

ELECTRIC POWER TRANSMISSION ECONOMICS

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According to Kelvin's law, maximum economy in electric transmission is obtained when the annual interest and depreciation charges equal the cost of the energy loss. This law, however, does not allow for additional capacity in lines to care for future growth in business, nor for voltage regulation; hence it does not hold good in practice to-day, where experience shows that both of these provisions are necessary for the highest economy ultimately. The transmission losses, permissible investment, and regulation are discussed in turn, and specific examples worked out to show their bearing on the economy of operation; and the impracticability of the Kelvin law to the average transmission system is also shown.—EDITOR.

Since the introduction of scientific management in the operating departments of light and power companies a great improvement has been made in both the quality and the economy of the electric service. Systematic cost keeping automatically exposes every weak spot in operation and institutes a study and analysis of its cause with the purpose of prescribing a remedy. These scientific methods, which are merely the application of common sense in the conduct of the business, were primarily directed toward improving the efficiency of the working force and were later extended to inanimate things, such as raw materials, tools, instruments, machinery and equipment; so that by keeping adequate records of their useful performances a selection based on merit could be made with a view to securing still better results.

The efficiency of a physical property is a broad subject, just as essential to the economical success of a business as is labor efficiency; it is a very fertile soil which, when properly tilled, yields a generous harvest of valuable information that is helpful in reducing the costs of operation and maintenance, and improving the reliability of the service.

In the transmission and distribution of electrical energy peculiar conditions are met which increase the ultimate cost of the product, due to two causes, viz., losses in transportation, and losses in conditioning for transportation and distribution. The ultimate cost of the product or commodity depends on the efficiency of the system of delivery. In the distribution of electrical energy it is a very important item, represented by the ratio of input to output of the electrical energy at each end of the system, or at the power house and the customer's premises where it is sold according to the units metered and delivered.

The transportation of electrical energy is widely different from other problems involving traffic; here the flow is continuous from end to end, while in railway transportation the traffic is intermittent and can suffer

demurrage if necessary without great inconvenience. The means of transportation consisting of tracks and rolling stock can be increased to meet the demand imposed by the volume of the traffic; improvements, additions, and repair and maintenance work can be undertaken without seriously impairing the operation; while in a power transmission system provisions and work of this nature are almost impossible to be carried out except at great expense and with considerable annoyance and difficulties.

The losses occurring in the transportation of electrical energy are governed by the resistance of the conductor through which the energy flows and also by its degree of staunchness, that is, its insulation properties. The resistance of a circuit intended to transmit alternating current depends primarily on the material used for the conductors, and on their cross section, both factors affecting the investment, which in turn is subject to financial considerations that prescribe an expenditure for construction that will net the largest return on the capital invested. A reduction in the transmission losses cannot be secured except at the cost of an increased investment, and a point is reached where any additional reduction in these losses becomes an expensive saving represented by interest on the capital invested and depreciation charges.

The maximum transmission economy is attained when the sum of the annual interest and depreciation charges equals the annual cost of the energy loss. Other important factors must also be considered in the calculations affecting the initial investment, such as voltage regulation and the possible increase in the demand for electrical energy at the receiving end of the circuit at a later date, all of which involve the exercise of good judgement in the appreciation of the requirements to be fulfilled in the design and construction of the transmission and distribution lines.

No special or definite rule can be laid for the solution of electric transportation

problems; each case must be considered separately and carefully studied, first on the basis of maximum transmission economy and then from the investment standpoint, estimating the additional capital expenditure that would be warranted by the immediate traffic to provide an increase in power carrying capacity from the start, and possibilities for further increases; bearing in mind that it is very seldom that a line has been designed in excess of the subsequent traffic requirements, but on the contrary it is generally found to be ultimately inadequate.

There is naturally a limit imposed on the power carrying capacity of electric lines by engineering considerations, such as strength of materials, stability and permanence of the supporting structures, and the important question of continuity and reliability of service, which may always be effectively improved by double tracking the circuit.

Transportation Losses

Neglecting certain constants only slightly affecting overhead transmission lines at voltages below 60,000 volts and at altitudes less than 3,000 feet, the total loss of energy in a transmission line is the sum of:

- Ohmic resistance loss
- Dielectric or leakage loss
- Inductive reactance loss

The ohmic resistance loss depends entirely upon the conductivity, permeability and shape of the conductor and its temperature constant. This loss is generally a function of I^2R , in phase with the current. The true resistance (R) to the flow of alternating current, which is affected by the frequency of

the current owing to skin effect, is slightly increased at ordinary operating frequencies, as shown in Table I.

The effective resistance of magnetic materials, such as iron wire, increases in a considerably greater proportion than that of non-magnetic material, due to the interference of eddy currents that are generated perpendicularly to the direction of the magnetic flux and that reduce the effective conductivity of the material to a very thin layer near its surface.

The dielectric loss in overhead transmission lines of voltages not exceeding 60,000 volts can be neglected when the conductors are properly insulated and are free from outside interference. It is appreciable, however, under certain weather conditions, inasmuch as there is no absolute dielectric material, but some of relatively high resistance that are used to insulate others of lower resistance. In insulated cables the leakage current through the insulating material, the lead sheath losses and the hysteresis losses in metallic conduit should all be considered, as well as the effect of capacity and low inductance. These losses are practically in phase with the current and can be added to the resistance loss.

Inductive reactance losses are those produced by a phenomenon of electromagnetic waves at right angles to a current changing in value or direction, as with alternating current. These losses are necessarily supplied by the current circulating in the conductor, from which originates the magnetic field, and they depend primarily on the frequency of the change in velocity or direction and on the intensity of the current

TABLE I

RESISTANCE OF HARD DRAWN COPPER AND ALUMINUM STRANDED CONDUCTORS.
CONDUCTIVITY: COPPER 97.3 PER CENT; ALUMINUM 61 PER CENT.
TEMPERATURE 20 DEG. CENT. OR 68 DEG. FAHRENHEIT

Gauge B.&S.	EFFECTIVE RESISTANCE IN OHM PER MILE OF WIRE					
	Copper			Aluminum		
	D-C.	25-Cycle	60-Cycle	D-C.	25-cycle	60-cycle
0000	0.2704	0.2706	0.2715	0.4330	0.4332	0.4337
000	0.3418	0.3420	0.3427	0.5438	0.5439	0.5444
00	0.4309	0.4310	0.4316	0.6893	0.6895	0.6898
0	0.5434	0.5435	0.5441	0.8670	0.8671	0.8674
1	0.6851	0.6852	0.6856	1.0932	1.0932	1.0935
2	0.8655	0.8656	0.8658	1.3786	1.3786	1.3788

themselves. They are also affected by the spacing of the conductors (mutual inductance), and by their size, shape and permeability.

Like the ohmic resistance loss, the inductive reactance loss can be written as I^2R_i , where $R_i = 2\pi fL$, f being the frequency of the current and L the coefficient of mutual self induction of the conductor.

The resultant of the ohmic resistance and the inductive reactance represents the equivalent resistance or impedance of the circuit, and can be written:—

$$Z = \sqrt{R_o^2 + R_i^2} = \text{impedance}$$

The effect of capacity reactance in a transmission line is to compensate for the lagging current produced by the inductive reactance, not only that of the line but also that of the load connected thereto, to the extent that the leading wattless component of the current charges the condenser represented by the line.

The capacity, and hence the charging current, of a line increases with its cross section, and as the separation between the conductors decreases. It is of special importance in insulated cable installations and its effect on the regulation and losses should be taken into consideration in such cases, as well as when treating long transmission lines of high voltage carrying a relatively small current with respect to the power transmitted.

Thus in an alternating current circuit the ohmic resistance loss is substituted by an impedance loss, in phase with the current, which is the resultant of the ohmic resistance, hysteresis, and eddy current losses of the circuit, and denoted by R_o ; and of an inductive reactance (R_i) having a negative sign, or of a condensive reactance (R_c)

having a positive sign, both being at 90 deg. to the ohmic resistance R_o .

The impedance can then be expressed as follows:

$$Z = R_o - jR_i, \text{ for an inductive reactance,} \\ \text{and } Z = R_o + jR_c \text{ for condensive reactance}$$

Inasmuch as the vectorial sum of these two quantities is in either case the hypotenuse of a right-angled triangle, they can be more conveniently written thus:

$$Z = \sqrt{R_o^2 + R_i^2} \text{ and } Z = \sqrt{R_o^2 + R_c^2}$$

The impedance of a conductor carrying alternating current can, in most short lines, be treated as the ohmic resistance of direct current circuits for the determination of losses and voltage regulation.

When a current I is not in phase with the voltage, but is either lagging or leading, it consists of a power component I_o , and of a wattless component I_x , at right angles to I_o , and such a condition can be expressed by

$$I = \sqrt{I_o^2 + I_x^2}$$

The line drop then becomes by Ohm's law:

$$e = \sqrt{(I_oR_o + I_xR_i)^2 + (I_xR_o - I_oR_i)^2}$$

for a lagging current and inductive reactance,

$$\sqrt{(I_oR_o - I_xR_i)^2 + (I_xR_o + I_oR_i)^2}$$

for a lagging current and condensive reactance

$$\sqrt{(I_oR_o + I_xR_i)^2 + (I_xR_o - I_oR_i)^2}$$

for a leading current and inductive reactance

$$\sqrt{(I_oR_o - I_xR_i)^2 + (I_xR_o + I_oR_i)^2}$$

for a leading current and condensive reactance

$$\text{where } e = IZ$$

Along with the line constants must be considered the character of the load, as the complete circuit consists of the line with the

TABLE IA

		Single-phase	Two-phase	Three-phase
True power.....	W	$EI \cos. \phi$	$2EI \cos. \phi$	$EI \sqrt{3} \cos. \phi$
True power losses.....	w	$eI \cos. \phi$	$2eI \cos. \phi$	$eI \sqrt{3} \cos. \phi$
or.....	w	$I^2Z \cos. \phi$	$2I^2Z \cos. \phi$	$I^2Z \sqrt{3} \cos. \phi$
The current per wire.....	I	W/E	$W/2E$	$W/E \sqrt{3}$
The true current per wire.....	I_o	$I \cos. \phi$	$I \cos. \phi$	$I \cos. \phi$
The wattless current per wire.....	I_x	$I \sin. \phi$	$I \sin. \phi$	$I \sin. \phi$
The potential drop per circuit.....	e	IZ	IZ	IZ
The impedance per circuit.....	Z	e/I	e/I	e/I
The impedance per wire.....	Z'	$e/2I$	$e/2I$	$e/I \sqrt{3}$
The per cent potential drop.....	P	$100e/E$	$100e/E$	$100e/E$
The per cent efficiency.....	F	$\frac{100W}{W-w}$	$\frac{100W}{W-w}$	$\frac{100W}{W-w}$

load at the receiver's end in series with each section. The treatment of such problems requires the analysis of each section separately.

Knowing the resistance, inductive reactance and condensive reactance of a conductor per unit of length, the impedance can be calculated and then the losses and line regulation can be determined for any line voltage, load and power-factor.

The constants of a transmission line carrying alternating current can be determined from Table IA.

To apply these formulæ to a practical case, we will assume for instance a three-phase, three-wire overhead transmission line 10 miles long, to transmit 1000 kw. at 60 cycle, 13,200 volts, at an average power-factor of customer's load 0.8, and with the necessary step up and step down transformers and substation equipment. The average annual load-factor is assumed to be 20 per cent, the revenue per kilowatt hour averaging 1.25 cents, and the ratio operating expenses to revenue 60 per cent.

Find:

- The permissible investment
- The gauge of the conductors
- The regulation of the line
- The transmission losses

Permissible Investment

From the information available the anticipated annual gross income is:

$$1000 \times 0.2 \times 8760 = 1,752,00 \text{ kw. h. at } 0.0125 = \$21,900$$

With a ratio of operating to gross income of 60 per cent, the net annual-revenue is:

$$21,900 \times 0.4 = \$8,760$$

The capital invested must earn a salary for the service it renders. Those who are responsible for its management are entitled to a compensation in the form of a profit; furthermore, the capital must be protected by a life insurance on the physical property it represents, to be taken care of by an allowance for depreciation, insurance, etc., and finally the investment is subject to fiscal taxes, all of which must be satisfied from the net earnings as follows:

- 6 per cent interest on investment
- 2 per cent profit
- 5 per cent depreciation
- 1.5 per cent taxes
- 0.5 per cent insurance

Total 15 per cent

The above net revenue therefore corresponds to a capital investment of:

$$\text{Permissible investment, } \frac{8,760}{0.15} = \$58,400$$

TABLE II

EFFICIENCIES OF AVERAGE STATION TRANSFORMER

% Load.....	5	10	20	25	30	40	50	60	70	75
% Core loss.....	20.00	10.00	5.00	4.00	3.33	2.5	2.0	1.66	1.43	1.33
% Copper loss.....	.05	.10	.20	.25	.30	.40	.50	.60	.70	.75
% Total loss.....	20.05	10.10	5.20	4.25	3.63	2.90	2.50	2.26	2.13	2.08
% Efficiency at 1.0 P.F.....	82.39	90.82	95.05	95.92	96.49	97.18	97.56	97.88	97.91	97.96
at 0.8 P.F.....	79.96	88.79	93.89	94.95	95.66	96.97	96.98	97.25	97.40	97.46
% Load.....		80	90	100	110	120	125	130	140	150
% Core loss.....		1.25	1.11	1.00	0.909	0.833	0.800	0.779	0.714	0.666
% Copper loss.....		.80	.90	1.00	1.100	1.200	1.250	1.300	1.400	1.500
% Total losses.....		2.05	2.01	2.00	2.009	2.033	2.050	2.079	2.114	2.166
% Efficiency at 1.0 P.F.....		97.99	98.03	98.04	98.03	98.01	97.99	97.97	97.93	97.88
at 0.8 P.F.....		97.50	97.54	97.56	97.55	97.52	97.50	97.45	97.42	97.36

This capital is to be invested in the contemplated improvement as follows, based on present market prices:

1000 kw. in step-up transformer installation, complete with switchgear and protective apparatus.....	\$8,000.00
1000 kw. in step-down transformer installation, also complete with some housing provision for the secondary switchgear and metering devices.....	12,000.00
Balance applicable to line construction	38,400.00
Total investment	\$58,400.00

Gauge of Conductors

The line and right of way, exclusive of conductors, may be estimated as costing to day, with a substantial type of construction using wooden poles, approximately (although varying according to localities) \$2,500 per mile, or a total of \$25,000.00, leaving for the conductors \$13,400.00, which, with copper at 30 cents per pound, equals 44,666 lbs, or 1488 lbs. per miles of wire, corresponding to No. 1 B.&S. copper conductor.

Regulation

With a 24 in. spacing between wires, at 60 cycles, a No. 1 B.&S. stranded copper conductor at 20 deg. Cent. has an ohmic resistance of 0.6856 and an inductive reactance of 0.644 ohms per mile.

Impedance per mile of circuit:

$$Z = \sqrt{0.6856^2 + 0.644^2} = 0.936 \times 1.732 = 1.61 \text{ ohms}$$

and for 10 miles a total impedance of 16.1 ohms.

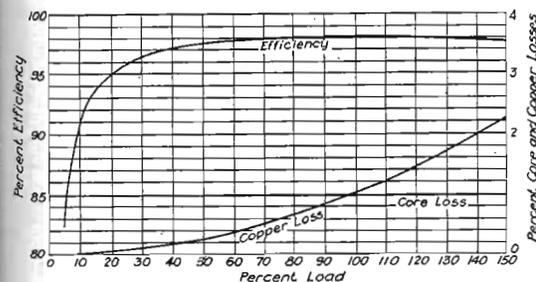


Fig. 1. Average Efficiencies and Losses of Large Substation Transformer

Line drop at full load,

$$e = \frac{43.7}{.8} \times 16.1 = 880 \text{ volts}$$

Per cent line drop $\frac{100 \times 880}{13200} = 6.66$ and also

regulation at 0.8 power-factor, and at unity power-factor $6.66 \times 0.8 = 5.328$ per cent.

Transmission Losses

At full load the power loss in transmission is:

$$880 \times 54.7 \times 1.732 = 83.432 \text{ kv-a., or } 83.432 \times 0.8 = 66.748 \text{ kw.}$$

or

$$54.7^2 \times 1.732 \times 16.1 = 83.432 \text{ kv-a., or } 83.432 \times 0.8 = 66.748 \text{ kw.}$$

or 6.66 per cent of the full load output. The transmission efficiency of the line:

$$\frac{100 \times 1000}{1000 + 66.748} = 93.74 \text{ per cent}$$

The annual transmission losses at full load are:

$$66.748 \times 8760 = 583,460 \text{ kw-hr., or } 6.66 \text{ per cent of the full load output.}$$

The immediate load-factor is expected to be only 20 per cent of the output, and consequently the annual losses will be a fraction of the above full load losses, although not in the same proportion as the load-factor, as will be seen later.

Transformation Losses

The losses in voltage or phase transformation occurring in transformers depend not only on the efficiency of the apparatus but also on the load characteristics throughout the daily operation; that is to say, on the power-factor of the load and on the load-time curve.

When a transformer is connected to a circuit, the winding so connected is equivalent to a resistance across the line completing the circuit; the energy consumed in that part of the circuit is in proportion to its impedance and consists of exciting current. The energy loss in a transformer is made up of core or iron losses through the magnetic circuit and of copper loss in the electric circuit. The core losses for a given voltage and frequency are practically constant, so long as the properties of the magnetic material remain unchanged, while the copper loss varies with the resistance of the secondary circuit; that is, in proportion to the load or to the volt-amperes, slightly affected by variation of temperature and changes in the frequency of the current.

The energy losses and efficiencies of station transformers operating on 60 cycle circuits are tabulated in table II and shown graphically in Fig. 1.

Pole type transformers for use on distribution lines have special characteristics on account of their intermittent duties. The core loss is kept as low as is consistent with good operation in order to reduce to a mini-

mum the expense of keeping them alive during periods of very light load or no load, specially in the day time. The losses and efficiencies of a typical pole type transformer of 10 kv-a. capacity are given in Table III and the curves of losses and efficiencies are shown in Fig. 2.

The effect of power-factor variation on the efficiency of the transformers is also indicated in both Tables II and III. It increases the losses and reduces the efficiencies proportionally to the angular displacement of the current with respect to the voltage. The regulation, or the per cent difference between the secondary voltage at no load and full load, is likewise affected by the power factor of the load. Station transformer regulation can generally be assumed to be from 1.5 per cent at 1.0 power-factor to 4.0 per cent at 0.8 power-factor, and the regulation of the distributing transformers varies from 1.5 to 3.0 per cent, although it is merely a question of design to meet the requirements of special cases, not only as regards regulation but also copper loss and core loss.

Lightly loaded induction apparatus, such as induction motors and transformers, draws from the line a current which lags behind the electromotive force in inverse proportion to the load supplied, the result being increased heating and a reduction in useful capacity.

Station and substation transformers for operation on transmission lines, (generally of high voltage) are designed with a higher

reactance than pole type transformers, in order to increase the safety of operation in case of short circuit. This is obtained at the expense of regulation, but with an additional reliability well worth the sacrifice. Ultimately the increased reactance will help the regulation when the line drop is compensated with synchronous condensers.

Transmission Losses

The transmission losses consist of line and transformer losses, depending on the character of the load supplied, and an individual

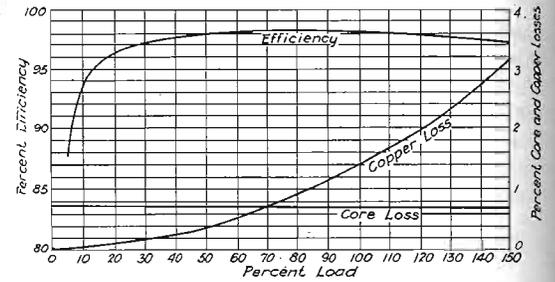


Fig. 2. Average Efficiencies and Losses of 10 Kv-a. Distribution Transformer

estimate must recognize the following factors in order to determine the total efficiency of the system.

Step-up transformer:—Load at receiver end, plus step-down transformer losses, plus transmission line losses.

TABLE III
EFFICIENCIES OF A 10-KV-A. POLE TYPE TRANSFORMER

% Load.....	5	10	20	25	30	40	50	60
Core loss.....	13.80	6.90	3.45	2.76	2.30	1.725	1.38	1.15
Copper loss.....	.07	.14	.278	.35	.417	.556	.695	.834
Total losses.....	13.87	7.04	3.728	3.110	2.717	2.281	2.075	1.984
% Efficiency.....								
at 1.0 P.F.....	87.82	93.42	96.90	96.98	97.24	97.76	97.96	98.05
at 0.8 P.F.....	85.03	91.91	95.55	96.26	96.72	97.23	97.46	97.58
% Load.....	70	75	80	90	100	110	120	125
Core loss.....	0.98	0.92	0.862	0.766	0.690	0.627	0.575	0.552
Copper loss.....	.973	1.043	1.112	1.251	1.390	1.520	1.668	1.737
Total losses.....	1.958	1.963	1.974	2.017	2.080	2.147	2.243	2.289
% Efficiency.....								
at 1.0 P.F.....	98.08	98.07	98.06	98.02	97.96	97.89	97.80	97.76
at 0.8 P.F.....	97.70	97.70	97.69	97.54	97.46	97.38	97.27	97.20

Transmission line:—Load at receiver end plus step-down transformer losses.

Step-down transformer:—Load at receiver end.

These losses are not only governed by the efficiency of the apparatus but also by the characteristics of the operation and cannot be estimated from the load-factor, unless a steady load is used continuously.

Where power is used continuously, with a load-factor practically constant, the losses, figured on the efficiencies of 60 cycle station transformers as given in Table II and for a line loss of 5 per cent at full load, are given in Table IV, all results being based on unity power-factor.

The efficiency of the transmission line decreases as the load increases, while that of the transformers increases from no load to full load. The maximum combined efficiency is reached when the load corresponds to the point where the curves cross each other, as shown in Fig. 3; and the maximum economy of operation of such a system would be between 40 to 60 per cent load. In Table IV it is assumed that the system does not contain

step up transformers, but distributes at station voltage.

Where the load is not constant, for instance under the conditions set forth before for the transmission of 1000 kw. to a point 10 miles distant, and reducing the losses to a unity

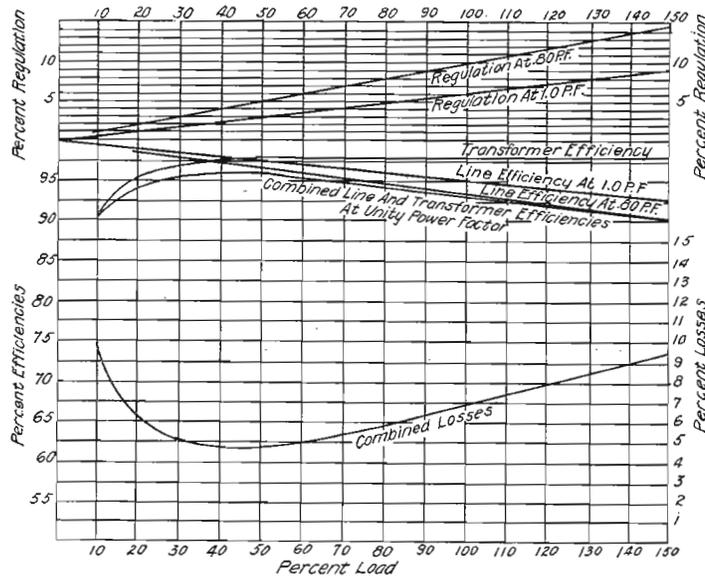


Fig. 3. Combined Efficiencies of Transmission Line and Step-down Transformer

power-factor basis at 20 per cent load-factor, the transmission losses would vary between

TABLE IV.

COMPARATIVE LOSSES AND EFFICIENCIES OF 60 CYCLE SYSTEM

Load Factor %	LINE		STEP-DOWN TRANSFORMER		Combined Efficiency %	Combined Losses %
	Efficiency %	Losses %	Efficiency %	Losses %		
10	99.50	0.50	90.82	9.18	90.36	9.64
20	99.00	1.00	95.05	4.95	94.10	5.90
25	98.75	1.25	95.92	4.08	94.72	5.28
30	98.50	1.50	96.49	3.51	95.04	4.96
40	98.00	2.00	97.18	2.82	95.23	4.77
50	97.50	2.50	97.56	2.44	95.12	4.88
60	97.00	3.00	97.88	2.12	94.94	5.06
70	96.50	3.50	97.91	2.09	94.48	5.52
75	96.25	3.75	97.96	2.04	94.28	5.72
80	96.00	4.00	97.99	2.01	94.07	5.93
90	95.50	4.50	98.03	1.97	93.61	6.39
100	95.00	5.00	98.04	1.96	93.13	6.87
110	94.50	5.50	98.03	1.97	92.64	7.36
120	94.00	6.00	98.01	1.99	92.13	7.87
125	93.75	6.25	97.99	2.01	91.86	8.14
130	93.50	6.50	97.97	2.03	91.61	8.39
140	93.00	7.00	97.93	2.07	91.07	8.93
150	92.50	7.50	97.88	2.12	90.53	9.47

the two extreme cases A and B as shown in Table V.

In both cases the load-factor is the same, but the hourly power demand is widely different and represents in case A a kilowatt-hour loss equal to 18.04 per cent of the kilowatt-hours supplied at the customer service, while in case B this quantity is only 11.39 per cent, the power being used continuously.

In case B the character of the load would require transformers having a capacity of only one-fifth of those of case A, inasmuch as the load is below 200 kw.; and if such transformers were provided the losses would be reduced from 10.24 per cent to 5.03 per cent, or about 50 per cent less than in case A, the transmission losses remaining the same.

These two examples emphasize the economical importance of switching apparatus to at least disconnect large transformer installations from the line during idle hours when it is not possible to cut off the service at the station on account of power demands at other places on the line.

Inasmuch as the efficiency of transformers ordinarily decreases rapidly at fractional loads below 50 per cent, due mostly to the core loss, it is very important in the case just mentioned to select a transformer having a relatively high efficiency at fractional loads in order to obtain the most economical performance. This is accomplished by designing a transformer to have a small core loss and large copper loss at full load. By thus properly proportioning the core and copper losses, the maximum efficiency of operation can be obtained at $\frac{3}{4}$ load or even less.

Transmission Economics

From Kelvin's law the investment theoretically permissible in a transmission

system should be such as to meet the following conditions on an annual basis:

$$\text{Investment} \times \% \text{ fixed charges} = \text{kilowatt-hour losses} \times \text{cost per kilowatt-hour.}$$

This economical law does not make allowance for business development and recognizes only certain immediate conditions which, if met, would preclude business expansion; and as experience shows that more business develops later, the above formula must be disregarded to a certain extent, compatible with the financial resources available at the time of the undertaking.

Returning to the concrete example taken before for the transmission of 1000 kw. to a point 10 miles distant, with an immediate load-factor of 20 per cent, we may assume a daily load curve average as shown on Fig. 4. Analyzing this curve gives the transmission efficiency shown in Table VI.

$$\text{Transmission efficiency} = \frac{100 \times 4800}{5574.06} = 86.11 \text{ per cent.}$$

The average daily losses are 774 kw-hr., and per year 282,510 kw-hr., which must be supplied by the generating station over and above the kilowatt-hours sold. To the cost of production of this power must be added the fixed charges on the power plant equipment, insurances, taxes, etc., all variable factors according to conditions and locations, but all of which average in a modern steam plant $\frac{1}{2}$ cent per kilowatt-hour generated.

We thus have Kelvin's formula as applied to this case modified as follows:

$$\frac{\text{investment}}{(13400 \times 0.15)} = \$2010 \text{ against } \frac{\text{losses}}{(282510 \times 0.005)} = \$1412.55$$

and we see the economical law upset. The investment in line conductor is too high by \$598, or 29.75 per cent. To comply theoretically

TABLE V

	LOAD			TRANSFORMER		LINE			TRANSFORMER			Total Kw-hr. Losses
	Hours Operation	Per Cent Load	Kw-hr.	Per Cent Losses	Kw-hr.	Per Cent Load	Per Cent Losses	Kw-hr.	Per Cent Load	Per Cent Losses	Kw-hr.	
A	4.8	100	4800	2.00	96	102	5.72	280.05	107.72	2.01	104.04	480.09
	19.2	0	0	1.00	192	1	.06	.18	1.06	1.01	193.92	386.10
	24.0		4800	5.10	288		5.72	280.23		5.73	297.96	866.19
B	24	20	4800	5.2	249.6	21.04	1.12	56.55	22.16	4.72	241.01	547.16

Case A:—Output 4800 kw-hr., input 5666.19, efficiency 84.71, losses 15.29.
Case B:—Output 4800 kw-hr., input 5347.16, efficiency 89.76, losses 10.24.

with the Kelvin law the line losses could be increased 80 per cent, or from 6.66 to 11.98 per cent, corresponding to a copper conductor having a cross section between No. 4 and No. 5 B.&S.

The question of regulation must also be considered here, as it is an important factor from the point of view of quality of service. The increase in line drop for the range no load to 75 per cent load, as in the above example, is from 5.48 per cent, a regulation well permissible, to 9.86 per cent, and if full load is added later the line regulation would become still worse, or 11.98 per cent—a value inconsistent with good service and impeding any further load addition on peak. Furthermore, allowance must be made for certain contingencies, such as arise from low power-factor due to lightly loaded motors or transformers, this again impairing the regulation.

If we now assume the same transmission line and equipment as before, but additional business to increase the load-factor to 30 per cent, or a load curve as in Fig. 5, the efficiency and losses become as shown in Table VII.

$$\text{Transmission efficiency} = \frac{100 \times 7200}{8079.67} = 89.11 \text{ per cent}$$

The Kelvin formula compares as follows:

$$\frac{\text{investment}}{(13400 \times 0.15)} = \$2010 \text{ against } \frac{\text{losses}}{(321029 \times 0.005)} = \$1505.15$$

That is, the losses are still below the original fixed charges, while the permissible investment in conductor could have been increased to \$42600 and the annual losses to \$6390, or more than four times the losses calculated above.

It is true that the original investment in line conductor once made can hardly be increased unless a second line is installed; but part of the additional permissible investment will be absorbed by the installation of feeder regulators or synchronous condensers to

improve the voltage regulation at the receiver end. This will prove to be a better investment up to a certain transmission capacity, beyond which a second line becomes necessary. A deferred improvement fund should in time be available for this undertaking.

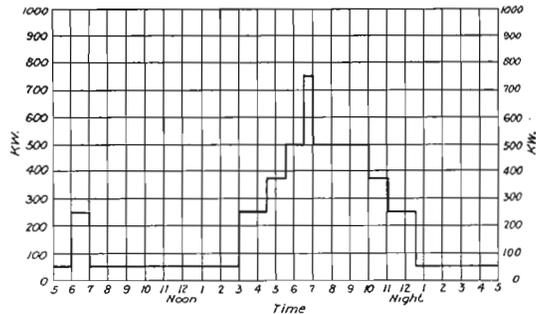


Fig. 4. Average Daily Load Curve 20 Per Cent Load-Factor

The Kelvin law is not applicable in most cases met in transmission problems and can at best be used only as a check on the calculations, the limiting factors being voltage regulation incident to good service, and allowance for future expansion in the scope of the business within the limits permitted by financial considerations, bearing in mind that all lines built into new territory are, in a sense, exploration lines opening the door to electric service, generally attracting business by the force of gravity through its economy and convenience.

The general use of electric service has been the result of its adaptability, convenience and economy; its success depends on reliability and the demand for a limitation in voltage variation. Therefore the question of regulation becomes more important every day, and this fact must be borne in mind when figuring on transmission and distribution lines, except in special cases of trunk lines where line drop can be conveniently compensated at either

TABLE VI

1000 KW. TRANSMISSION, 20 PER CENT LOAD-FACTOR, 80 PER CENT POWER-FACTOR

Hours Operation	LOAD		TRANSFORMER		LINE		TRANSFORMER			Total Input	
	Per Cent Load	Kw-hr.	Per Cent Losses	Kw-hr.	Per Cent Losses	Per Cent Load	Kw-hr.	Per Cent Load	Per Cent Losses		Kw-hr.
.5	75	375	2.60	9.75	76.95	5.48	21.08	82.43	2.54	10.30	416.13
4.0	50	2000	3.12	62.40	51.56	3.67	75.69	55.23	2.95	63.07	2201.16
2.0	37.5	750	3.80	28.50	38.92	2.77	21.56	41.69	3.52	28.16	828.22
4.0	25	1000	5.31	53.10	26.26	1.87	19.69	28.13	4.79	51.38	1124.17
13.5	5	675	25.06	169.15	6.35	0.45	3.79	6.80	18.45	156.44	1004.38
24.0		4800	6.72	322.90		2.76	141.81		5.87	309.35	5574.06

end. In computing the regulation of a line the regulation of the transforming apparatus must be considered and added to that of the line; the sum of both must be within allowable limits of efficient operation of the apparatus connected thereto, these limits being generally

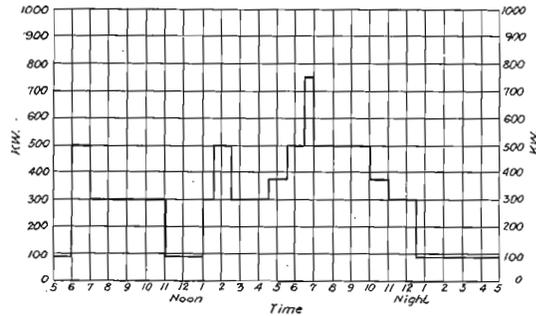


Fig. 5. Average Daily Load Curve 30 Per Cent Factor

fixed by commissions, with provisions made for further load additions and power-factor variation.

A thorough investigation of future requirements should be made in all cases in order to prepare for the service. At the same time

financial considerations must be carefully weighed, as they are in many occasions another limiting factor, and in such cases engineering provisions should be made as far as possible in anticipation of prospective emergencies, either in the style of construction for a duplicate line, loop, or for operation at a higher voltage.

The preliminary calculations can be made along the line described before to ascertain if the undertaking will bear the expenses from the start or within a reasonable time and yet allow for future growth. If the first check shows a narrow margin and there is evidence of future increase of business, a second calculation should be made on the basis of the ultimate probable requirements to determine if additional expenses can be carried until the new business is secured.

It is not necessary in all case to go into the tedious analyzis made in this paper, such a course is only indicated in case of doubt as to the successful development of a contemplated enterprise. The motto which must govern all electric transportation of power is "service," and all efforts must be bent toward maintaining this at its best.

TABLE VII

1000 KW. TRANSMISSION, 30 PER CENT LOAD-FACTOR, 80 PER CENT POWER-FACTOR

Hours Operation	LOAD		TRANSFORMER		LINE		TRANSFORMER			Total Input	
	Per Cent Load	Kw-hr.	Per Cent Losses	Kw-hr.	Per Cent Losses	Per Cent Load	Kw-hr.	Per Cent Load	Per Cent Losses		Kw-hr.
.5	75	375	2.60	9.75	76.95	5.48	21.08	82.43	2.54	10.30	416.13
6.0	50	3000	3.12	93.60	51.56	3.67	113.53	53.23	2.95	94.60	3301.73
2.0	37.5	750	3.80	28.50	38.92	2.77	21.56	41.69	3.52	28.16	828.22
8.0	50	2400	4.52	108.48	31.35	2.23	55.93	33.58	4.13	105.91	2670.32
7.5	9	675	13.61	91.86	10.02	.71	5.44	10.73	11.78	90.97	863.27
24.0		7200	4.61	332.19		2.88	217.54		4.25	329.94	8079.67