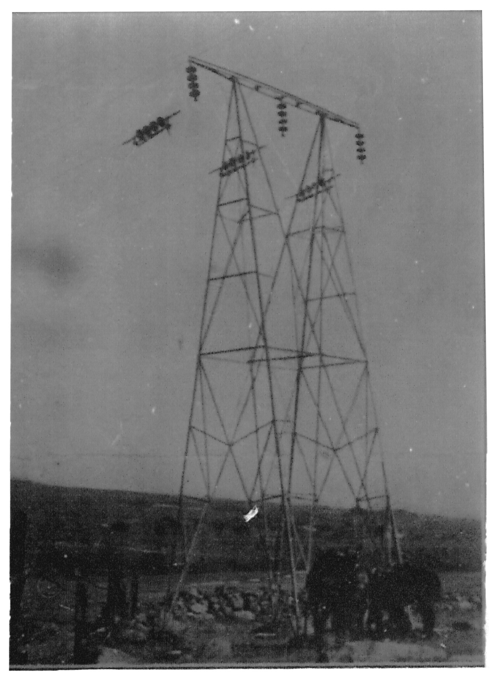


Fig. —Transposition Tower with Copper-Cable Jumpers i: Galvanized Pipe

Fig. 11.

PROBABLE EFFECT of PITCH BLENDE.

The altitude factor alone may not account for all of the lowering in corona point observed on this line. One other factor might be suggested. The Shoshone circuit traverses one of the principal pitch blende deposits known. This is located in Gilpin county about 40 miles west and south of Denver. A new mineral carnotite rich in radium is abundant also. A very probable theory has been advanced as a result. This large pitch blende deposit is mined in places for the recovery of uranium, radium, and other radio-active materials. It has been proven that such elements cause copious ionization of the air, and modern views associate the corona phenomenon and atmospheric conduction with ionization. It seems probable that the proximity of the line to these radio-active deposits would increase the corona effects.

The dielectric strength of the air would also be lowered due to these ionizing influences thus aiding the lowering due to the rarified air.

PROTECTIVE DEVICES.

A line operating under such severe conditions would need to be equipped with the best of protective devices. At the present time, the transmission systems are strongly in need of improvement in their protective devices, chiefly for lightning surge protection.

The following covers the devices used by the Colorado Power Co. 1. Guard wires. 2. Reverse current relays. 3. Aluminum arresters. 4. Grounding switch. 5. Tower Gaps.

1. The entire line was originally equipped with two grounded guard wires. These consisted of two 1/4 inch solid steel strung midway between the line conductors. I deal with their effectiveness in a later paragraph.

2. When stations are operating in parallel, a reverse current overload relay is indispensible. The function of such a relay is to prevent one station feeding into a short or ground occurring upon the line from the other station. At the Denver Substation, reverse current overload relays are placed between the low tension side of each bank of transformers (Shoshone and Boulder) and the bus bars. In the case of a ground upon the Boulder line for example, the reversed current from the bus bars onto the Boulder line will actuate the relay upon that line and open it up. These relays are set in this case for a time limit of 20 seconds. I have heard that such relays are not dependable but no trouble is being experienced with them upon this system.

3. The two stations which are subjected to the worst lightning, Boulder and Leadville are equipped with 100000 volt aluminum arresters. Practically all of the 13200 volt feeders are also equipped with the same type of arrester. Their effectiveness will be discussed later on.

4. Each generating station and the Denver Substation is equipped with a grounding switch. This is illustrated in fig.24 page 69. It has become an important piece of apparatus. Frequent use has been made of them. One illustration of their application is that frequently lightning comes in on the 100000 volt bus bars and grounds them by shattering the insulators. Also the transformer bushings ground with the same result. Even tho the station operator can pull his own generators off the transformers, other stations will feed into the ground and the only recourse to be had if the relay is too slow to act is to ground the line and force the other station to pull off. The switch is located on the last tower.

5. All of the dead end spans on the line are provided with a set of tower discharge gaps mounted so as to shunt each string of strain suspension insulators. These are explained in full at a later point.

OPERATING DIFFICULTIES.

The Denver Substation was first tried out July 4, 1909. I say tried out because it was not until a month later that the station carried a load. Some very serious electrical breakdowns occurred. The voltage was built up slowly first on the line and station connected. As soon as full potential was about reached, one of the lines grounded at the entrance roof bushing. As shown in fig. 4 , the insulators were supported on a 14 inch sewer tile which in turn rested upon the concrete roof. A 6 inch fibre bushing filled with insulating compound is suspended at the center of the tile. The potential stress occurred between the conductor in the bushing and the metallic lath in the roof and the whole bushing was shattered, the whole seven gallons of insulating compound being distributed over the transformer and the floor.

A radical change was necessary to remedy this weakness. Holes 4 feet square were cut in the roof so as to locate the bushing at their center. These holes were then filled in with 3" x 12" poplar boards thoroughly impregnated with paraffine by about 10 hours boiling under pressure. Every bushing on the system has been modified in the same way. This includes those in the roof of the K-10 100000 volt switch houses as shown in fig. 3 , page 7.

The second time that the voltage was built up, one of the transformer terminals grounded to the case although no damage was done. This was sort of a "freak" occurrence as I have not heard of a repetition of the same since then except during an unusual surge.

The third time that the voltage was built up, the most serious interruption occurred. As seen in the photos of the transformers, the two bushings taper toward each other until the interior ends under the oil were distant (in this case) three inches between the copper terminals. To break down this gap in good oil would require several times 100000 volts, in fact, one would expect the breakdown to occur first ouside the oil at some other point. The resulting arcing short severely carbonized the oil. I was evident that a greater spacing should be allowed and each bushing was removed, taken to town, and machined so that the terminals inside were spaced about 6 inches. The trouble was never repeated.

The following January 1910, a severe short circuit took place in the primary windings in one of the Denver transformers. The heavy cast iron cover had been secured in place as usual with the 1/2 inch bolts in place. A lesson was soon learned. The explosive violence of the short tore the cover off and every window frame in the lower floor was blown out. The effect is shown on the next page in the upper photo. The second picture shows the transformer on its way to the repair shed. Note the condition of the steel

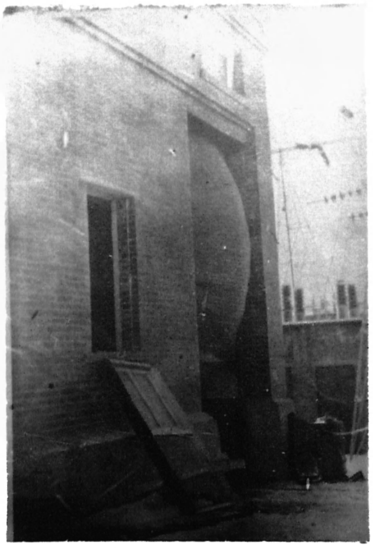


Fig. 12.

roll slat door. A new set of primary coils was necessary. Since this accident, not a large transformer on the system has its iron cap in place. Instead, a light cover of pressed asbestos board is used. In addition, one more transformer has been lost. I am not able to state the cause of these primary shorts. However, I am very much inclined to believe that they were the result of severe potential stresses at the end turns of the primary windings.

Effect of a Transformer Short Denver Substation.

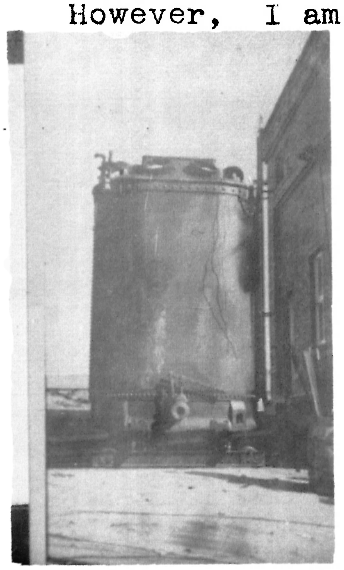


Fig. 13.

On March 4, 1910, one of the conductors on the Shoshone line dropped and grounded. The resulting surge caused a high rise of potential in the generator coils and a severe ground occurred which necessitated the replacing of 20 percent of the coils. I would not expect in this case however that any abnormal induced potential got through the transform-

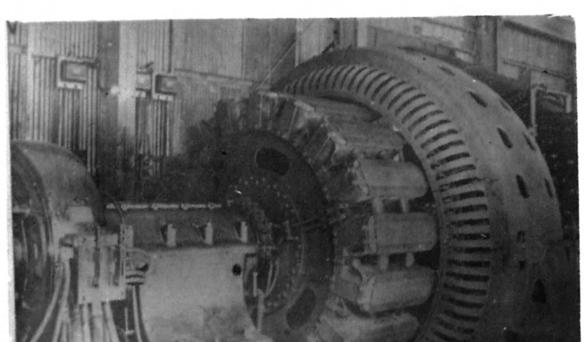


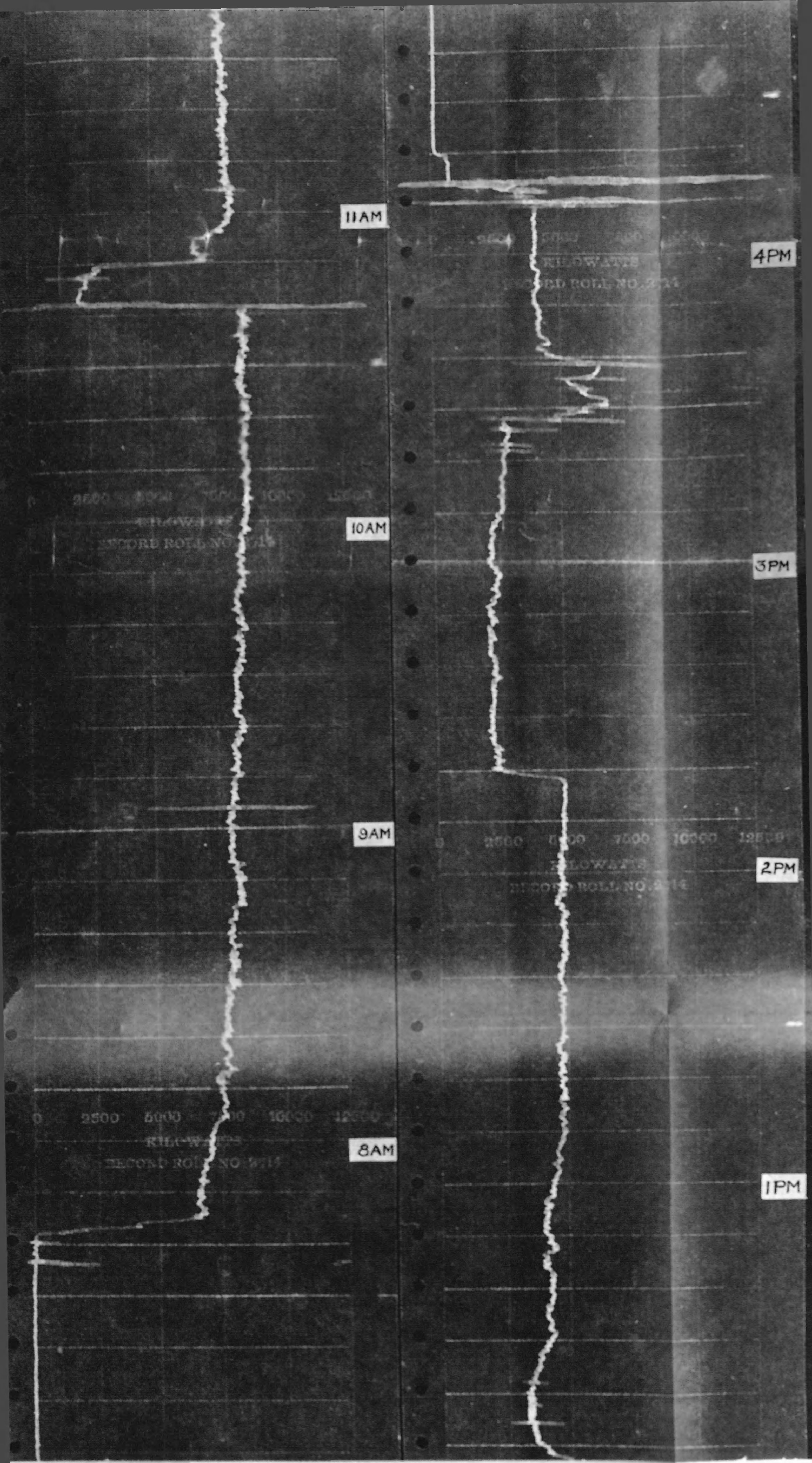
Fig. 14. Grounded Generator.

ers from the line. I offer this incident as an illustration of what might be expected to follow any severe short or ground.

Such phenomena as the foregoing would lead one to believe that dangerous rises of potential were being brought about in the system by some combination of conditions. Any sudden unexpected change from normal current or potential in a system is usually called an electrical surge. An induced voltage is caused by a current change and is proportional to the rate of change of current. Hence any disturbance tending to cause abnormal current changes will result in abnormal potential rises.

Many other minor troubles in addition to the above tended to show that such surges were occurring and becoming very detrimental to good operation. The substations, especially those at higher altitudes, were subjected to very frequent interruptions caused by the puncturing of roof bushings. Numerous surges on the system were clearly indicated by the station meters. Switching, governor trouble, and poor synchronizing gave evidence as causing trouble.

The worst forms of line trouble resulted from lightning I submit on the next page a "brown-print" impression of the curve drawing wattmeter chart for July 18, 1913 at the Boulder generating station. On this day, lightning storms occurred at several points on the system. A study of this



LOG RECORD FOR THE ABOVE CHART. BOULDER STATION JULY 18 1913.

7:36 AM Shoshone paralleled and Boulder took system load.
Work on the Shoshone line.
10:42 Denver knocked off. 10:47 Denver on again at 55 cycles.
11:53 Shoshone paralleled and took 7500 KW acc. storm on system.
3:28 PM Shoshone knocked off. Line surging previous.
3:36 Shoshone knocked off again after being on about 2 minutes.
3:39 Shoshone on again.
4:10 Bad line surging. Ammeters (2) and (3) higher than (1)
4:20 Pulled off the line @ low voltage per Sta. Supt. Line down.

curve and the accompanying log book entrys will show several important things. Frequent power surges are shown. A direct stroke of lightning, perhaps, grounded one phase at 10:42 AM which knocked the Denver substation off the line. At 3:28 PM, Shoshone was knocked off by lightning. Finally at 4:10 PM, a direct stroke on the Boulder line caused an arcing ground or short and the resulting flow of dynamic generator current into it burned off the conductor, putting the Boulder line out of service for 12 hours.

During July and August, such storms occur daily hardly without fail at some point on the system. Four times during the summer of 1913 a conductor was burned in two.

THE APPLICATION of the OSCILLOGRAPH to DETECT LINE OSCILLATIONS DURING SWITCHING.

Such phenomena as the above indicated that destructive rises of potential were occurring on the line. It was decided to make a comprehensive test on the line with the oscillograph. The oscillograph has been applied widely in recent years to transmission systems, for the purpose of detecting current and voltage surges and higher harmonics. With increasing potentials both in underground and in overhead distribution, our present forms of insulation are being taxed to their utmost. A rise of 100% in voltage which, by the way, is not uncommon, becomes very dangerous especially when the factor of safety of the insulation is low. Furthermore, it has been shown that repeated potential stresses in insulation at a certain point weakens its dielectric strength very materially until finally it undergoes rupture.

The chief object of the application of the oscillograph in this test was to observe the current and voltage relations during switching under varying conditions and connections. Undesirable methods of switching could thereby be avoided. At the same time, some approximate idea could be obtained as to what stresses would be reached during arcing grounds. No attempt was made to create any actual arcing grounds on the system or do any switching under load conditions.

It was plainly evident that such a procedure would be dangerous to station apparatus.

The test was made in the spring of 1910 by Mr. Guiseppe Faccioli and his assistant W. W. Lewis from the transformer department of the General Electric Co. at Pittsfield Mass. This test could not be called conclusive for the reason that the true conditions on the high tension lines and windings of the transformers were not observed. Furthermore, no switching was done under load and no overtension surge determined during an arcing ground. The dangers resulting from this case of trouble are the greatest.

Approximate potential surges on the high tension lines ~~was~~ were determined by using a needle spark gap in shunt with a choke coil and the interesting and practical results will be discussed later

The one definite result of the test was a determination of the higher harmonics present during switching and normal operation. Recent and comprehensive tests have been made in other instances with this point in view. The presence of higher harmonics in generating systems is detrimental for two reasons.

In the first place, if the potential waves of higher frequency are superimposed upon the fundamental, the resulting complex wave may be distorted to such a degree that its maximum instantaneous value is considerably increased. This distortion of wave leads to several undesirable results all of which do not concern us here. One effect is that the resulting increased potential strain is a continuous one and should not be confused with the strains resulting from high frequency surges due to arcing shorts, grounds etc which affect a small portion only of the transformers. This continuous strain through the entire winding tends to lower the factor of safety of a large transformer from about 2 to at least 1.4 in extreme cases.

A second result of the higher harmonics is that, if any are present which are equal to the natural period of oscillation of the system.or some part of it, the phenomena of resonance may occur giving dangerous rises of potential.

However to my mind, the application of the oscillograph to the low tension side of a transformer would not detect these higher harmonics causing resonance owing to the damping action of the transformer iron. I was not my intention to attempt the theoretical discussion of any of the oscillograms obtained during this test. Astudy of the entire group taken would be necessary for a complete understanding of the varying results. The interpretation of these curves is a tedious process and demands the skill of the experts in this line. Any one interested specially in these results is referred to the fourth and fifth articles given in the bibliography which cover the test thoroughly.

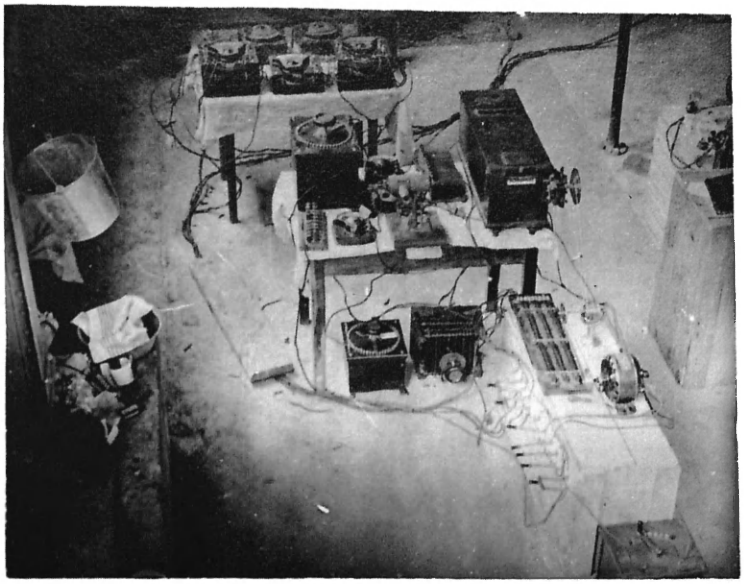
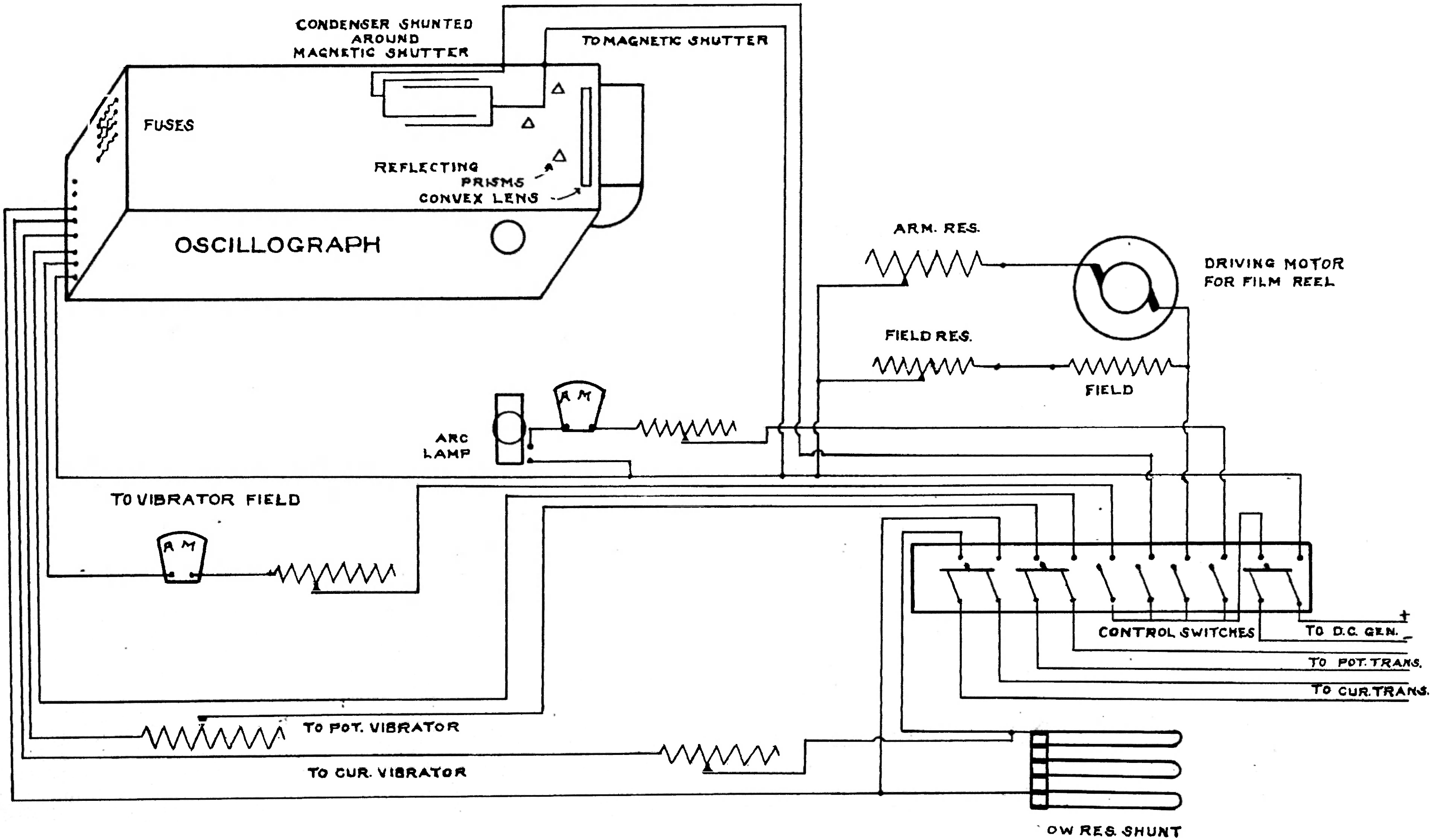


Fig. 15.
Oscillograph and Accessories.

I have shown above a photo showing the necessary apparatus including meters for the test. On the next page I have given the circuits used. In the oscillograph shown, the ray of light from the small arc lamp is focussed through an aperature 5/8" diam. in the side of the box. Three small prisims with faces 1/4" wide are placed so that each one will send a ray of light to its respective vibrator. This ray on reachin the vibrator is 1/2" in diam. A slot in front 1/32" x 1/4" allows the ray to strike the mirror and be reflected upwards to the front of the box where it impinges upon a convex lens 5" x 1". This lens brings each ray to a focus upon the ground glass. A small centimeter scale on the glass aids in securing the proper amplitude of the wave. After the right amplitude is secured, the ground glass frame is removed and the film roll holder is slipped into place. The tripping apparatus run by motor holds the shutter open for one revolution of the roll. The shutter opens magnetically.

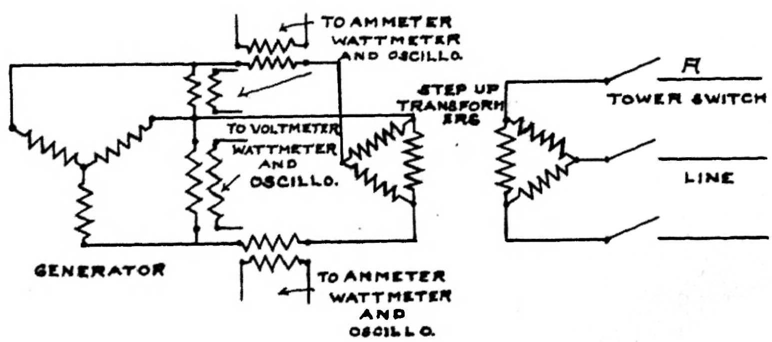


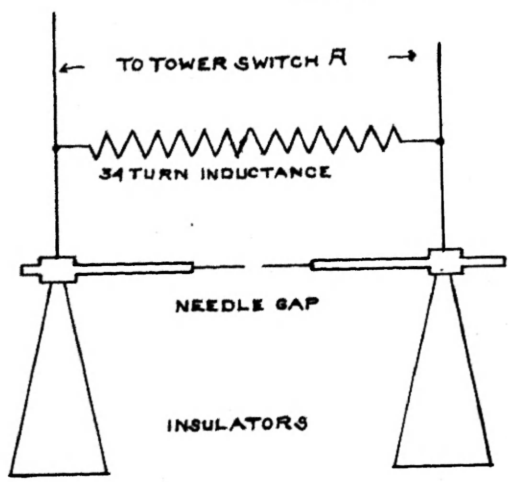
OSCILLOGRAPH CIRCUITS
COLORADO POWER COMPANY
SHOSHONE LINE TEST
MAY 1 1910

In addition to these oscillograph circuits, I have included below a diagram of the connections immediate to the bus bars and transformers. The location of the inductive spark gap is shown in the figure as shunted around one of the tower disconnecting switches.

It was my intention to follow these necessary and general remarks by stating the methods of switching and emphasizing the safest procedure. However, these conclusions have been made all the more evident from the data obtained by introducing the spark gap along with the oscillograph test. A discussion of this apparatus and method should precede these conclusions.

SHOSHONE BUS CONNECTIONS TO OSCILLOGRAPH





USE of the INDUCTIVE SPARK GAP.

The object of the application of the inductive spark gap was to detect potential stresses resulting from switching and other current surges through inductances. A heavy surge of current through an inductance results in a induced E M F or a piling up of potential at that point. The location of the spark gap used in this test is shown on the preceding page together with the method of placing it in series with the line. Each side of the gap is mounted upon a 100000 volt wall type insulator. The choke coil proper is hung from each side of the single pole disconnecting switch located on the first tower at each station so that if the switch is open the coil is in series with the line. The spark gap is shunted around the coil with light jumpers. The coil of course was located out of doors.

Each choke coil consisted of 34 turns of 1/2 inch copper rod, the mean diameter of the coil being 6 inches. The length of the coil was 32 inches, the inductance being .0326 mh. Let us suppose thatthe maximum instantaneous current in a line conductor is 100 amperes. The voltage drop across the coil would be $E = IX = I\omega L$ or

$$E = 100 \times 2\pi 60 \times .0000326 = 1.33 \text{ volts.}$$

The induced E M F is proportional to the inductance and the rate of change of the current. It can be seen therefore that the voltage across the coil is a measure of the magnitude of the current and the steepness of the wave front.

The behavior of this choke coil should be very similar to what would occur at the first few turns of a transformer. A sudden rush of energy through the coil gives rise to potential in proportion to the magnitude of energy and velocity of transmission, and a rupture occurs across the spark gap. At the transformer, the insulation would give way between adjacent turns or across the first coil perhaps.

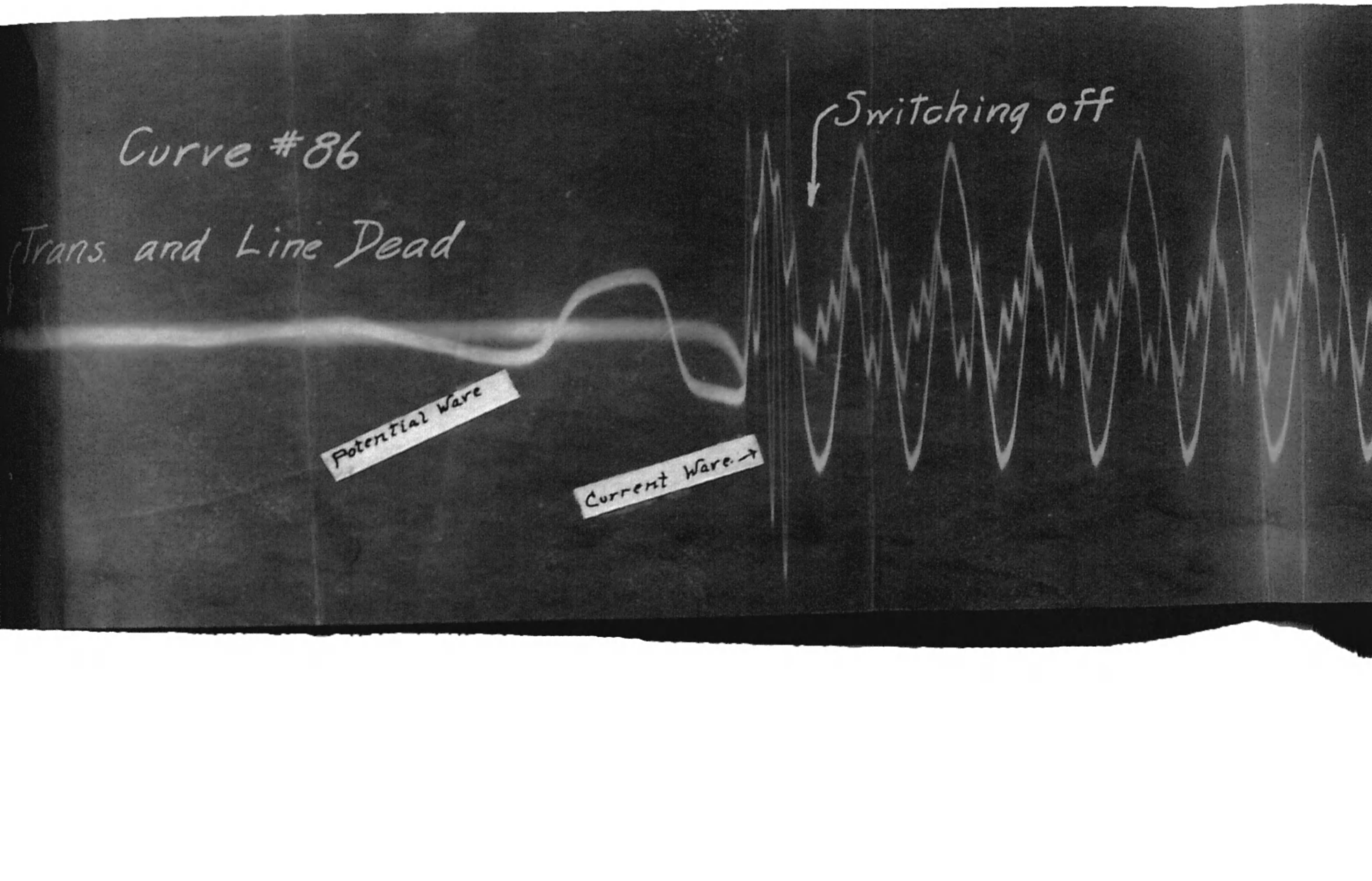
The following brief but important results were obtained during no load switching. The normal full voltagecexciting current is about 50 amperes to Denver.

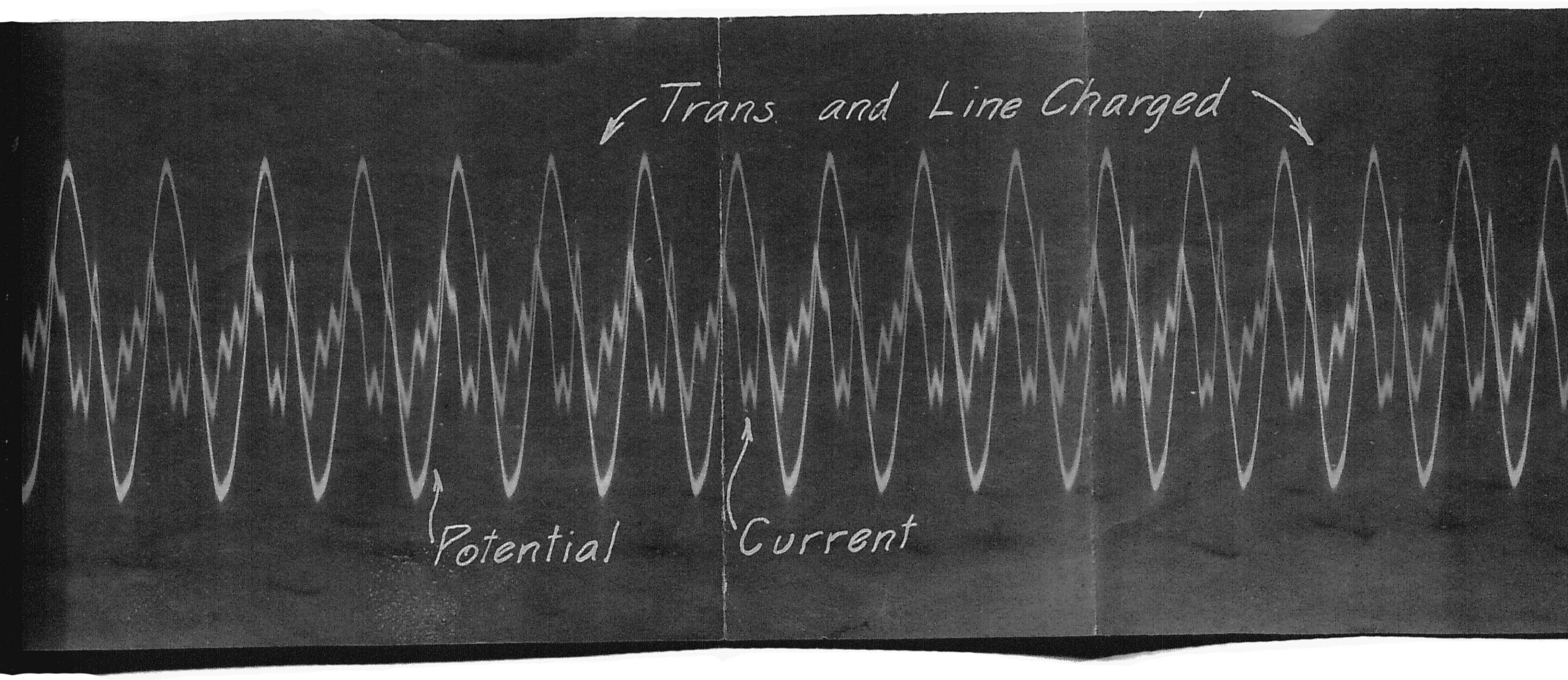
1. The entire line from Shoshone to Denver 153 miles was excited and the transformers at Denver thrown by the high tension switch. A spark gap at Denver broke down when set at 30000 volts. A high resistance carborundum rod in series with the gap was shattered by the flow of current. This gap was spaced at 1 5/8 inches.

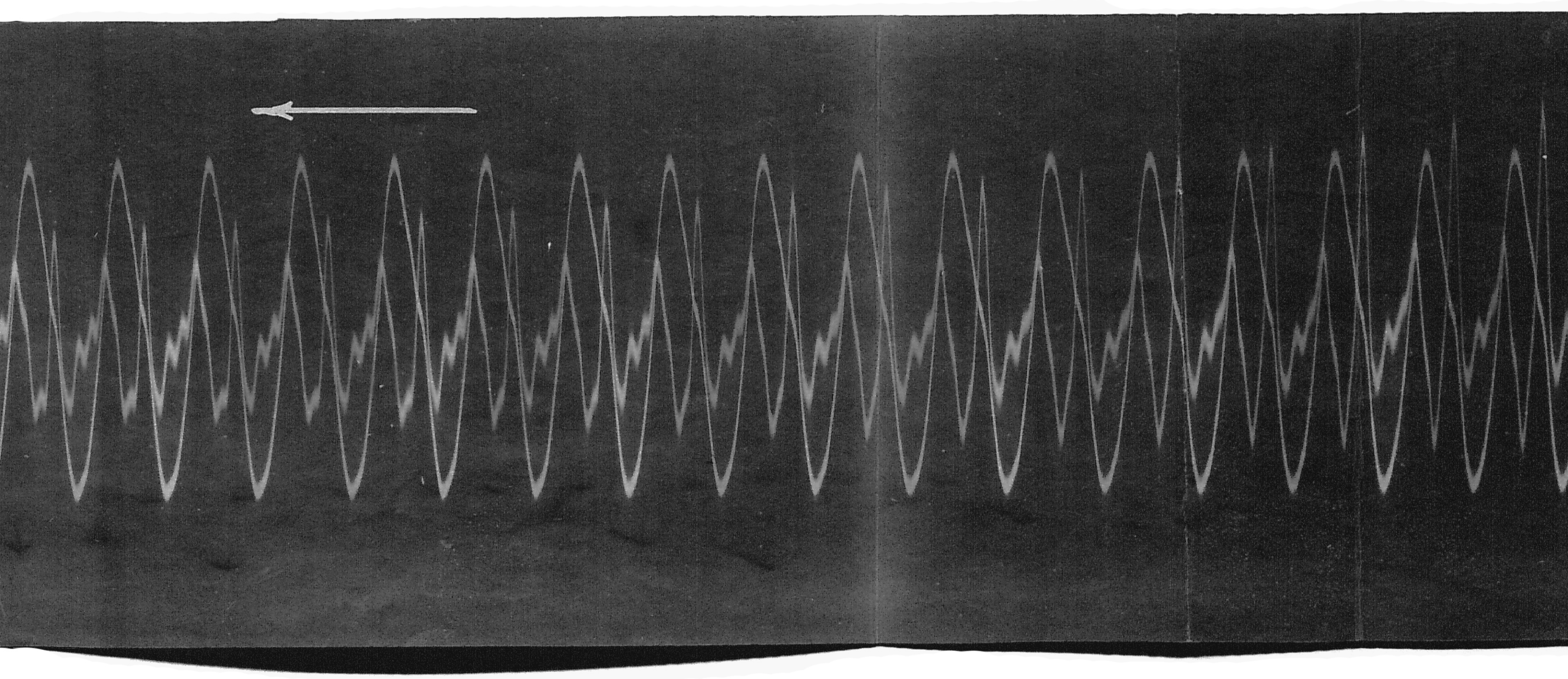
2. The line and transformers were thrown together by means of a low tension switch at Shoshone and the gap at Denver broke down when set at 20000 volts.

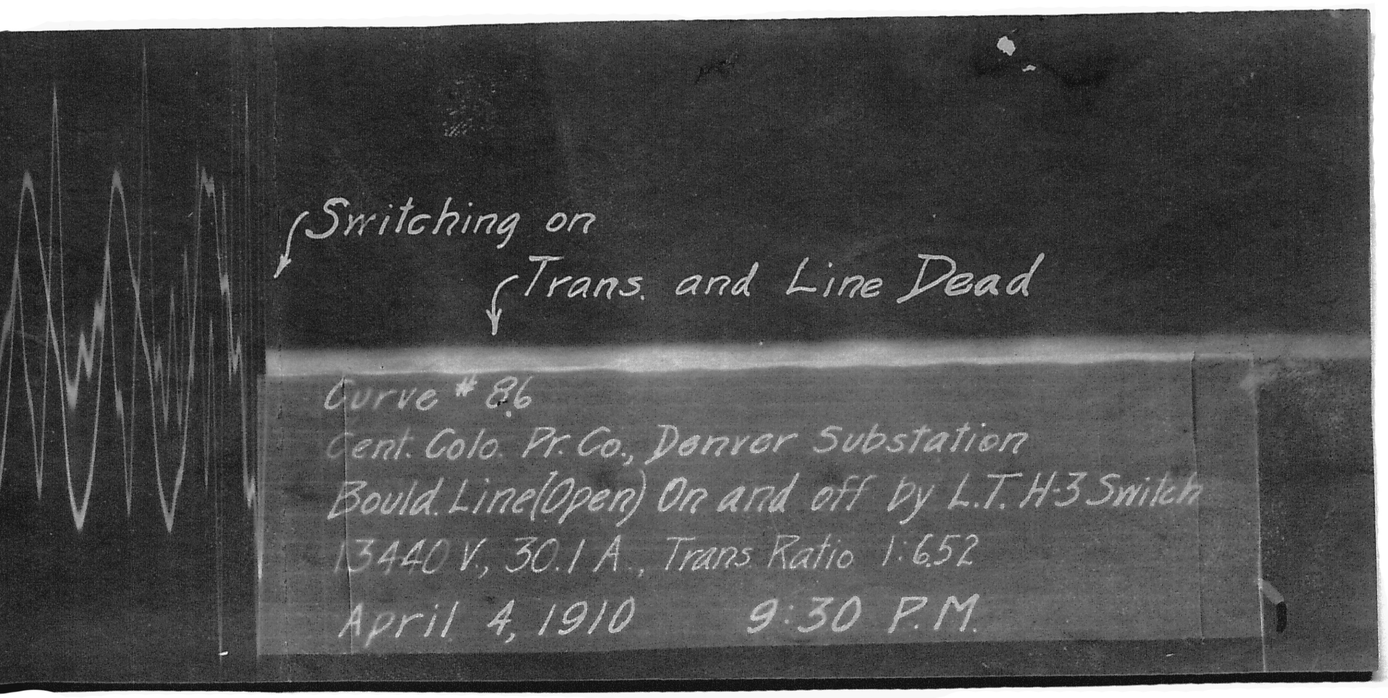
3. With the stepdown transformers connected to the line at Denver and excited, the 28 mile unloaded line to Boulder was switched onto the transformers and the Denver gap broke down set for 15000 volts.

This important conclusion follows from these three switching operations, that there is less danger when the


Curve #86
Trans. and Line Dead
Switching off
Potential Wave
Current Wave →


Trans and Line Charged
Potential
Current





Switching on
Trans. and Line Dead
Curve # 86
Cent. Colo. Pr. Co., Denver Substation
Bould. Line (Open) On and off by L.T. H-3 Switch
13440 V., 30.1 A., Trans Ratio 1:6.52
April 4, 1910 9:30 P.M.

receiving transformers and line together are excited by the generator than when the line is excited first and the receivinf transformers thrown in, and still less danger when switching is done on the low tension side of the receiving transformers. The reason for this is that when the line and transformers are hooked together, the former takes a leading current and the latter a lagging current and the two neutralize each other. But when the transformers are switched onto the live line, a rush of magnetizing current occurs together with an exchange of the stored energy between the line and the transformers which is severe in some cases. Switching on the low tension side is made safer on account of the damping or sluggish effect of the transformer iron.

One important factor in high tension switching is the production of arcs thru the oil at the instant of break. The accompanying oscillogram was taken on the low tension side of a single phase 100000 volt transformer energizing the Boulder line from the Denver bus bars. The potential wave shows 1 1/2 cycles arcing through the oil at switching off. The switch has opened at the instant of zero E M F approximately. It is interesting to note that what would be the last complete half wave of current has been replaced by three complete waves of current two of which are twice normal. Therefore, twice normal current in 1/6 the time would tend to induce abnormal voltages in the primary windings. This curve shows the exciting current in the low tension side only.

These oscillations become quite severe if the switch closes at the instant of maximum E M F of the wave. The result is high frequency energy impulses at the terminals of the transformer producing locally steep wave fronts and resulting potential strains. Of course, if a potential difference of 30000 volts occurs across this choke coil of 34 turns, the voltage between turns may not be over 1500 volts even tho we consider the spark lag or time element of discharge of the gap. Our commercial transformers are now designed at the end turns to stand many times this amount, usually 40000 volts.

I will point out however at this time that these tests were made under ideal conditions of no load. It was found that the maximum rise in potential in the impressed waves was not over 60% normal E M F, a figure not to be considered dangerous. In conclusion, our articles try to lay down some rules regarding proper methods of switching. I consider a large part of this experimental data of theoretical interest only. Practical operation of lines shows more clearly than these tests that conditions arise very frequently when fluctuating energy of large magnitude causes damage. Furthermore, in extreme cases of line trouble, and emergency operation, set rules cannot be followed. It is during such switching that losses of apparatus occur. The practical solution of the problem of protection is being arrived at by actual subjection of such apparatus to the extremes of service.

LINE LOSS TEST.

On May 1, 1910 at the same time that the oscillograph was used at Shoshone, a line loss test was made. The losses on long transmission lines employing high voltages reach a high value and must be considered in the design of the line, and its regulation.

The greatest losses on such lines cannot be calculated but must be arrived at from actual tests on existing lines. For this reason, much effort has been put forth in recent years to compile such data under as varying conditions as possible. The most comprehensive test that has been made of late is that by Ralph D. Mershon in 1904-1907 at Niagara falls upon a specially constructed line.

The data obtained in the Colorado Power Co. test is very important since it pertains to conditions of high altitudes.. A discussion of the line losses should first be made.

Transmission line losses are of two kinds first, insulator losses and second, atmospheric or corona losses. The insulator losses consist of a leakage of current through the body of the insulator and over the surface of the insulator through the film of dirt always present.

Corona is the term given to that electrical discharge into the atmosphere from a conductor when the dielectric is stressed to high difference of potential. If present to a sufficient extent, a pale violet light is seen at the surface of the conductor. The effect of this corona is to render the air more conducting, due probably, to the ionization of the gas molecules. At higher altitudes, the corona effect on this line is so very pronounced that it may be observed easily at night. An appreciable leakage current and accompanying line loss is the result. The energy is perhaps entirely dissipated as heat. The appearance of the corona seems to coincide with a certain definite critical voltage depending various conditions. The important factors which affect this critical voltage are spacing, diameter of conductor, and barometric pressure. The larger these quantities the higher will be the critical voltage. Of course at the same time, these three factors affect the losses on high voltage lines, any decrease in these factors will increase the losses. Another factor has been discovered by one investigator Ralph D. Mershon at Niagara, which evidently plays some part in the losses but to what extent has not been proven definitely. This factor is the "vapor product", or the product of the relative humidity and the vapor pressure in the atmosphere.

Since relative humidity = p/P where p is the actual aqueous pressure existing and P is the maximum pressure which would occur if the air were fully saturated at that temperature. We have then,

$$\text{Vapor product} = \frac{p}{P} \times p = \frac{p^2}{P}$$

Experiment has clearly shown that the losses increase noticeably with an increase in vapor pressure but it has not been proven that the vapor product shifts the critical voltage.

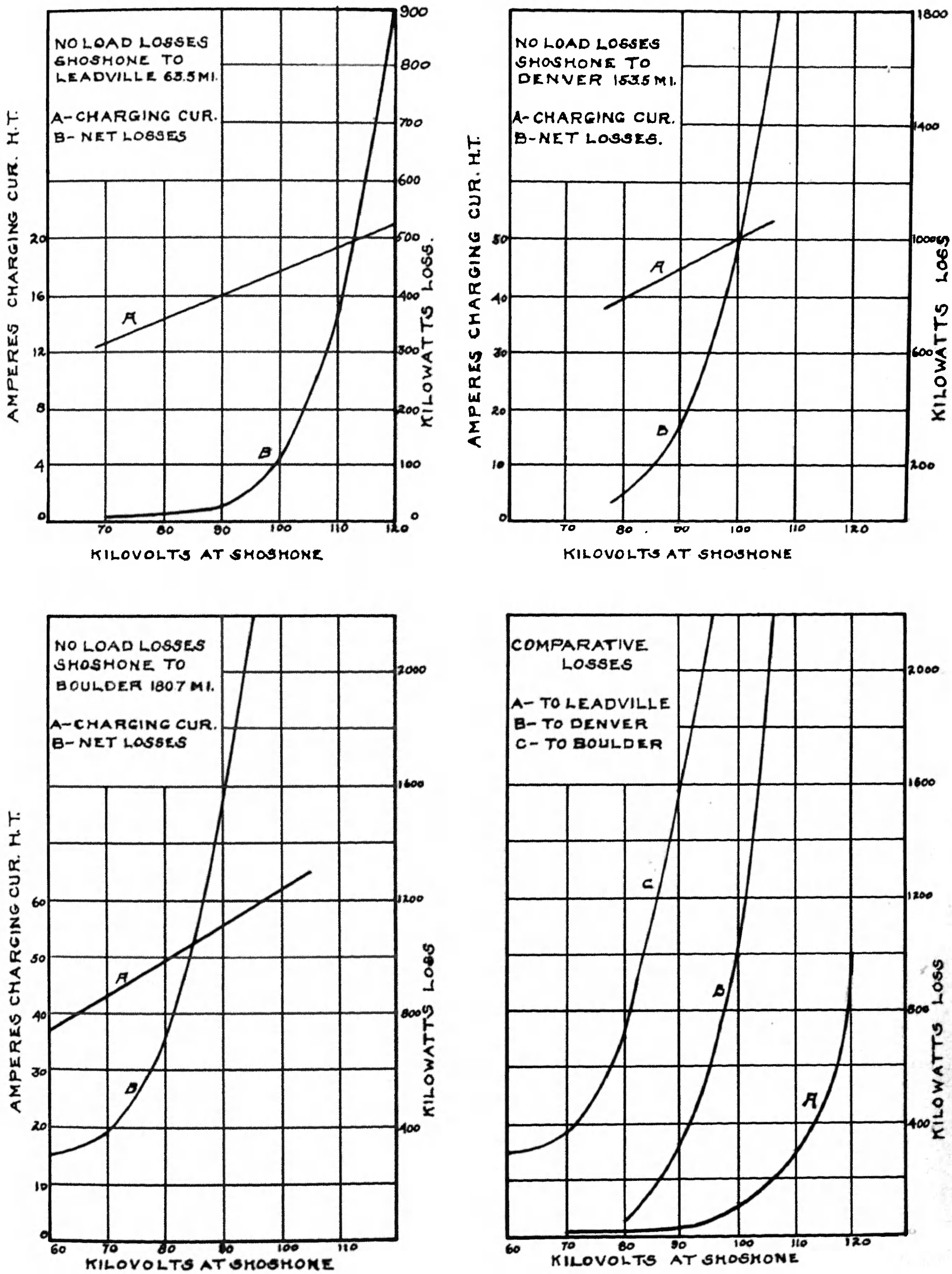
Method of Test and Results.

The line loss test on the Colorado Power Co. system consisted of two separate tests, each for a definite end in view. A series of readings was made at Shoshone for the purpose of merely observing the magnitude of the line and atmospheric losses on the entire line and its various sections. In addition, a series of readings was made at Denver upon the 28 mile line to Boulder for the purpose of checking chiefly the existing theories regarding variation of the critical voltage or formulating new theories.

No conclusions could be drawn from the data taken at Shoshone in regard to the critical voltage or its variation for the reason that the large rise in voltage toward the receiving end of the line made its location impossible. A voltage of 70000 at Shoshone gave 100000 volts at Boulder on 182 miles of line or a rise of 43%. The highest voltage used in the test on the full length of line was 80 kilovolts which gave about 120 kilovolts at Boulder a value not to be exceeded for safety.

The test made from Shoshone was made in three parts, first, on the 63.5 miles to Leadville (it would be well for the reader to refer to the profile page 8a showing the rise in altitude on these sections). Second Shoshone to Denver

Fig. 16.


NO LOAD LOSSES
SHOSHONE TO
LEADVILLE 63.5 MI.
A- CHARGING CUR.
B- NET LOSSES
AMPERES CHARGING CUR. H.T.
KILOWATTS LOSS.
KILOVOLTS AT SHOSHONE
NO LOAD LOSSES
SHOSHONE TO
DENVER 153.5 MI.
A- CHARGING CUR.
B- NET LOSSES.
AMPERES CHARGING CUR. H.T.
KILOWATTS LOSS
KILOVOLTS AT SHOSHONE
NO LOAD LOSSES
SHOSHONE TO
BOULDER 180.7 MI.
A- CHARGING CUR.
B- NET LOSSES
AMPERES CHARGING CUR. H.T.
KILOWATTS LOSS
KILOVOLTS AT SHOSHONE
COMPARATIVE
LOSSES
A- TO LEADVILLE
B- TO DENVER
C- TO BOULDER
KILOWATTS LOSS
KILOVOLTS AT SHOSHONE

153.5 miles, and third, from Shoshone to Boulder 181.1 miles. On page 43 are grouped these three curves which are self explanatory. The method of making a reading was to first excite the transformers with the line disconnected at the first tower and take a reading. This gave the transformer loss at that voltage. Second, the same voltage was impressed on the line and transformers. From this reading, was subtracted the transformer loss leaving the net line loss (ohmic insulator, and atmospheric). The data was taken by means of accurate portable meters sent out by the General Electric Co. The current coils of the meters were excited by the secondary current from a series current transformer in the bus bar. Owing to the fact that this secondary current is out of phase with the E M F, an error of about 1.5% at 100 kilovolts is introduced in the wattmeter.

An inspection of the curves will show that the line in some portion of each section was operating above its critical voltage. This fact can be ascertained as follows from the "Mershon Method". See fig.19 page 45. To determine the critical point or voltage on the line loss curve, first prolong the lower part of the curve making it follow its apparent equation. Then the point where this curve branches off marks the critical voltage.

The characteristic feature of these curves is that beyond the noticeable bend or critical point, the losses in-

Fig. 17.

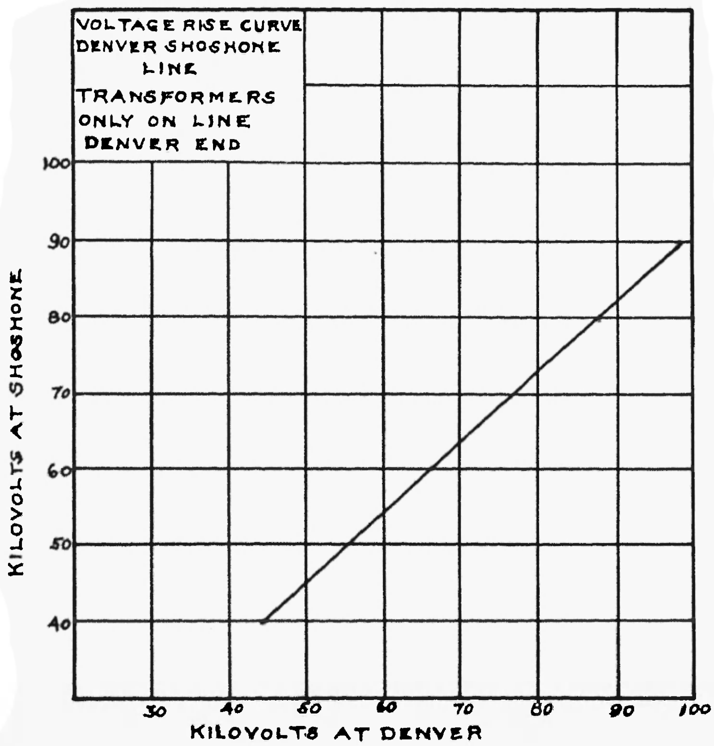


Fig. 18.

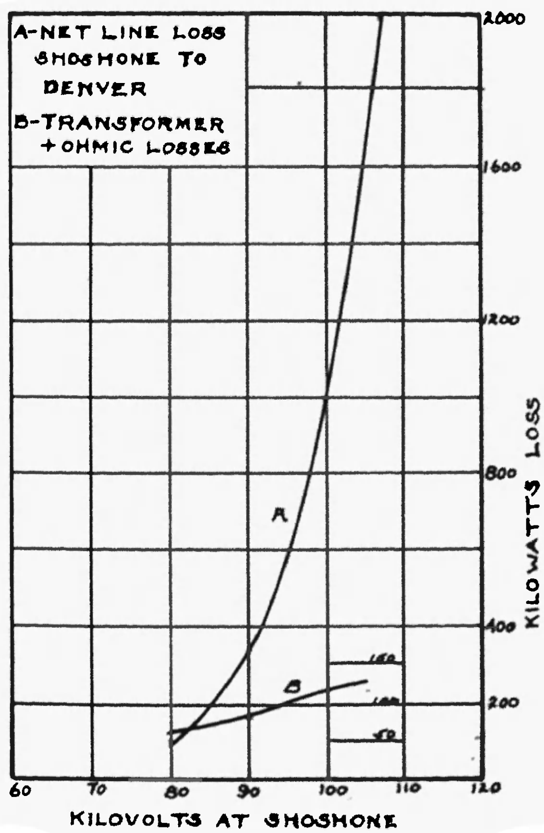
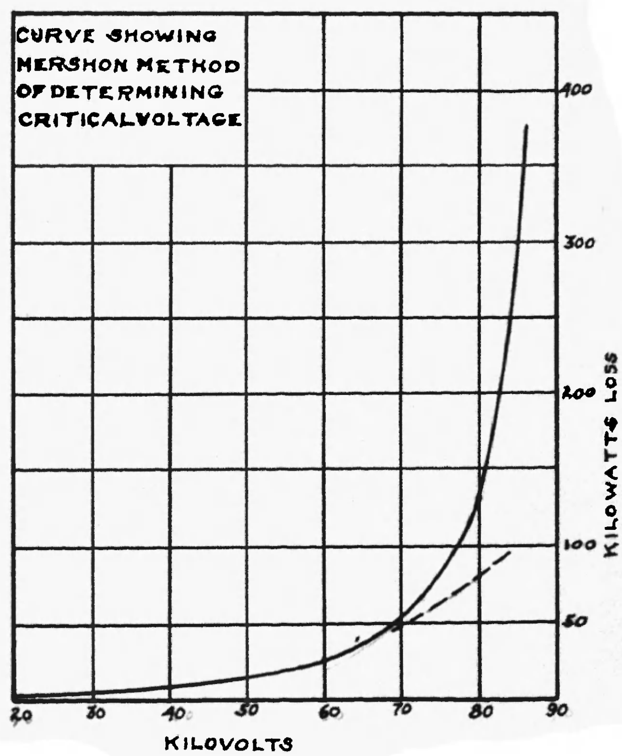


Fig. 19.



crease much faster than in proportion to the voltage giving in fact a pronounced logarithmic curve.

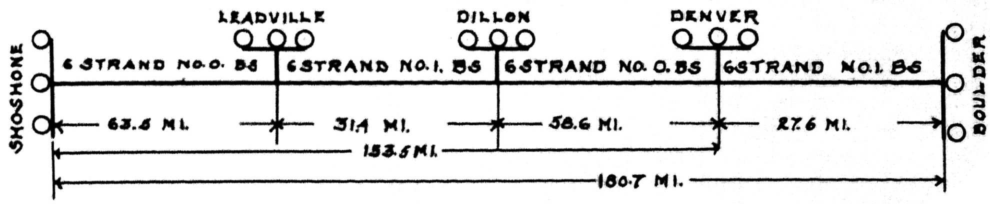
I have prepared on the following page in tabular form the data taken from these curves and some taken on the full length of line (181 miles to Boulder) at an earlier date July 23 1909 under the direction of Mr. West the general manager at that time. This table shows line loss only, including ohmic losses, the transformer loss being subtracted from the total losses. I have prepared it in this form for the purpose of direct comparison

Now as to the practical value of this data; it merely shows us that the losses may assume prohibitive values if any attempt is made to transmit power at much higher potentials than are used at present.

Though the losses here shown seem enormous, the line does not show such losses at normal operation. The greater part of these losses are concentrated near the receiving end of the line where the no load rise in voltage is very great. When the line is loaded, the inductive reactance and ohmic drop become so great that the losses are much reduced. As shown on the curve, the total no load loss to Boulder at normal voltage is about 2300 K W but with unloaded transformers on the line at Denver and Boulder, the losses drop to 1300 K W. To show this more conclusively, for the month of August 1913 the total generated on the system was 7002616 K W hours and the line loss high

Kilovolts at Shoshone	Kilowatts Shoshone to Leadville	Kilowatts Shoshone to Denver	Kilowatts Shoshone to Boulder
80	16	207	676
90	77	757	2207
100	128	1148	2850 (EXTERPOLATED)

Table represents total losses - transformer loss.



	$\dfrac{\text{Denver loss}}{\text{Leadville loss}}$	$\dfrac{\text{Boulder loss}}{\text{Leadville loss}}$
80 K V	$\frac{207}{16} = 12.9$	$\frac{676}{16} = 42.2$
95 K V	$\frac{757}{77} = 10.8$	$\frac{2207}{77} = 28.6$
100 K V	$\frac{1148}{128} = 8.9$	$\frac{2850}{128} = 22.3$

$$\frac{100 - 80}{80} = 25\% \qquad \frac{1148 - 207}{207} = 445\%$$

At 100 K V , normal operating voltage, the losses from Shoshone to Leadville, 63.5 miles, are 128 K W, while if 90 miles more to Denver are added, the losses are increased to 1148 K W or nine fold and if only 27.6 miles further to Boulder are added, the losses become 2850 K W which is 22 times the loss to Leadville or 2 1/2 times the loss to Denver from Shoshone 153.5 miles.

tension plus transformer loss was 648566 K W hours or a loss of 9 1/4% an average value for transmission systems. The transformer portion of this loss is between 20% and 30%.

This data shows clearly that if it is attempted to operate lines much abobe their critical voltage, the losses approach an appreciable value.

Boulder Line Loss.

The second part of the line loss test was made upon the Denver-Boulder line for the purpose of investigating or determining the critical voltage. As no extreme altitude is found on this portion of the line, the data obtained could be compared more favorably with our existing data. The average altitude of this short line is 5300 feet ~~miles~~, and at only one point does the line cross a range. This is near Boulder at an altitude of 7500 feet.

In order to measure the line losses, the following method was resorted to. A 2500 K W transformer of ratio 13200-100000 was excited from the 13200 volt bus bars at the Denver substation and by changing both the primary and secondary leads, a variable voltage was obtained. The diagram Fig. 20 page 49 shows the connections used. one transposition occurs on the line so that 2/3 of the line is spaced at 124" and 1/3 at 248". The wattmeters was connected in series with the low tension side of the

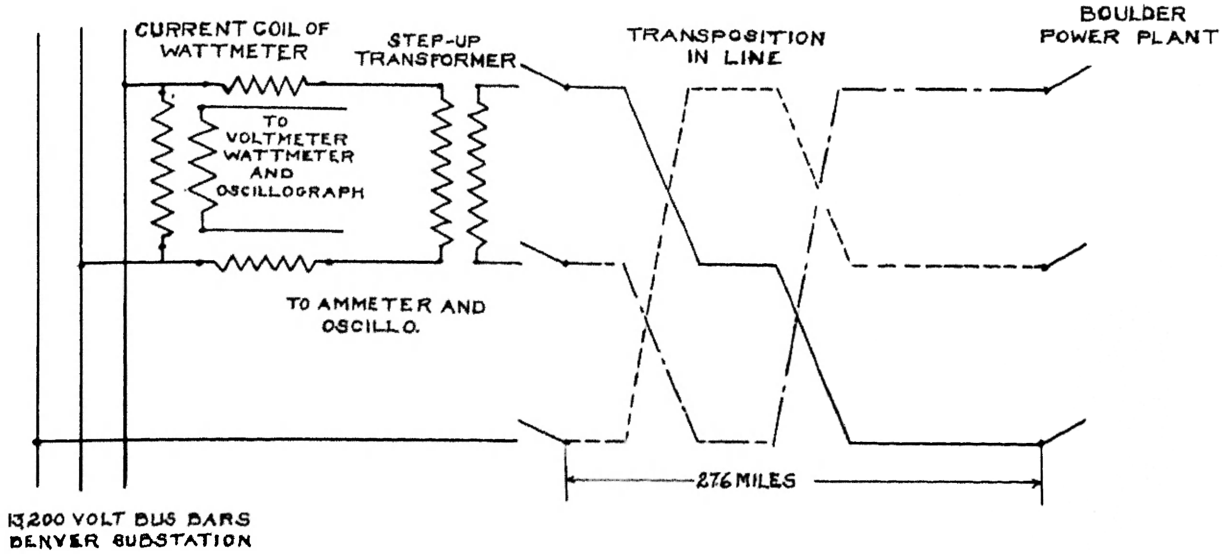


Fig. 20. Boulder Line Test. Bus Connections.

Fig. 21.

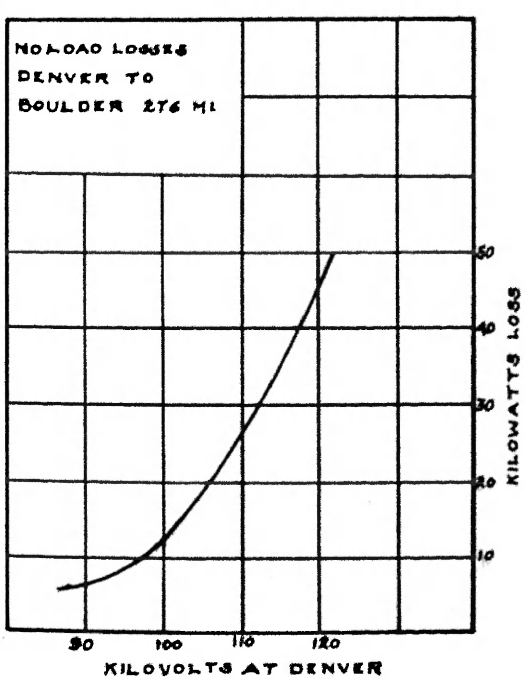
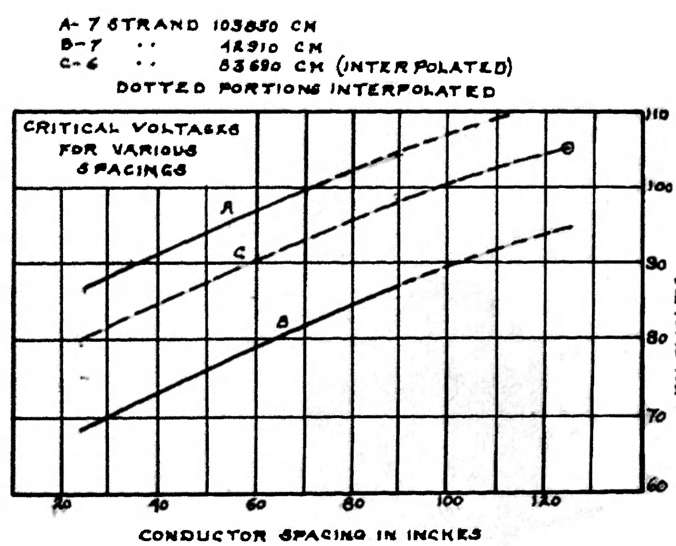


Fig. 22.



transformer thereby avoiding the error due to the leading current in a series transformer. The curve fig. 21 on the same page shows the resulting data and interesting conclusions may be formed from it. According to the Mershon Method of determining the critical voltage, the value 92.5 kilovolts would be obtained. However, since the lower portion of this curve is so very limited, an error is introduced into this approximation with a probability of a lower value than 92.5. On the same page, I have reproduced two curves obtained by experiment at Niagara by Mershon. These cover data taken upon two 7 strand cables; one of 103850 cm and the other of 42900 cm at various spacings. The variation between critical voltage and spacing is shown. Now existing data shows that the critical point varies proportionally with the radius of the conductor, hence it is an easy matter to interpolate a curve for a No. 1-6 strand 83690 cm conductor and exterpolate for a spacing of 124". We find that the critical voltage for such constants is 106 kilovolts.

Now experiments have shown that the critical voltage is proportional to the barometric pressure. We have then,

$$\frac{24.6}{29.6} \times 106 = 88.5 \text{ kilovolts.}$$

these pressures representing average conditions of pressure at 5300 feet and at Niagara. This value of 88.5 kilovolts following from this previous test and the value of 92.5 kilovolts obtained from curve fig. 21 check fairly well and shows no doubt that the critical voltage varies in proportion to the barometric pressure.

The curve shows also that, between Denver and Boulder, the line is operating a little above its critical voltage.

The curves shown here are reproduced from curves already published in the proceedings of the A. I. E. E. as indicated in the bibliography. I have merely interpretated and discussed these curves in such a manner and to such an extent to make them fit in with the balance of this article.

LINE SURGING. - CAUSES.

There are two really vital points to be considered in the operation of long distance high voltage transmission systems, prevention of interruptions and protection of apparatus. This statement of course would apply to any transmission system but, in the first mentioned class, these two things are the most difficult to secure.

The greatest danger to continuous operation and safety of apparatus is line surging. A good definition of an electrical surge is not easily stated. In the following discussion, I will take it to mean any abnormal rush of energy in a portion of a circuit at either impressed, natural, or high frequency. The following causes of line trouble invariabley give rise to surges of some nature, usually severe.

1. Arcing shorts. 2. Arcing grounds.
3. Permanent shorts or grounds. 4. Lightning
5. Switching.

1. An arcing short usually results from two conductors swinging sufficiently close to strike an arc through the air. The resulting surge of power can assume large proportions. and very high frequencies depending upon the length of the arc and the constants of the circuits. The usual indication of such line trouble to the station operator is a swinging of the wattmeter pointer and an equal displacement of two of the station ammeters.

2. An arcing ground may result from a line conductor swinging too close to a guard wire, or an insulator failure due to some cause followed by dynamic current. The energy exchange and frequency may be the same as for arcing shorts. The indication of such line trouble to the operator is a high varying reading on one line ammeter. An arcing ground is a very serious case of surging as I will attempt to show later.

3. Permanent shorts or grounds are self explanatory terms. It is possible for two conductors to swing into permanent contact. One or more conductors may break and ground to earth or tower resulting in a permanent ground or short. The resulting rush of power through the inductive circuits of the station apparatus becomes dangerous.

4. Line surging resulting from lightning is one of the most serious with which our operating companies have to contend. The conditions which the Colorado Power Co. have to meet are unusually severe. Colorado has the worst lightning storms in the country. The extreme altitude enhances the trouble due to both induced charges and direct strokes. A study of the curve drawing wattmeter chart page 28 shows the effect of lightning storms. During the three summer months, such conditions as these are expected on the average one day out of two. Most lightning surges result from induced charges. Suppose a cloud charged say positive to hover near to the transmission line. A negative

loaded conditions is to my mind even more dangerous. Another objectionable form of switching surge is that due to poor paralleling of stations or synchronizing at the wrong phase relations. The above mentioned surges due to switching result in overtensions or large induced potentials in proportion to the magnitude of the energy involved. Another type of surge which frequently occurs during "switching off" is characterized by its high frequency. This frequency is much less than that of lightning and nearer to the limits at which we would expect resonance to occur. It is caused by the continued arcing of the current through the oil of the switch and occurs at its worst when the switch happens to open at the instant of the maximum on the current wave.

EFFECTS of SURGES.

It would be very difficult to distinguish between these various surges as to their nature or effects. Their bearing upon operating features must be discussed in a general way. I will attempt this in the following pages and make myself clear by including and explaining actual effects, some occurring during normal operation, and some created both experimentally and upon existing systems.

The most of our experimental data up to the present time has been obtained with the oscillograph and the spark gap. However, though this data gives us a good idea as to the dangers of line surging, it does not bring us close enough to the true conditions. The dangers of such surges increase in proportion to the operating voltage. Some of our best data has been obtained by actually creating surges on systems operating normally. Such experiment has been confined to systems using low potentials. It is clearly evident, from our already numerous failures of apparatus, during surging, that any attempt to create surges upon our higher potential systems would be too dangerous. The worst surges occur on the high tension sides of the transformers and line. The oscillograph cannot picture the true conditions there. The dielectric spark lag of the inductive spark gap is so great relatively that its responses to energy pulses and potentials fall very short of the maximum of the surge potential. The conclusions of our investigators are, I think, too mild. It has been clearly impressed upon me from my past experience with the Colorado Power Co. system that these line surges are much more dangerous to apparatus than these conclusions point out.

Suppose that for one thought, that an article was published by a famous General Electric Co. investigator saying that the Colorado Power Co., for example, was operating under conditions too severe for economical operation and good service. Would new customers risk a contract under such conditions? Would the General Electric capital invested with this company be worth as much?

It is actual operating conditions that determine the sale of power. On the day that the curve drawing wattmeter record page 29 was made, two representatives of a prospective consumer for 2000 K W made a visit for inspection to the Boulder plant of this company. I was in charge of the switchboard at the time. One of the men was an electrical engineer. For one hour during their visit, a series of the worst line surges I ever saw were evidenced on the station charts and culminated by the burning in two of a conductor. It is easy to see the result of such a performance. The prospective consumer in this case represented a large smelter. An interruption to such a consumer would mean a loss of money.

There are four effects of line surges which seem to affect operating to the greatest extent.

A. They cause a severe strain on the end turns of transformers.

B, They tend to cause line failures at the insulators.

C, They lead to resonance of E M F at high frequencies.

D. They impair the synchronous operation of rotaries.

A. STRAIN on the END TURNS.

I will reproduce here the result of a test made by Ernst J. Berg* showing very truly the conditions resulting at the end turns of a transformer when an arcing ground is

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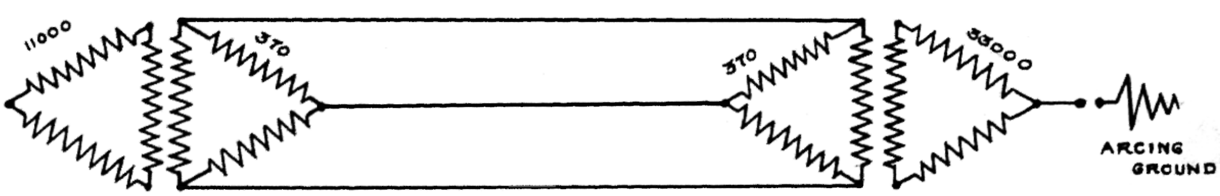
* A. I. E. E. Proceedings May 1908 page 673.

is playing on the line.

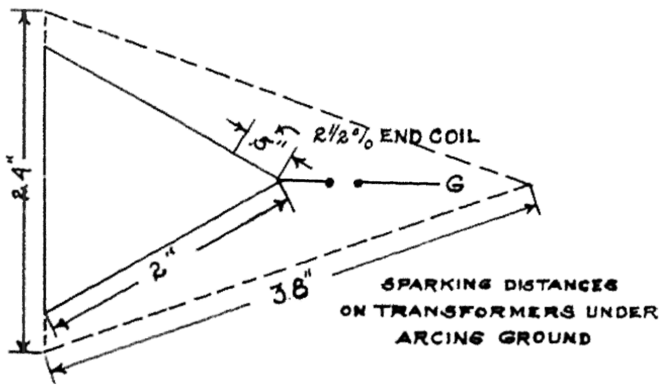
The apparatus used was two banks of transformers as shown in the figure below, one bank to step down from 11000 to 370 volts to feed a three conductor cable 4000 feet long and the experimental bank of transformers which stepped up the voltage from 370 tp 33000.

The special feature of this step up bank was that a tap was brought out from the winding so that an end turn coil of 213 turns or 2.5% of the total high tension winding of 8564 turns was available for a voltage measurement.

As shown in the figure, an arcing ground was created at what would be a line terminal of the transformers, by making a small wire approach this junction. Before the ground was created, the normal sparking distance across each transformer was found to be 2" and across the 2 1/2% coil about .03". After the ground, the needle spark gap used to measure the potentials gave 3.8" across each of the two transformers nearest the ground and 2.4" across the third while the gap across the 2.5% tap broke down at .5".

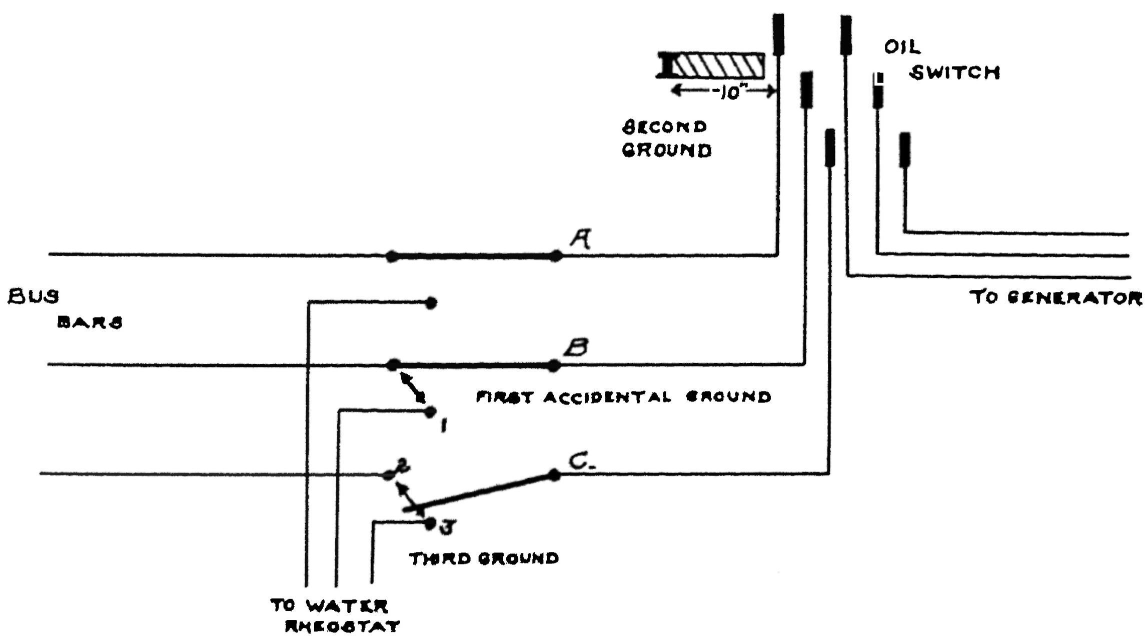


CONNECTIONS FOR ARCING GROUND TEST



The diagram above shows relatively the increase in voltage across the transformers. The voltage across the two transformers nearest the ground was 1.9 times normal whereas the voltage across the 2.5% tap was .5/.03 = 18 times normal. It was found also that using both relatively large resistances and air choke coils in series with the ground arc affected results to a very small degree.

At this point, I would like to cite a personal experience which will show that even on the low tension side of a transformer a surge or arcing ground can do damage. While assistant operator at Shoshone, I had an accident during the act of closing some knife switches on the 4200 volt bus bars. The arrangement of the switches is shown on the next page. The three knives A-B-C served to throw the generator G off from the bus bars and onto the water rheostat for a special purpose. With the oil switch open, I had pulled the knives from the three rheostat clips and commenced to close them on to the bus. While closing the second knife B, the iron hook on the wooden switch stick slipped and caused a very slight arcing ground from B to the water rheostat lead No. 1. At the same instant, a heavy ground occurred in the oil switch, the potential having risen to such a value that it arced from the switch to the iron of the switch chamber a distance of about 10 inches. This was followed by a vicious arcing ground from bus clip No. 2 to the water rheostat clip No. 3. The time element of perhaps a second between the first and third ground enabled me to crawl away quick enough to save my eye sight. The arc continued until the oil switch chamber was completely ruined.



As an actual result of such surges, the Colorado Power Co. has lost two large 2500 K W transformers through the medium of a primary short in addition to numerous failures to roof bushings. I have been present also when several secondary transformers and one potential regulator have failed from surging on the system.

B. INSULATOR FAILURES.

Insulator failures may result both from surges on the high tension line due to local conditions or they may result from lightning or static discharges. I think that, in a way, the insulators act as a relief valve for surges especially if the surge is local to the station where, if it were not taken care of otherwise, it would make itself felt in the station apparatus. Surges at a great distance from the station tend to dissipate their energy and intensity the further they are propagated.

The usual result of a surge arcing over an insulator is to puncture or shatter it and allow an arc to continue from the line conductor to ground through the steel tower. The generator current following burns off either the insulator links or the conductor itself. In steel tower transmission, it is very rare that more than one tower at a time suffers damage. I am showing here by photo some evidence of very recent insulator failures upon the lines of the Colorado Power Co. I call attention in particular to the insulator numbered 6 (see next page) which shows a single puncture near the exact center of the insulator. The other pieces are explained as follows:-

Links #1 and #2 were taken off a string of insulators which broke under a high tension surge. Insulator #6 was one of a string of four dead end span strain insulators. The remaining three were shattered.

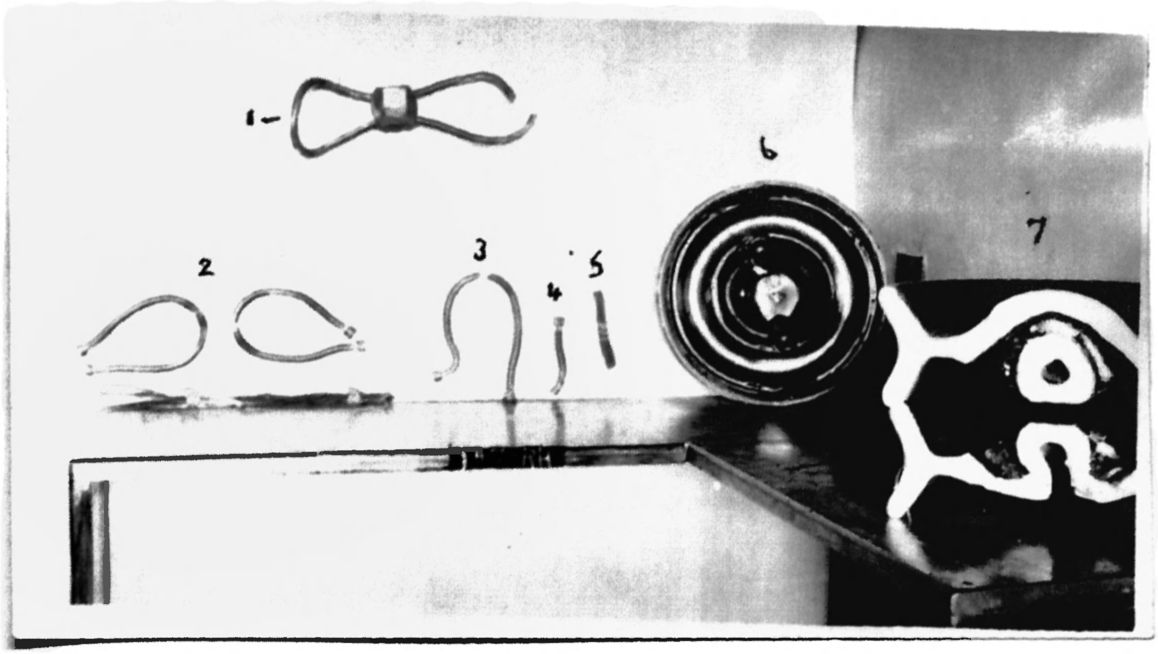


Fig. 23. Insulator Failures.

No's 3-4-5 show portions of links and line conductor burned off during a static lightning discharge. Strain insulator No. 7 is interesting in that it broke down mechanically apparently after being weakened by a surge.

I will add in this connection that it has been proven that a high frequency static discharge through and over an insulator imposes an unusual strain upon it.* As a comparison, it has been shown that (using a thorough laboratory test) a 100000 volt high frequency static discharge will easily pass over and often puncture an insulator which at ordinary operating frequency flashes over at 150000 volts.

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*A. I. E. E. Proceedings. Dec. 1912. Percy H. Thomas.
High Frequency Tests.

It follows from this test that a static lightning discharge becomes very dangerous inasmuch as its frequency is high. Insulator No. 6 on the preceding page shows a clean puncture through its center showing a high frequency strain at that point.

C. RESONANCE due to HIGH FREQUENCY.

High frequency surges resulting for example from an arcing short or from an arc during the opening of a switch, become more dangerous when their frequency approaches the natural frequency of the line and connected apparatus. The result is similar very much to resonance of sound waves in a long tube. If an incident wave approaching the reflecting medium meets the reflected wave at the same phase, an increase in energy and amplitude occurs at that point and the effect upon the ear is a loudness of tone.

In a transmission line, the line itself has its own natural period of vibration. An approximate figure for this constant can be obtained as follows:-

Calculate the inductance of two conductors spaced at 124" of diam. .325" and length 153 miles.

$$L = 0.14 \log \frac{L_s}{L_r} + 0.015244 = .418 \text{ mil henrys per 1000 ft}$$

$$.000418 \times 153 \times 5280 = .338 \text{ henrys.}$$

To calculate the capacity. Assume a condenser at each end of the line. Charging current = 50 amperes. Voltage at Shoshone of 100000 gives 125000 at Denver end.

$$I = 2\pi fCE$$

$$50 = 2\pi 60 \times C \frac{(100000 + 125000)}{2} 10^{-6} = 1.18 \text{ MF}$$

To calculate natural frequency.

$$\text{Natural frequency} = \frac{1}{4\sqrt{LC}} = \frac{1}{4\sqrt{.338 \times 1.18 \times 10^{-6}}} = 400 \text{ cycles.}$$

Of course, if the inductance and capacity of the connected apparatus enters into the oscillation, a different value of natural period would result. It is possible then for waves of a frequency equal to the natural frequency of the line to add up their ordinates if the wave reflected from the end of the line returs in the correct phase. An increased potential will result. The wave shape is changed and a higher maximum value reached. This must not be confused with the superimposing of a higher frequency wave upon the fundamental. The effect of resonance is not as severe as low frequency surges through inductive apparatus. It is possible to control conditions in transmission systems so that higher harmonics will not approach too near to the natural frequency. However, oscillatory discharges may easily obtain a frequency equal to this natural frequency. Experiment and practice show that apparatus undergoes considerable strain during such conditions.

D. EFFECT of SURGES onROTARY OPERATION.

I visited, during the summer of 1913, a substation in Denver containing one 1500 K W 60 cycle rotary converter, at present the property of the Colorado Power Co. It has been known that converters of large units do not give satisfactionin 60 cycle work even if their design is altered. I was informed that the operation of this machine in question was unusually unsatisfactory. A slight surge even such as arising from switching or paralleling would induce such a rise in voltage on the direct current side that a vicious arc would occur and throw the machine off the line. The interruptions at the time of my visit averaged about 10 per day. The Colorado Power Co. is making an attempt to secure a large load from the Denver tramway Co. and the purpose of trying this single unit had this end in view. The results of the test look very discouraging toward carrying a rotary load at the end of this line.

PROTECTION FROM SURGES.

A large amount of investigation has been carried on to date with a view toward eliminating interruptions and loss of apparatus from surges. More or less satisfactory solutions of the problems are in sight. However, it is evident that to make any system practically free from interruption would demand an expenditure too great to warrant this ideal condition.

At the beginning of service, the Colorado Power Co. placed its greatest dependence for lightning protection upon its grounded guard wires. Experience has proven to them and in fact to many other companies that the expense of putting up such wires is not retured in protective value. Corona losses from the transmission line cause ionization near the conductors. It is an accepted fact that a direct stroke of lightning will discharge itself through the shortest path to ground or at least through that path offering the least resistance. However, local ionization affects this discharge and introduces a factor which would make it necessary to consider the spacing of the guard wires from the main conductors and their relative positions. Nothing has been done to solve this problem. The fact that severe winds and long spans resulted in swinging shorts and grounds has forced the Colorado Power Co. to remove all ground wires from its transmission line with the exception of 5 miles on each side of any station and upon the entire Boulder line where no mechanical difficulties of severe nature have developed. Upon the high passes, the guard wires are still used but have been raised several feet further above the conductors.

Experience has shown that a high frequency surge will not follow a straight conductor for any great distance, and at the most will not be propagated far enough to permit the installation, at various points along the line, of some form of arrester or discharge surge protector to protect the line from insulator failures. One solution of insulator protection is to install additional lightning arresters along the line but for practical results the number of such arresters would be too great to warrant the expense. A direct stroke of lightning upon a line rarely follows the line past more than one or two towers. The great impedance offered by even the low value of line inductance to the flow of this high frequency current causes such a rise of potential, that a breakdown occurs usually at the nearest insulator. The greatest damage is done to the insulator by the generator current which always follows this first arc.

The Grounded Phase Protector.

The most recent surge protector, theoretically the most efficient, and so far practically successful, has been devised by Prof. E. E. F. Creighton. The reader is referred to the A. I. E. E. Proceedings for March 1911 for the description and operation of this apparatus. The arcing ground offers the greatest injury to our transmission lines. Probably the first suggestion which lead to the development of the grounded phase protector came from C. P. Steinmetz. He pointed out that the best way to eliminate an arcing ground was to throw a soild ground upon the affected phase. In brief, the grounded phase protector consists of three single pole switches the function of which is to ground one or more line conductor. They are controlled automatically by a three pole selective relay operated either electrostatically of electromagnetically. Any unbalancing of potential upon the line or connected relay , caused for example by an arcing ground, will cause the relay to operate and ground the affected line in turn, actually shunting the arc with a low resistance path and thereby extinguishing it. The apparatus has given excellent practical results already in tests which have shown that the resulting quick extinguishing of the arc will practically always save the insulator except perhaps in the case of a direct lightning stroke.

The Aluminum Cell.

The only apparatus available at the present time for protection of station apparatus is the electrolytic aluminum cell. I have included here on the next two pages photos showing the method of applicatio of a set of 100000 volt arresters of this type. They are valuable only to take care

Horn Gaps and Roof Construction at Boulder.

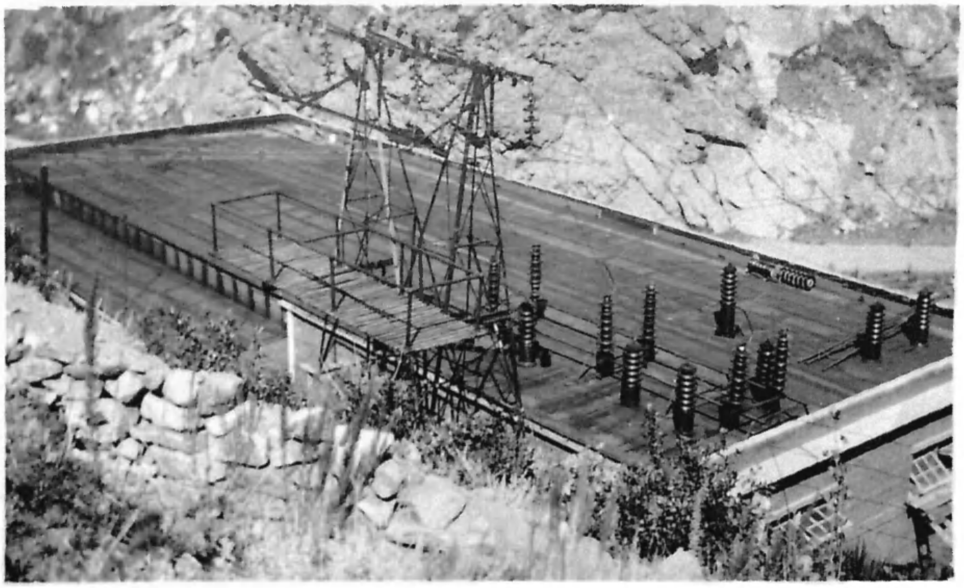


Fig. 24.

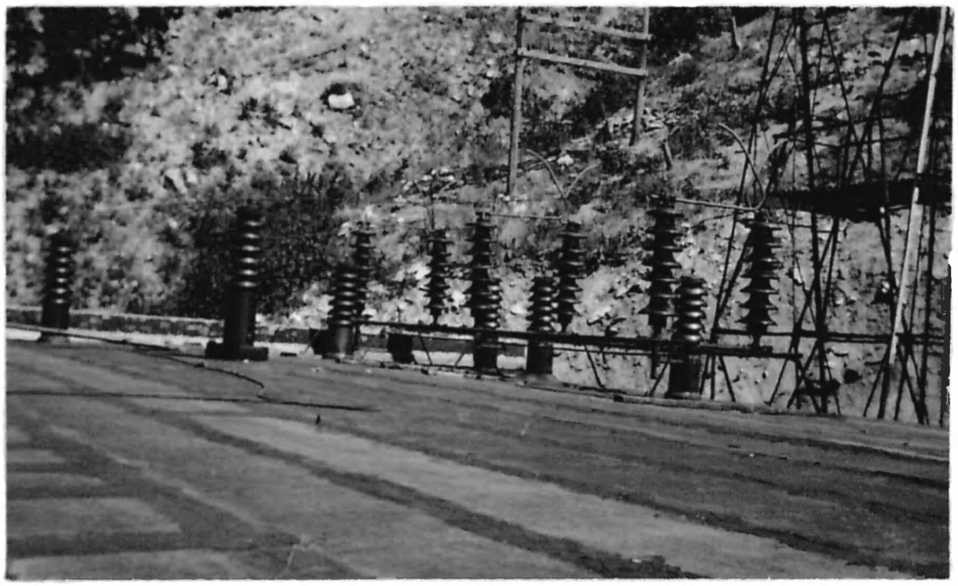


Fig. 25.

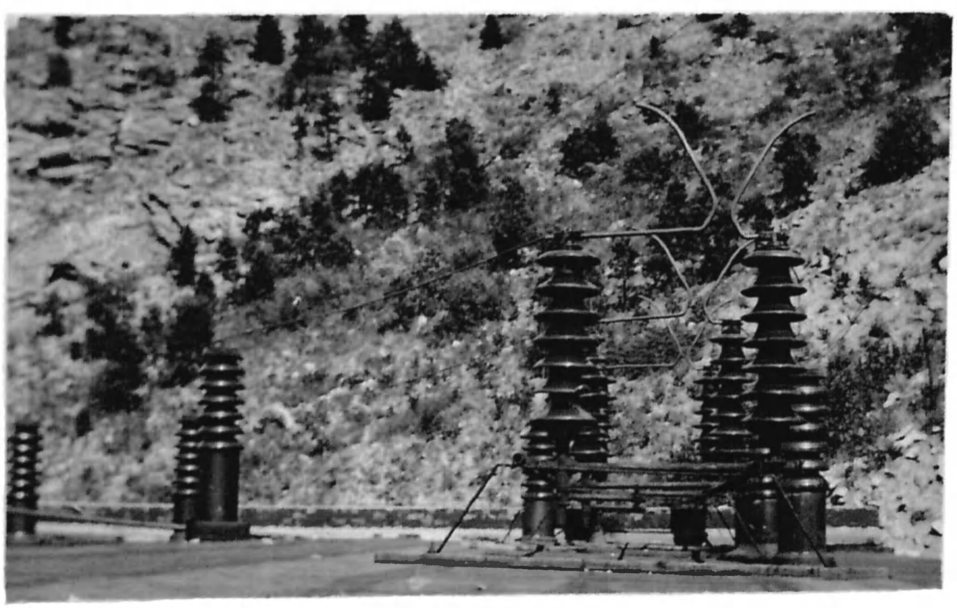


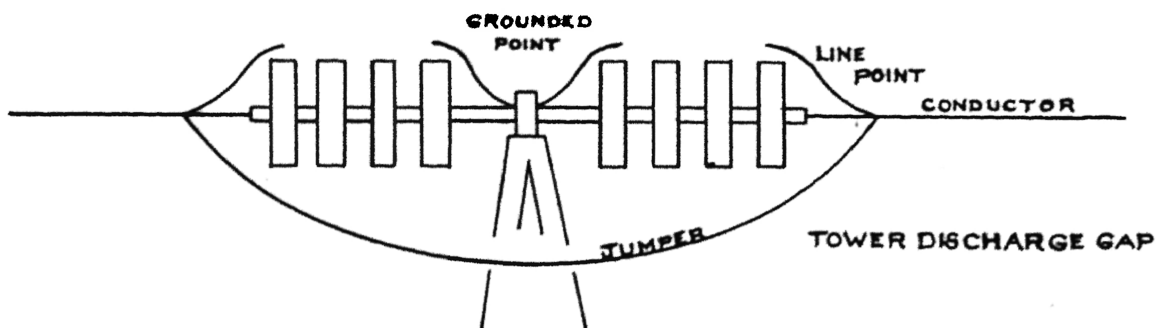
Fig. 26.

of lightning and other high potential surges local to the arrester or within say 1/4 mile of the protected station. The theory of the cell is simple. It has been found that if two aluminum plates separated by an electrolyte consisting of an alkaline solution are charged for a moment by passing a current through the solution, a very thin film of aluminum hydroxide will form upon the cathode. This film has a very high resistance but breaks down suddenly when the potential across it reaches about 400 volts. After the charge of electricity has passed through, the films upon the electrode are reformed. After breakdown, the cell becomes an excellent conductor. To apply the cell to higher potentials, several cells are used in series. Each cell consists of a shallow aluminum tray holding the electrolyte and for 100000 volts, about 200 cells must be used in series. They may be connected directly to the line protected but as a leak of current is thereby maintained through the cell, it is better to put a spark gap in series. The photos show the spark gap set at 14 inches. The choke coils as shown in figure28 serve to hold back the high voltage and high frequency surges long enough for the arrester to get into operation. These choke coils are placed as close a practical to the transformers.

At the Boulder station, no dependence is placed on these arresters. During the lightning season of 1913, not a single indication was shown at the tell tale gap in series with their ground that they had taken care of a surge. In the preceding pages, I have given one instance where these choke coils actually forced a heavy surge of lightning to ground over a string of insulators above the transformers. I think that a 14" setting is too great for these 100000 volt arrestors.

Tower Discharge Gaps.

In conclusion, I will explain briefly the best line protection used by the Colorado Power Co. This is the discharge tower gap. It is applied only at the dead end spans, many of which are used on this line.



As shown in the diagram, each string of dead end suspension insulators of the strain type is shunted by a discharge gap one side of which is fixed on the tower. This gap is shorter than the spillover distance of the insulator string and in case of serious surge, the breakdown will occur between these points causing a momentary ground.

The company has found these very valuable in protecting insulators against surges with high wave fronts. This recommendation of their success came to me March 1914 by letter from Mr. Norman Read the present Asst. General Manager.

Approved March 17, 1914. Geo. C. Shaad.