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150,000-VOLT TRANSMISSION SYSTEM

SOME OPERATING CONDITIONS OF THE BIG CREEK DEVELOPMENT OF THE PACIFIC LIGHT & POWER CORPORATION

BY EDWARD WOODBURY

ABSTRACT OF PAPER

The paper describes operating conditions on the 150,000-volt transmission line of the Pacific Light and Power Corporation which delivers power from the Big Creek hydroelectric development to Los Angeles, Cal., 240 miles away. In daily operation 60,000 kw. are generated, utilizing a total hydraulic head of 4000 ft., in two steps. Plans for the future contemplate the building of two more power houses, operating under somewhat lower heads.

Of particular interest is the complete success of the constant potential system, *i. e.*, operation at the same voltage at the generating and receiving stations, by means of synchronous condensers at the receiving end, in conjunction with automatic voltage regulators, one for each condenser as well as for the generators at each of the power houses. The line has been operated with unusual freedom from short circuits.

Appendixes describe the development of the system, and give data relating to the equipment of the Big Creek transmission line.

THE most striking feature of the Big Creek development and transmission is the magnitude of the figures in which the plant data are expressed. In daily operation, 60,000 kw. are generated, utilizing a total hydraulic head of 4000 ft. (1219 m.) in two steps, and transmitted 240 miles (386 km.) at 150,000 volts, thus entailing some conditions of operation which are rather striking.

The transmission line is of course the element of greatest importance in satisfactory commercial operation, although there are many features of engineering interest in the generating and receiving parts of the system.

The most critical problem to be solved proved to be that of regulation. It must be remembered that the inherent regulation of the line alone, without terminal equipment, is from 10 per cent above power house voltage at no load, to 20 per cent below at full load; that the effect of the transformer inductive

reactance at the generating end practically doubles the boosting at light load, and that the self-exciting characteristics of the generators, when supplying charging current only, tend to produce abnormal voltages at light load.

The complete success of the constant potential or zero regulation system, *i.e.*, operation at the same voltage at the generating and receiving stations, is of particular interest. This result is obtained by the use of synchronous condensers at the receiving end, in conjunction with automatic voltage regulators, one for each condenser as well as for the generators at each of the power houses. Since there are two 15,000-kv-a. condensers and four 17,500-kv-a. generators to be controlled, the regulator problem received most serious consideration, and was made the subject of careful experiment under working conditions before being proved satisfactory, as it now is. It has been

FIG. 1—EXCITER CONNECTION, PLANT No. 1, BIG CREEK.

found necessary to arrange the regulators to control field currents from a maximum to zero.

In one generating station the excitation system consists of three direct-current units, one of which is the exciter proper, the other two being connected in series opposition, and used to excite the field of the main exciter. See Fig. 1. The two units making up the secondary exciter are designed to generate 125 volts and 275 volts respectively. With a potential regulator on the 275-volt unit, arranged with auxiliaries to prevent a reversal of the field in the 125-volt unit of this set, the voltage applied to the exciter field may be changed from that required to give maximum excitation to zero excitation, within a range of voltage on the 275-volt unit, which can be readily handled by the standard alternating-current automatic voltage regulator.

The alternators at the other generator station are excited directly by 200-kw., 250-volt exciters, the main field of which

is controlled by a new type of alternating-current automatic voltage regulator, which has no direct-current magnet and which can therefore be adjusted to reduce the exciter voltage to zero. The exciters on this system have three shunt windings on the field, as shown in Fig. 2. One auxiliary field is provided to give the reversed excitation necessary to hold the voltage down when charging the line, the current being supplied to this field, through a variable resistance, by means of a storage battery. The other auxiliary field, which is solely for the purpose of maintaining the correct polarity, also takes its current, which is small, from the same storage battery.

A reduction of the excitation to zero by means of the potential regulator, has not been necessary at the generating stations, but operation of the synchronous condensers at the receiving

FIG. 2—EXCITER CONNECTION, PLANT No. 2, BIG CREEK.

station, over the range required, would not be feasible without a complete reduction of the exciter voltage.

With 150,000 volts at the receiving end of the line, the charging current is about 40 per cent overload for one generator. With normal voltage of 6600 volts at the generator, the charging current overloads the generator 65 to 70 per cent. Hence in normal operation a line is usually energized by using two generators, under which condition a small field excitation in the normal direction is required. Abnormal conditions sometimes make it necessary to charge the line from a single generator, until the condensers at the receiving station can be started.

The self-exciting characteristics of the system with leading current are such that in one of the generating stations a single 6600-volt generator, when connected to an unloaded line without its condenser and run at normal speed with the field switch open, would excite itself to 7000 volts, corresponding to 176,000 volts on the transmission line at the generating station, and

demand from the generators 34,000 kv-a. and 850 actual kilowatts.

At the other station, where the generators were designed by a different manufacturer and had slightly different characteristics, the results were greater and the self-excitation under similar conditions would reach 9000 volts at the generator or 230,000 volts on the line at the generating end. For this con-

FIG. 3—TYPICAL DAILY OPERATING CURVES OF BIG CREEK SYSTEM, WITH ZERO LINE REGULATION.

dition the generator would have to deliver 5000 kw. and about 50,000 kv-a.

Means had therefore to be furnished for using current in a reverse direction in the generator fields to counteract the excitation due to the leading current.

The curves of Fig. 3 show typical daily operating conditions as follows:

- (A) System-generated kilowatts.
- (B) Big Creek-generated kilowatts.
- (C) Delivered kilowatts from Big Creek.
- (D) Generator power factor at Big Creek.
- (E) Condenser kilovolt-amperes at receiving station.

The difference between A and B is on account of other generating stations being in operation on the system and being used to the limit of their capacity for correction of load power factors.

The speed regulation by the waterwheel governor has been excellent, so that no complications have arisen from this source.

As might be expected with a system of this magnitude, special consideration has been given to minimizing the effects of short circuits. Accordingly, the reactance of the generators of the two manufacturers has been made 70 per cent and 85 per cent respectively; of generating station transformers 5 per cent and 8.5 per cent; of receiving station transformers 5 per cent and 8.5 per cent. The result is that the instantaneous short-circuit current is only 330 per cent of full load on the generators and the sustained short-circuit current 110 per cent with normal excitation of full load. Under these conditions the waterwheel governors shut off water on short circuit before any serious change in speed can take place.

On account of the use of aluminum cable for the transmission line, it is very desirable to suppress an arc on the line before the wire can be seriously injured; and there is now under consideration the installation of a field-killing relay to be installed in the neutral of the generating station transformers, which will very quickly extinguish the arc and automatically permit the restoration of voltage immediately.

Of the short circuits which have occurred, none have been sufficiently serious to burn down the cable. Some of the outer strands have been scorched, but not sufficiently so to diminish strength. The scorched sections are of course removed at the earliest opportunity.

The causes of the short circuits, which have occurred, may be stated as follows:

1. In the rush of construction, a tree was left standing too close to the line and blew against it. The cable was scorched, but not seriously hurt. This occurred during the tryout period, and while the voltage was returned to normal in a fraction of a minute, the load was transferred to the steam plant, for some

time, while experimenting was done to endeavor to locate the trouble.

2. An irrigator tried to clean out a well near the line with a heavy charge of dynamite, blowing a lot of mud and water into the line. The current arced to the ground cable, but did not seriously injure the transmission cable.

3. One of the insulators on a disconnecting switch in one of the stations flashed over.

4. Seven other line short circuits have occurred, five of which have been found to be due to flash-over of insulators, one to be due to an arc from line to a tree during high wind, and the location and cause of the other has not been discovered. In every case of the above, trouble was cleared by reducing the voltage at generators upon current being observed in the ground ammeters, after which service was immediately resumed.

In all cases of insulator flash-overs, the damage to insulators was so slight that service could be resumed, without repairs, immediately on extinguishing the arc. In two cases, two disks out of the string of nine were broken down or badly shattered. In the third case, two of the disks were slightly chipped on the edge.

In the remaining two cases the arcing bars with which the insulator hardware is furnished (see Fig. 4), protected the insulators against any damage. It is found that a flash-over will sometimes burn from one to two inches off the end of the arcing bar, and apparently does not go to the cable unless the direction and strength of the wind are such as to carry the arc out along the cable. The separation of the arcing bars is 51 in. (129.5 cm.), equivalent to a break-down potential of over 500,000 volts at normal frequency.

5. The most serious line interruption was caused by a mechanical defect in a dead-end clamp at the end of a 2700-ft. (823-m.) span across a wide and deep river. The weight and tension of the cable make a repair of this kind a serious matter. The clamp which failed was one out of 5000, so the percentage is not high.

Various features of the system have been described in detail in different technical journals and do not need repetition, but, for convenience, appendixes follow, showing how the growth of the Pacific Light & Power Corporation system made an installation of the magnitude of Big Creek an economic possibility, and giving the principal physical data of the develop-

ment. The author desires to thank Mr. H. A. Barre and Professor R. H. Sorensen for their generous assistance in the preparation of this paper.

APPENDIX I

HISTORICAL

In 1897 the San Gabriel Electric Co. built at Azusa a hydroelectric plant consisting of four 300-kw. generators, which received their energy from a small stream with a 400-ft. (122-m.) head. The water power converted into electric energy by these generators at a potential of 500 volts was transformed to a potential of 15,000 volts and transmitted at this potential a distance of 25 miles (40 km.) to Los Angeles. Later, four other small hydroelectric plants varying in size from 150 kw. to 1500 kw. were added, and a "standby" steam plant of 2000 kw. was constructed, giving a total capacity of 6000 kw., 4000 kw. of which was water power.

January 1, 1905, the Kern River plant, a hydroelectric plant made up of five 2000-kw. generators, which transmitted its energy over 125 miles (201 km.) of line at a potential of 60,000 volts, was developed, and two years later, the original Redondo steam plant, which at that time made such a record for efficiency, was completed and its 15,000 kw. contributed to the service of the community. Even this, however, was not sufficient, for in 1911 it was found necessary to add to Redondo two 12,000-kw. turbine units, thus bringing up the available capacity of the system to 55,000 kw.

Even this tremendous supply of power rapidly became insufficient to meet the demand, and the company prepared to carry out the development of the now famous Big Creek project, which was to convert the energy available in Big Creek into electric energy and transmit it 240 miles (386 km.) to Los Angeles.

To transmit electric energy over such a distance with economy requires, of course, the highest practical potential, which in this case was selected as 150,000 volts, and plans for transmission at this voltage were drawn. These plans called for the immediate development of 60,000 kw. maximum, delivered at this voltage to the Los Angeles receiving station known as Eagle Rock substation.

This energy is generated by four 17,500-kv-a., 6600-volt

generators, two in each power house. At Power House No. 1 the water is delivered to the wheels under an average head of 2050 ft. (624.8 m.) from a reservoir about five miles (8 km.) long and one mile (1.6 km.) wide, with sufficient storage capacity to operate the plant at full load about four months, which is equivalent to six or eight months of operation based upon a 60,000-kw. peak on the two plants. After leaving Power House No. 1 the water enters a second tunnel, whence it is carried $4\frac{1}{2}$ miles (7.2 km.) to Power House No. 2, where it is delivered at an average head of 1857 ft. (565 m.).

PROJECTED DEVELOPMENT

Each of the two present power houses is so designed that its capacity may be doubled, simply by raising the height of the storage dam and installing the necessary generators, waterwheels, transformers and switching equipment. Future plans contemplate the erection of two other power houses, each as large as No. 1 and No. 2 will be when completed, at a lower elevation. These will operate under a somewhat lower head than power houses No. 1 and No. 2, but the difference in head will be supplemented by the addition of more water.

CONSTRUCTION

In order to take up the construction of the Big Creek project, it was necessary to construct 56 miles of standard-gage railroad over a very mountainous country, where even with the many curves the average grade is over 4 per cent. Materials were hauled over this track to the power house sites with shay locomotives, very often three engines being applied to a four-car train of heavy machinery.

It was also necessary to build two inclined railways, one to transport material from the end of the railway to the reservoir site and one to let material down to power house No. 2 from the railroad. When the work was at a maximum of activity 3500 men were employed, all of whom were housed in fifteen camps located in the mountains a long distance from supplies.

APPENDIX II

EQUIPMENT DATA

Two power plants, total capacity 64,000 kw.

Four 17,500-kv-a. generators.

Eight tangential waterwheels, each pair develops 16,000 kw.

[WOODBURY]

FIG. 4—150,000-VOLT SUSPENSION INSULATOR, SHOWING ARCING RODS.

FIG. 5—150,000-VOLT STRAIN INSULATOR. [WOODBURY]

[WOODBURY]

FIG. 6—TYPICAL DEAD-END TOWER USED FOR LINE SECTIONALIZING
BY OPENING JUMPER LOOP.

[WOODBURY]

FIG. 7—ANGLE TOWER, SHOWING BRACKET TO PREVENT LOOP FROM
SWINGING.

[WOODBURY]

FIG. 8—METHOD OF TYING DOWN CONDUCTORS TO PREVENT UPLIFT
IN COLD WEATHER.

[WOODBURY]

FIG. 9—STEEL FOOTING FOR STANDARD TOWER.

One generator, full load, 24 hours, uses 240 acre-feet of water.
 Maximum head of water plant, No. 1, 2100 ft. static. Plant No. 2, 1900 ft.
 Reservoir capacity, initial development, 51,600 acre-ft. Cubic yards concrete in dams, initial development, 120,000.
 Reservoir will operate plants 220 days on 50 per cent load factor.
 Drainage area 88 square miles.
 Five miles of 12-ft. tunnels through solid rock.
 Single-phase transformers, largest yet built, weigh 81 tons and contain 10,000 gal. of oil.
 Power station transformers connected delta 6600 volts, Y 150,000 volts, with grounded neutral.
 Receiving station transformers connected delta 150,000 volts, delta 60,000 volts and 18,000 volts respectively.
 Two 15,000-kv-a. synchronous condensers at receiver end each require 10,000 kv-a. to start.
 Under no-load conditions, 137,000 volts at generator rises to 150,000 volts at receiver.
 Charging current is 90 amperes at 137,000 volts, equals 21,500 kv.-a. Fifty amperes reversed excitation necessary to bring generator "down on line" to zero potential, no-load condition.
 Power factor of generators is high, being above 95 per cent the greater part of the day.
 Current is unbalanced approximately 12 per cent under no-load conditions on account of the conductors being in horizontal plane.
 Under normal load conditions, above 12 per cent is reduced at approximately 2 per cent.
 A potential of 4200 volts is induced in a dead section of the duplicate line 100 miles in length, distant 82 ft. center to center.
 Line loss at full load is $9 \frac{1}{2}$ per cent. In addition there is 5 per cent loss in transformers, auxiliaries, etc.

DATA ON BIG CREEK TRANSMISSION LINE

General:

Length, 240.41 miles power house No. 1 to Eagle Rock substation, plus 0.74 mile tap to power house No. 2, total 241.15 miles.
 Voltage, 150,000 volts, 50 cycles.
 Number of tower lines, 2.
 Number of circuits per tower line, 1.
 Capacity of each circuit, 57,500 kw. at 0.85 power factor for 11 per cent regulation using two synchronous condensers.

Right of Way:

Width of right of way, 150 feet.
 Separation of center lines of tower lines, 82 ft.

Towers:

Normal spacing in valleys where no sleet occurs, 660 ft.
 " " " " " sleet occurs, 550 ft.
 Maximum span, 2871 ft. (Sunland), 2776 ft. (Kings River).
 Maximum span on standard towers, 1822 ft.
 Maximum angle on standard tower, 0 deg. 49 min. (Normal span no sleet $1 \frac{1}{2}$ deg. plus wind). Insulators take 45 deg. position.

Maximum angle on anchor towers, 48 deg. designed for 60 deg. 114 deg. 2 min., under special conditions at tower No. 1.

Total number of towers, both lines, 3388.

Average number of towers per mile, single line, 7.08

Classification	Standard	Anchor and Angle	Special
Weight above foundation.	4300	6450	4485
Weight of steel footings . .	1305	1605	1305
Total steel per tower	5605	8055	5790
Spread at base with line.	20 ft.	24 ft.	20 ft.
“ “ “ across line	18 ft.	24 ft.	18 ft.
Height above ground to insulation support	43 ft.	37 ft.	43 ft.

Unit Stresses:

Tension = 20,000 lb. per sq. in.

Compression = $\frac{16,000}{2}$ lb. per sq. in.

$\frac{L}{R}$ for corner posts, 125.

$\frac{L}{R}$ for bracing, 175, except where a larger value is approved by the purchaser.

Minimum thickness of members, 3/16 in.

Unit stress in bolts:

Shear 15,000 lb. per sq. in.

Bearings 30,000 lb. per sq. in.

Design Assumptions:

Standard Towers:

(1) Wind load, 22 $\frac{1}{2}$ lb. per sq. ft. of exposed area, with or at right angles to the line; wind pressure simultaneously applied to both faces of tower, and

(2) A pull in the direction of the line of 4250 lb. at the points of support of two adjacent conductors pulling on the same side of the tower, and

(3) A vertical load of 1000 lb. at each conductor support where conductor is unbroken, and of 530 lb. at each ground wire support, and of 500 lb. if conductor is broken, and

(4) A wind load of 600 lb. at right angles to the line at each conductor support where conductor is unbroken, and of 300 lb. at right angles to the line at each conductor support where conductor is broken, and of 500 lb. at each ground wire support.

The above loads are simultaneously applied.

Ground wire support designed to withstand an unbalanced pull of 5000 lb. in the direction of the line.

Anchor and Angle Towers:

Anchor and angle towers are designed for each of the following groups of conditions, only one of which groups is to be taken at a time:

I. (1) A wind load of $22\frac{1}{2}$ lb. per sq. ft. of exposed area, with or at right angles to the line; wind pressure applied simultaneously to both faces of tower, and

(2) A pull in the direction of the line of 8000 lb. at each of the three conductor supports, on either side of tower, and of 8000 lb. at each ground cable support, and

(3) A vertical load of 500 lb. at each of the three conductor supports and of 265 lb. at each ground cable support, and

(4) A wind load of 300 lb. at each of the three conductor supports, and of 250 lb. at each ground cable support.

II. (1) A wind load of $22\frac{1}{2}$ lb. per sq. ft. of exposed area, with or at right angles to the line; wind pressure applied simultaneously to both faces of tower, and

(2) A pull at right angles to the line of 8000 lb. at each of the three conductor supports, and of 8000 lb. at each ground cable support, and

(3) A vertical load of 1000 lb. at each of the three conductor supports and of 530 lb. at each ground cable support, and

(4) A wind load of 600 lb. at each of the three conductor supports and of 500 lb. at each ground cable support.

Number of conductors supported by each tower, 3.

Arrangement, in same horizontal plane.

Number of lightning ground wires, one at first; space for two if needed.

Smallest size angle iron used, $1\frac{1}{2}$ by $1\frac{1}{2}$ by $3/16$ in.

Conductor:

Material, aluminum with steel core; steel double-galvanized.

Composition Metals	No. strands	Cir. mils.	Weight		Elastic limit square inch	Ultimate tensile strength sq. inch
			per mile	per foot		
Aluminum.....	54	605,000	2940		13,000	26,000
Steel.....	7	78,500	1118		115,000	195,000
Total.....	61	683,500	4058	0.77		33,600

Total resistance 35 ohms per leg.

Maximum working tension allowed—13,000 lb. per sq. in. in aluminum.

Stringing tension at 80 deg. fahr.

Ice allowance.....3130

No ice allowance4740

Type of joints, McIntyre sleeve on steel inside of compression aluminum sleeve.

Ground clearance:

On right of way.....25 ft. at 140 deg. fahr.

At crossings.....Legal, as required.

Ground Wires:

Number per tower, 1.

Size, $\frac{1}{2}$ in. 7-strand.

Material, Siemens-Martin steel.

Breaking tension, 13,000 to 15,000 lb.

Maximum working tension allowed, 6500 lb. sleet—2100 ft. span; 5500 lb. no sleet.

Insulators:

Number, 190,000; 58 per cent of which are on dead ends.

Type, 2565-P Locke.

Diameter, 10 in.

Dry flash-over voltage.	590,000 suspension	} 9 disks
	720,000 anchor.	
Wet flash-over voltage.	420,000 suspension	
	420,000 plus anchor	

Routine Tests:

First test per disk, electrical, flash-over voltage.

Second " " " mechanical, flash-over voltage, 5000 lb., after first elec.

Third " " " electrical, flash-over voltage 5 min. after mechanical.

Ultimate tensile strength, 10,500 lb.

Maximum working tensile loading allowed, 4250 lb.

No. of disks used per chain, straight line, 9

" " " " " " dead end, $2 \times 11 = 22$.

Two chains are used in parallel on all dead ends to divide mechanical load.

Distance center to center of insulator, $5\frac{3}{4}$ in.

Two telephone circuits on an independent pole line 300 miles long.

Resistance per circuit 4000 ohms. Storage batteries used on transmitters, and power-driven machines for ringing.

Eleven patrol stations are necessary, each requiring an equipment of tools and material weighing 10 tons.