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POLYPHASE SYSTEMS OF GENERATION, TRANSMISSION, AND DISTRIBUTION.

By M. A. Sammett, A. M. Can. Soc. C. E.

(Read before the Electrical Section, November 15th, 1906.)

Every electrical development possesses some typical peculiarities which should be the determining factors in the selection of the frequency of the system as a whole, as well as the selection of the generating and distributing systems as to phases, that is, whether it should be two or three phase.

These are the problems with which we will concern ourselves in the discussion of polyphase systems, with a transmission line of 100 miles or less and pressures up to and including 50,000 volts at the receiving end. While the paper is limited to these two considerations alone, the ground to be covered is rather wide, requiring therefore a concise treatment of various characteristics.

It is but natural that a system with a railway load principally will call for a layout which will not answer best the needs of a lighting and power company, and a development where the power is to be used for some particular application may again call for a layout differing from the two mentioned above.

Every system is, therefore, influenced in its design by the nature of the load, and while a purely railway system will prove most economical and satisfactory with a given frequency, and two phase synchronous converters at the substations, lighting and power companies will require a different frequency and strictly three phase system. To compare the advantages of the three phase as against the two phase systems and of the two principal frequencies is the aim of this paper.

We shall take up first the question of phases.

Whatever the generation and distribution, the transmission of power is always accomplished by three phase. This arrangement allows of most economical transmission of power with a given drop in the line. While the transmission of power is invariably accomplished by three phase, the generation and distribution is often by two phase.

Modern engineering practice shows, however, the abandonment of the two phase generator in connection with hydro-electric power houses, where power is to be transmitted and consequently transformed from two to three phase. The common belief of the simplicity of the two phase generator and switchboard is more imaginary than real and came about as a result of clinging to the more familiar two phase generator which at the time just preceding the era of generation for transmission purposes was the standard apparatus, answering best the needs of small central stations with a lighting load, the amount of power forming a very small proportion of the total load.

It must be admitted that a two phase system for distribution purposes is somewhat simpler to operate than a three phase system. The two phases may be controlled independently for single phase lighting circuits without any appreciable effect of one phase on the other.

In the case of motor connections on two phase circuits, all that is necessary is to connect the two transformers with the primary coils to the line, and the secondary coils to the motor. No special attention is required as to polarities of transformers. The impedance of transformers need not be the same for proper division of load, as is essential in connections of three phase installations.

It was this at first sight simplicity which appealed to the engineer in laying out the first hydro-electric power houses, and even at the present time some engineers persist in their preference for the two phase generators, and at the receiving end go through another transformation from three to two phase in order to supply two phase current at the distributing end.

Let us take up the generating plant first and see which of the two systems, three or two phase, is more efficient as well as more economical.

POWER HOUSE: It is pretty well known that for a given capacity, speed and voltage, at a given frequency, the three phase generator will prove the more efficient machine. Manufacturers standardizing apparatus use the same frames and punchings for the two different types. This enables the manufacturer to turn out a better three phase generator as to efficiency and heating, retaining the same core loss. Should he, however, select to keep the same density in the copper of the three phase as in the two phase machine, he will be in a position to reduce the magnetic flux by virtue of the larger number of turns that can be accommodated in the same slots, and thus considerably reduce the core loss. Inasmuch as the core loss in machines of large capacity is considerably greater than the copper loss, this will result in a material increase in the efficiency of the generator.

Switchboard: Taking up next the switchboard, we will find that the only advantage the two phase board has in comparison with the three phase, is the saving of one ammeter. It is standard practice to use an ammeter in each leg, therefore the three phase board will require three ammeters. It is also maintained that the figuring of the K. V. A. load from the instruments is a more difficult matter with a three phase than with a two phase installation, as no factor is used in the latter case in computing the apparent K. W. of the station's output. The above objections have very little weight when compared with the advantages of a three phase board.

All busbars, oil switch contacts and switch compartments, all cables from generators to switchboard and from the board to the transformers are reduced in the ratio of 4:3, and while 15.6% larger cross-section of copper is required in the instance of the three phase installation, maintaining the same current density, the 25% saving in the number of individual parts necessary for the installation will be in favour of the three phase board.

Transformers: The use of two transformers for a given load allows a greater individual transformer capacity, and therefore a more efficient transformer. This would have been a decided advantage, favouring the two phase system, were it not for the fact that the transmission of power is to be by three phase. To accomplish this phase transformation by the well-known Scott connections, unless all transformers are provided with a heavier high tension winding, the transformer capacity would of necessity be reduced, due to a higher current in the three phase winding, namely that of 115.6% of the normal current. Should, however, the transformers be designed with provision made for this higher current, it would necessitate larger transformers, or in other words, a more expensive installation. Beside this increased transformer capacity, another disadvantage must be added, that of a possible resonance with T connected transformers for two-phase-three-phase transformers. Whenever one of the phases is open, due to a failure of making proper contact of various switches or any of the auxiliary connections, the high reactance of the high voltage transformer will get in series with the capacity of the transmission line and a resonance is likely to take place with the consequent disastrous results.

We have shown the advantages of using a three phase generator. This advantage is further augmented by the possibility of using transformer connections with which the danger of resonance is eliminated. Of the transformer connections in vogue, there are two which are free from the danger of resonance, namely △ to △ for step-up and △ to △ for step-down, or △ to Y and Y to △. Neither of these two has the objectionable characteristic of resonance and while the △ to Y and Y to △ is selected for transmissions where highest voltages are made use of, it is the △ to △ and △ to △ which gives the most reliable service. With the latter style of connections, should one of the transformers fail, as soon as this transformer is cut out, the service may be restored. This latter connection, namely △ to △ and △ to △ which insures both continuity of service and freedom from resonance, is introduced now on one of the 60,000 volt transmission lines and is destined to become the standard, inasmuch as high tension transformers of 60,000 volts as well as the insulators, especially if the latter are carefully selected and tested, have the requisite factor of safety, making the resort to the Y connections, at a sacrifice of continuity of service, unnecessary.

Distributing System: The considerations which held true in the discussion of the transmission line, will also hold true in the distributing system. The three phase delta connections should be made use of, since on motor service a complete shut-down due to a failure of one transformer must be carefully guarded against. Again, the three wire three phase distribution will result in a saving of 25% of copper and insulators. It will reduce the maintenance expense by the same percentage.

The advantages thus enumerated show clearly the desirability of three phase distribution from the purely commercial standpoint and still more so from the point of view of reliability and permanency of supply. Some engineers object to the three phase distribution on the ground of the difficulty of balancing loads. This objection must not be given much importance. With the mixed load of lighting and power, the power load has an equalizing tendency on the balancing of the system and with some attention given to the proper division of the connected lighting load, no difficulty will be encountered.

The station records should be carefully watched, and occasional re-adjustment of the load, based on station records as well as tests of individual installations, will permit of as careful a balance as one may desire.

Record of Amperes per Phase on a Three Phase Circuit.

Time.	A	B	C
12 Midnight	20	25	25
1 A. M.	25	25	25
2	5	5	5
3 "	10	10	18
4 "	5	10	18
5 "	10	10	10
6 "	10	10	10
7 "	25	25	25
8 "	95	93	95
9 "	92	90	90
10 "	93	93	93
11 "	97	97	97
12 Noon	87	87	87
1 P. M.	75	70	75
2 "	90	87	90
3 "	92	92	92
4 "	75	75	75
5 "	105	100	95
6 "	125	130	120
7 "	40	40	35
8 "	55	55	50
9 "	50	45	45
10 "	40	40	40
11 "	40	40	40
12 "	12	12	15

It is imperative for the success of any central station to build up a good load and to broaden out the peak. This means to secure a considerable motor load. Let us see, therefore, what are the relative advantages comparing two and three phase motors. The induction motor is the one upon which to base our comparison, as it is the motor in general use.

While the characteristic which affects the central station is that of power factor, the power being sold by the energy input, we must not confine our comparison to this point alone, but having in mind the good derived by the motor user in securing a better motor, we will discuss the relative merit of the two phase and three phase motors in a general way.

The comparison can best be made from a summary of a convention paper by Mr. Bradley McCormick read recently before the American Institute of Electrical Engineers. Given two similar frames without windings, how shall the two phase and three phase windings differ in order to secure proper operation? What will be the comparative losses if the two machines are given the same rating?

1. A two phase machine should have 22% more conductors per slot than the corresponding three phase Y connected machine, designed for the same voltage and flux per pole.

2. The magnetizing current is the same in both the two and three phase machines when expressed in percentage of the current, which corresponds to the full load output.

3. The copper loss of the two phase machine is 12% higher than that of the three phase.

4. The leakage factor of the two phase machine averages 25% greater than that of a three phase machine, therefore the power factor is lower.

Actual results show from 1 to 3% lower power factors.

These considerations show that the two phase machine will have a higher temperature rise as a result of a higher copper loss. For the same reason the efficiency of the two phase motor will be lower. The slip of the two phase machine will also be greater. Tests and theoretical calculations show 20% greater slip.

Thus we see that the two phase induction motor is a poorer motor for the central station company, due to a poorer power factor. It is also less advantageous to the power user, as a smaller efficiency means a larger motor input for a given output. The higher temperature rise will result in a shorter life and larger slip will mean a greater fluctuation between synchronous, partial and full load speeds.

While the three phase service should be made standard, two phase motors may be used by the aid of three-phase-two-phase transformers. This, however, should be discouraged, as such transformers require special taps, which make them more expensive, especially so when core type transformers are used. It also means the carrying of a stock of these special transformers as spare units. The above consideration as well as the larger capacity of transformers required in cases of phase transformation makes the two phase motor objectionable and its use should be discouraged.

This will conclude the remarks as to the advantage of a three phase as compared with a two phase system.

We will take up now the discussion under the heading of frequency.

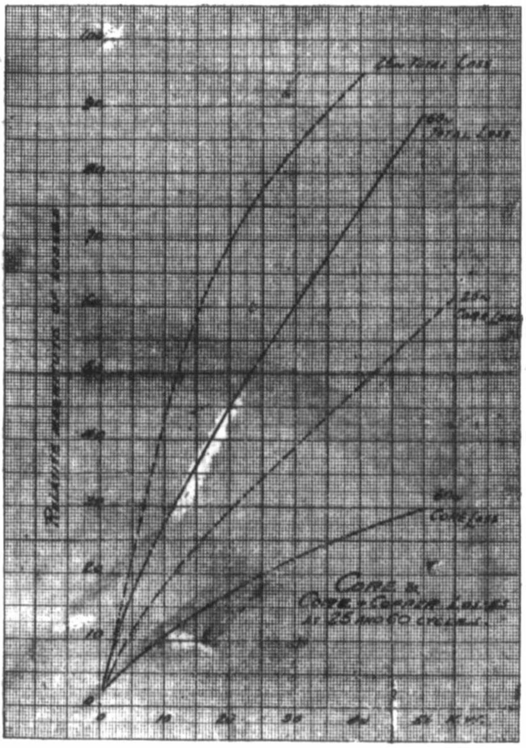
FREQUENCY: The frequencies most widely used on this continent are those of 60 and 25 cycles. While other frequencies are made use of these are the predominating ones. Let us, therefore, analyze them with a view of determining their adaptability for such developments as are under discussion in our paper. We shall make our analysis not from the transmission point of view alone, but analyze the generating and distributing systems as well.

REPORT OF COMMITTEE ON HIGH TENSION TRANSMISSION.

Class.	Number of Plants	Transmission Voltage.			Total mileage of transmission lines.	Total power transmitted in kilowatts	Length of Lines in miles.			Phase			Frequency, cycles per second:						Range of power-factor	Distance between conductors in inches		
		Maximum.	Minimum.	Average.			Maximum.	Minimum.	Average.	Single	Two	Three	25	30	33	50	60	66		Maximum.	Minimum.	Average.
A	19	12 000	4 600	8 000	217	31 135	25	3	9.5	1	4	14	2	1	2	—	14	2	80 to 100	36	14	19
B	7	16 000	14 500	15 000	297	65 425	31	7	23	—	—	7	2	1	—	1	3	—	80 to 97	40	18	27
C	9	24 000	20 000	22 600	394	64 999	60	107	32	—	—	9	2	1	—	—	5	1	80 to 90	48	26	33
D	4	27 000	25 000	25 500	127.50	23 400	46	16.6	32	—	—	4	—	—	—	—	3	1	80 to 90	50	18	39.5
E	4	34 000	30 000	31 300	276.30	18 825	83	29	62	—	—	4	1	—	—	1	2	—	90 to 95	40	24	31
F	4	60 000	40 000	51 600	328.25	14 875	101	60	75		—	4	—	1	—	—	3	—	65 to 100	108	42	76

Transactions A.I.E.E. 1904

TABLE I


25~ Total Loss
60~ Total Loss
25~ Core Loss
60~ Core Loss
Core &
Core + Copper Losses
at 25 and 60 cycles.
Relative magnitudes of losses
0
10
20
30
40
50
60
70
80
90
100
0
10
20
30
40
50
K.W.

As far as the transmission line is concerned, the lower the frequency, the less the induction drop, the smaller the charging current and the better the regulation. It is a foregone conclusion that as a purely transmission problem we will have to adopt the 25 cycle frequency. Our problem, however, is more complicated. The transmission line is only a chain in the link, and important as it is, it should not overrule the advantages of a higher frequency as applied to the distributing end of the system. In our composite problem the various advantages and disadvantages should be carefully weighed and the selection made on the merits of advantages of the entire system taken in its totality.

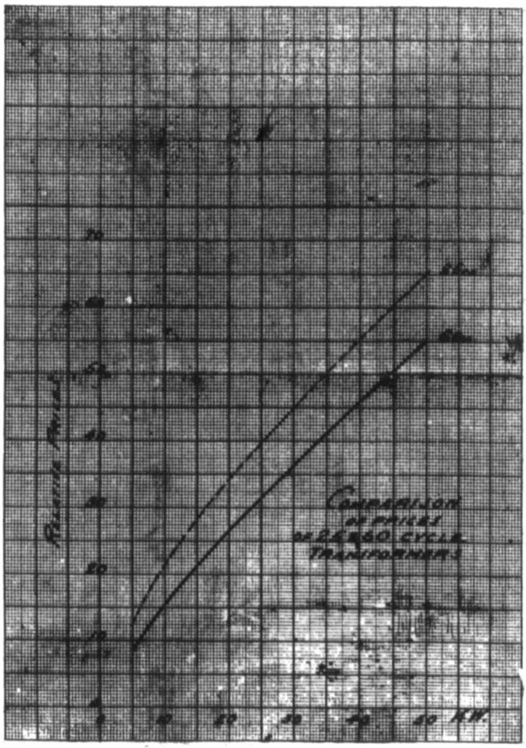
Power House: The table of speeds of generators at 60 and 25 cycles shows a wider range of speeds, hence a greater flexibility when laying out a 60 cycle hydro-electric power house.

R. P. M. 25 cycles 300 250 214 187 166 150.
R. P. M. 60 cycles 327-300-277 256-240-225 212-200 190-180 172-164 156-150.

The speeds of turbine-generator units are limited by the number of wheels, type, head and output. Therefore a wider range of speeds permissible with a 60 cycle system will enable the selection of the most efficient generator-wheel combination. Inasmuch as increased peripheral velocities will result in a decrease in active material, the selection of higher speeds will enable us to choose cheaper hydro-electric sets. The above conclusions hold true except when higher speeds call for special construction, which will rapidly increase the cost.

Switchboard: The switchboard under the two frequencies is unaffected. All meters and potential and current transformers are designed for satisfactory operation on frequencies from 25 to 125 cycles. In our comparison of 60 and 25 cycles it may be said that while the temperatures of the switchboard shunt transformers will be less at 60 cycles, the series transformers will operate at higher temperatures, due to a higher iron loss. The temperatures, however, will be well within the margin of permissible safe operation.

Transformers: Transformers built for 25 cycles are a much more expensive piece of apparatus as well as less efficient than when built for 60 cycles. Considering that there is with a generation, transmission and distribution of power a total transformer capacity equivalent to from 3 to 4 times the capacity of the generating apparatus, one will readily see the advantage of a higher frequency. This, however, must not be done at a sacrifice of other considerations, such as excessive charging current in transmission or extremely poor regulation. We shall come to the questions of charging current and regulation later on and now will take up the con-


Relative Prices
70
60
50
40
30
20
10
0
0
10
20
30
40
50 K.W.
Comparison
of prices
of 25 & 60 cycle
Transformers

sideration of frequency and endeavour to determine the best frequency with loads such as we are to handle, that is:—

Incandescent Lighting, Arc Lighting, Power Service by Induction or Synchronous Motor and Railway Load: With incandescent lighting while 30 cycles is the limiting frequency, 40 cycles is unsatisfactory when moving objects are viewed by it. On this continent 60 cycles is the standard frequency for such a service, while 50 cycles is European practice. For arc lighting 40 cycles is the limiting frequency. Lower frequencies are made use of in the application of the recently developed mercury vapour converter and magnetite lamps. This new system, however, will probably have to go through a process of further experimenting. The conservative investor will still select the higher frequency series alternating enclosed arc lamps.

Induction Motors: Analyzed from the standpoint of frequency, induction motors show characteristics which make it difficult to decide as to the best motor. Both motors under careful design can be made of equal performance as to power factor, efficiency, etc. But the motors will be of radically different designs. From the commercial standpoint the 60 cycle motors have a decided advantage, namely, a somewhat higher speed. Speed and cost are inversely proportional, hence the 60 cycle motor will prove the cheaper of the two. Another point which favours the 60 cycle motor is the greater demand for it, and the manufacturing companies have developed a finer design of this frequency. As a rule lower frequency motors are adaptations to standard 60 cycle frames and punchings, hence their performance does not show characteristics of the same high standard. Of course the low frequency motors have advantages of their own, such as better starting torque, higher instantaneous but not continuous overload capacity and lower speeds. As stated before, unless the motors of the lower frequency are standardized for best and most efficient design, the high frequency motors are more satisfactory.

The principal factors in favour of the 60 cycle motors are better continuous overload capacity and also a cheaper product commercially as a result of higher speeds. Therefore, with equally good performance as to efficiency and heating, the 60 cycle motor will still be ahead of the 25 cycle motor.

	Revolutions per minute—Synchronous speed									
Poles	2	4	6	8	10	12	14	16	18	20
25 Cycles—	1500	750	500	375	300	250	214	187	166	150
60 Cycles—		1800	1200	900	720	600	514	450	400	360

Railway Load: The suitability of low frequency synchronous converters for railway work is a well established fact. While 60 cycle synchronous converters are used for such purposes, they are rather an exception and their operation is less satisfactory. What should then, under the circumstances, be a desirable way of supplying street railway loads without resort to frequency changers? The latter are out of the question, due to excessive cost, beside the great reduction in the efficiency of the systems, resultant from their use.

Motor generator sets may be and are advantageously used in this connection, and while not possessing the advantages of 25 cycle synchronous converters, have features which make them particularly suitable for use on long distance transmission systems, permitting of a partial or complete control of the power factor of the system depending as to whether induction motors or synchronous motor sets are used.

Wherever large capacity is present, due to long transmission lines, induction motor generator sets of large size can be used to great advantage. For perfect control of the power factor of the transmitted power, synchronous motors should be employed, as in this case the regulating of the field excitation allows of a close control of the power factor of the transmitted energy, allowing the maximum energy for a given current, and under certain conditions will permit of carrying the load at unity power factor in the generating and transforming apparatus and transmission line.

While the synchronous converter is the most efficient of the three means of supplying railway loads, whenever this load constitutes only the minor portion of the total output of the plant, the interests of the lighting and power load cannot be sacrificed for a most efficient conversion of the alternating current to direct current for railway purposes.

In our discussion of frequency we may conclude that for a mixed load of lighting and power with a railway load not exceeding one-third of the total power generated, 60 cycles will be the frequency to select.

We are to take up now two more questions. These are charging current and the regulation of the line. The above factors under adverse conditions will limit certain developments, making them impossible, commercially considered, at 60 cycles. The same development at 25 cycles may present a very attractive proposition using power for a different application.

Let us see how the two frequencies affect our case. What will be the relative magnitude of the charging current and regulation?

TABLE OF REACTANCES.

By H. W. FISHER.

Size of Conductor in B & S Gauge	Diameter in Inches	Resistance in ohms per 2,000 ft. of Wire at 68° fahr.	Reactance in ohms per 2,000 feet of Wire at a frequency of 60 cycles per second. Distances between centres of conductors in inches.													
			½	1	2	3	4	5	6	8	12	18	24	36	48	60
Solid 10	0.1018	1.994	0.116	0.148	0.1803	0.199	0.212	0.223	0.231	0.244	0.2626	0.281	0.294	0.313	0.326	0.337
8	0.1285	1.254	0.107	0.138	0.1695	0.189	0.202	0.212	0.220	0.233	9 2519	0.271	0.284	0.302	0.315	0.326
6	0.1620	0.7888	0.095	0.127	0.1589	0.178	0.191	0.201	0.209	0.222	0.2412	0.260	0.273	0.292	0.305	0.315
4	0.2043	0.4960	0.085	0.117	0.1482	0.167	0.180	0.190	0.198	0.211	0.2305	0.249	0.262	0.281	0.294	0.305
Strand 4	0.232	0.4960	0.078	0.111	0.1424	0.161	0.174	0.185	0.193	0.206	0.2247	0.244	0.257	0.275	0.288	0.299
3	0.260	0.3934	0.072	0.105	0.1372	0.155	0.168	0.178	0.186	0.199	0.2195	0.237	0.250	0.269	0.282	0.293
2	0.292	0.3120	0.067	0.099	0.1318	0.150	0.163	0.173	0.181	0.194	0.2142	0.232	0.245	0.264	0.277	0.288
1	0.328	0.2474	0.063	0.095	0.1261	0.145	0.158	0.169	0.177	0.190	0.2088	0.228	0.241	0.259	0.273	0.283
0	0.373	0.1962	0.056	0.089	0.1205	0.139	0.152	0.163	0.171	0.184	0.2029	0.222	0.235	0.253	0.267	0.277
00	0.418	0.1556	0.052	0.084	0.1153	0.134	0.147	0.158	0.166	0.179	0.1977	0.216	0.230	~~0.248~~	0.262	0.272
000	0.470	0.1234	0.046	0.078	0.1099	0.129	0.142	0.152	0.160	0.173	0.1923	0.211	0.224	0.242	0.255	0.265
0 000	0.528	0.09786		0.073	0.1046	0.123	0.136	0.147	0.155	0.168	0.1869	0.206	0.219	0.237	0.251	0.261
Cir. Mils.																
300 000	0.630	0.06902		0.064	0.0964	0.115	0.128	0.138	0.146	0.160	0.1788	0.197	0.210	0.229	0.242	0.253
400 000	0.728	0.05178		0.058	0.0898	0.109	0.122	0.133	0.141	0.154	0.1722	0.192	0.205	0.224	0.237	0.247
500 000	0.815	0.04042		0.053	0.0846	0.104	0.117	0.127	0.135	0.148	0.1670	0.186	0.199	0.218	0.231	0.241
600 000	0.893	0.03452		0.048	0.0804	0.099	0.112	0.123	0.131	0.144	0.1628	0.181	0.195	0.213	0.226	0.236
700 000	0.964	0.02958		0.045	0.0769	0.096	0.109	0.120	0.128	0.141	0.1593	0.178	0.192	0.210	0.223	0.233
800 000	1.031	0.02598			0.0738	0.093	0.106	0.116	0.124	0.138	0.1562	0.175	0.188	0.207	0.220	0.230
900 000	1.093	0.02300			0.0711	0.090	0.103	0.113	0.121	0.135	0.1535	0.173	0.186	0.205	0.218	0.228
1 000 000	1.152	0.02070			0.0687	0.087	0.100	0.111	0.119	0.132	0.1511	0.170	0.183	0.201	0.215	0.225
1 250 000	1.289	0.01657			0.0635	0.083	0.096	0.106	0.114	0.127	0.1459	0.164	0.178	0.197	0.211	0.221
1 500 000	1.412	0.01381			0.0594	0.079	0.092	0.102	0.110	0.123	0.1417	0.160	0.174	0.193	0.206	0.216
1 750 000	1.526	0.01183			0.0558	0.075	0.088	0.098	0.106	0.120	0.1382	0.157	0.170	0.189	0.202	0.212
2 000 000	1.631	0.01053			0.0527	0.072	0.085	0.095	0.103	0.116	0.1351	0.154	0.167	0.185	0.199	0.209

A	1.05	1.10	1.15	1.20	1.25	1.30	1.35	1.40	1.45	1.50	1.60	1.70	1.80	1.90	2.00
B	0.0022	0.0044	0.0064	0.0084	0.0103	0.0121	0.0138	0.0155	0.0171	0.0186	0.0216	0.0244	0.0270	0.0295	0.0319

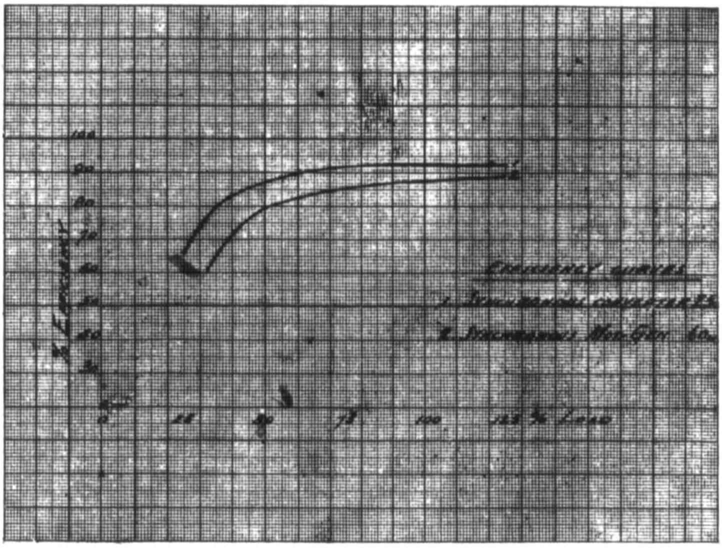
For any other frequency *f*, the reactances given in the table must be multiplied by $\frac{f}{60}$.

The reactances for diameters of conductors which lie between the sizes given can be found by direct interpolation.

The reactance for any distance *D* not given in the table can be found as follows: let *d* = the nearest smaller distance in the table. Divide *D* by *d* and taking a value of *A* nearest to the quotient find the corresponding value of *B*, which must be added to the reactance corresponding to the size of conductor and distance *d*.

Transactions A.I.E.E.

TABLE II


100
90
80
70
60
50
40
30
% Efficiency
0
25
50
75
100
125 % Load
1
2
EFFICIENCY CURVES
1. Synchronous Converter 25
2. Synchronous Mot.-Gen. 60

Line 100 miles long.
Load 10,000 H. P. for each transmission circuit.
Conductor 4/0.
Voltage at receiving end 50,000.
Space between conductors 60"
Charging current at 60 cycles = 23 amps.
Charging current at 25 cycles = 9.6 amps.
Regulation 60 cycles.
100% P. F. full load 9.0%
80% P. F. full load current 23.0%
(Step up and step down transformers included in this calculation.)
Regulation 25 cycles (Including transformer).
100% P. F. full load 5.5%
80% P. F. full load current 10%

The regulation and capacity or charging current are decidedly in favor of the 25 cycle transmission. The results for the 60 cycle system, while considerably in excess of those at 25 cycles, are considered quite normal for commercial purposes and inasmuch as the increase and decrease in the load is gradual the regulation is well within control of the central station operators or automatic devices.

As to the railway load, this had better be carried on a separate circuit, whenever a multiplicity of circuits is used in transmitting the power. In our case there are three transmission circuits.

Considering the successful operation of one of the long distance transmission lines of 150 miles in California where the charging current forms 40% of full load current, and where the regulation is 40% at full load, 80% power factor, we need not hesitate to operate our line with a regulation of 23%, 80% power factor.

The power factor of the system, however, is to a large extent within the control of the operating company, as it may recommend to power users such apparatus as will best answer the purposes of the system as a whole. Beside this, by employing synchronous motors running as rotary condensers, it will be enabled to regulate the power factor of the system and keep it if necessary at unity. These synchronous motors running idle, used supplementary to the synchronous motor generator sets, will allow of a perfect control of the power factor of the system, reducing the regulation to 9% under full load condition.

In conclusion, we will say, that under the conditions as stated, for a mixed lighting and power load, with a railway load not exceeding 33% of the total output, a 3 phase 60 cycle system should be employed throughout and all transformation should be accomplished by △ to △ connections.