"Operation of a 3-Phase, 15 K.W. Alternator as a Synchronous Motor."

By

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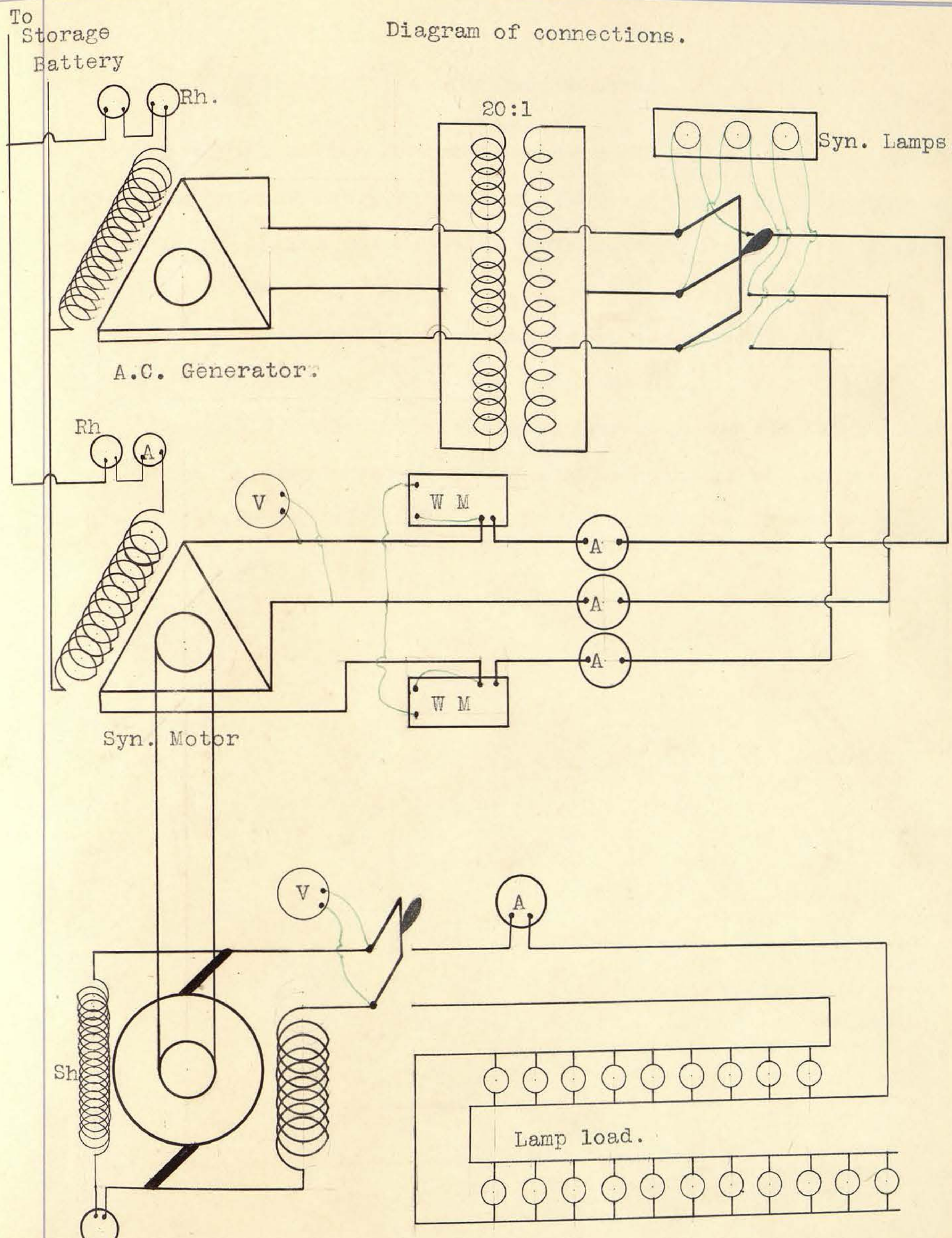
Diagram of connections.



Theory of the Synchronous Motor.

The theory of the synchronous motor and its operating characteristics can be shown very clearly by the use of diagrams. In this way, the variation of the power-factor with the load and with the exciting current is shown.

Figure 1 shows the relation between the supply E.M.F.,(A), the motor counter E.M.F. (B), the resultant E.M.F.,(E) and the current (I). The angle θ which the current makes with the resultant E.M.F. is constant for any one circuit of armature winding and connections, and is equal to $\tan^{-1}X/R$, where R is the resistance in the circuit and X the inductance.

Fig. 1.

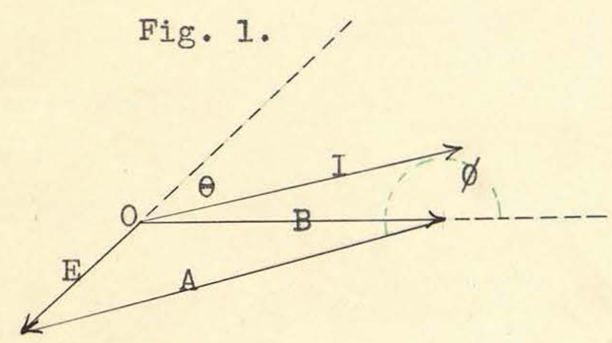


Fig. 3.

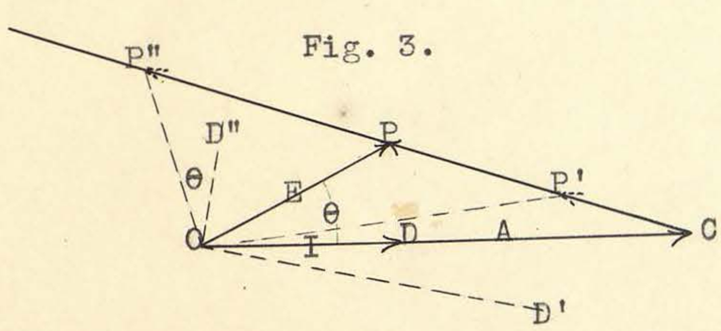


Figure 2 is the diagram which shows the value of the power in-take of the motor, with the increase of the load, the e m fs being kept constant, in other words the field excitation of the motor is kept constant. The supply voltage is supposed to be kept constant throughout this discussion. In this fig., OC represents the motor e m f, (B), CP the supply voltage, (A) , OI the current in the circuit. Then OP will represent the resultant e m f (E).

If we draw through O the line EF, making the angle θ with the line OC, the projection of (E) upon EF, or OQ will be proportional to the power in-take of the motor. This is proved in the following manner:-

The out-put of power of (B) = $B \cdot I \cdot \text{Cos (COI)}$

$(POQ) = (COI)-180^{\circ}$, $\quad \text{Cos } (POQ) = -\text{Cos } (COI)$

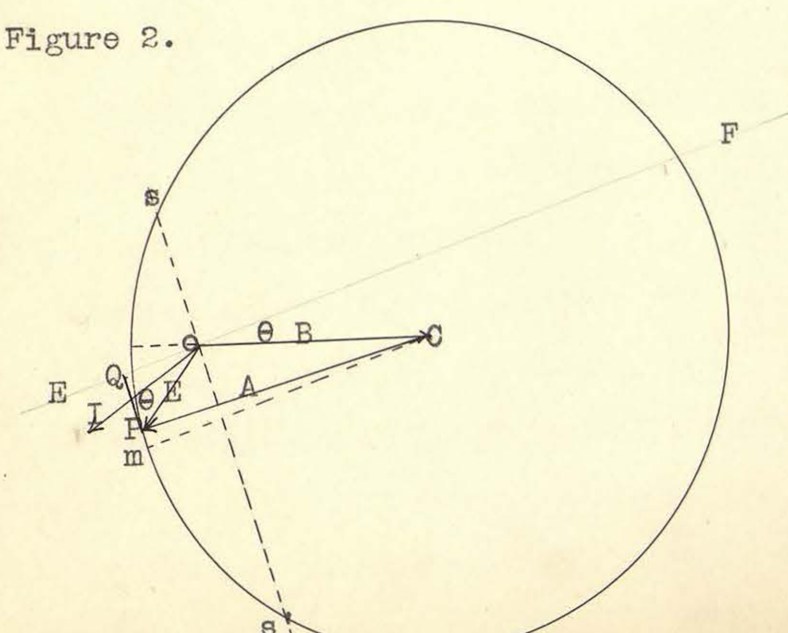
$OQ = E \cdot \text{Cos}(POQ) = -E \cdot \text{Cos}(COI) = -\sqrt{R^2 + X^2} \cdot I \cdot \text{Cos}(COI)$

$-OQ/\sqrt{R^2 + X^2} = I \cdot \text{Cos}(COI)$

$\therefore$ Power out-put of (B) $= -\dfrac{B \cdot OQ}{\sqrt{R^2 + X^2}}$

or power in-take of (B) = $B \cdot OQ/\sqrt{R^2 + X^2}$, (B), (R), and (X) being constants, the power in-take will be proportional to OQ.

Figure 2.



The supply e m f and the motor e m f being kept constant, the angle between the e m f must change as the load changes, in order that the resultant voltage may become larger, resulting in an increase of current and power in the circuit of the machine. Suppose the load to so vary. Then (A) must revolve about (C), the point (P) describing a circle. The line ss' being drawn perpendicular to EF, the scope of operation of (B) as a motor will be points on the arc sms' . At the points s and s', OQ is equal to zero and (B) recieves no power from the circuit. In order that the e m f (A), may pass beyond s and s' it will be necessary for (B) to run as a generator, in which case it will give out power to the circuit.

If the line CM is drawn parallel to EF, then the limit of steady operation of the motor, the e m fs being constant, is between the points s and m. In this region, any increase in load, resulting in an increase of phase difference between (B) and (A) will be met by an increase of OQ and the power in-take. Between the points m and s', an increase in load results in a decrease of power in-take. Therefore, if the motor is loaded until the point (P) passes by m, the motor will stop or "break down".

The angle between the current and the supply voltage will change with the load. The current will be in phase with the supply voltage when the angle CPO is equal to θ. At this point we will have unity power-factor and consequently maximum efficiency.

If we keep the angle between the two e m fs comstant and vary the motor e m f by varying the field current of the motor, we will have the conditions shown in figure 3. Here CP, CP' and CP"represent three different values of field current. OC represents the supply e m f and the lines OD, OD' and OD" the current which lags behind the resultant e m f an angle equal to θ. As this angle is constant, the angle between the current and the supply e m f will change with the field, the load being kept constant. When the motor e m f is equal to CP, the current is in phase with the supply e m f and the power-factor is unity. If the field current is increased, the current will lead the e m f and the motor will have a condenser effect on the circuit. If the motor e m f is less than CP, the current will lag behind the supply voltage, and the motor will have an inductive effect on the circuit. As the angle of lead or lag increases, the current increases. The increase of the current over that where the power-factor is unity, is a wattless current , and causes a great I^2R loss in the circuit. If the field current was either increased enough or decreased enough, a point would be reached where the current was at right angles to the supply voltage. In that case the current would all be wattless, the motor would recieve no power, and it would stop.

The machine used in this test was a General Electric type ATB one to six phase, 15 kilo-watt alternator, with rotating fields and laminated pole faces. Power was supplied by a Westinghouse, 2300 volt three phase alternator, and stepped down to 110 volts by transformers. Care was taken that this voltage as well as the frequency was kept constant. For a load, the motor was belted to a 15 kilo-watt Westinghouse, compound wound, 110 volt D.C. generator, loaded with a bank of incandescent lamps. This gave us a very stable and easily measured load. Before the test was run , an efficiency curve of the D.C. generator was obtained by running it with a calibrated motor. In this way the out-put of the motor was determined.

When the machine was first started, there was trouble due to hunting. This was to be expected as the poles were laminated, and the machine was not designed for ~~the~~ operation as a synchronous motor. The difficulty was finally located in the belting which was too loose. After that the belts were kept tight, both on the D.C. generator and the motor. We then found no difficulty with hunting during the remainder of the test.

Due to the inadequacy of the power supply we were unable to load the motor heavily enough to find the break down points of the different field excitations used. We did get full load on the motor, rated as a generator at which load the operation was entirely satisfactory.

Starting the Synchronous Motor.

Alternators are convertible into motors; and one alternator will run in synchronism with another similar machine after it is brought to the same speed, or, if of unlike number of poles, to the same multiple of the speed of the driven dynamo, provided the number of pairs of poles on the motor is divisible into the multiple. Such motors will run as if geared to a driven alternator even up to two or three times its normal full torque or capacity. Single-phase synchronous motors have no starting-torque, but synchronous motors of multiphase circuits will come up to synchronism without much load giving about 25% starting-torque, starting as induction motors, with the d.c. field open.

Since the synchronous motor has very little starting-torque, it has to be started at practically no-load and the load thrown on gradually after it has reached full speed. One method of starting the synchronous motor is by a separate prime mover, which for simplicity take a d.c. motor. In this method the alternator which is to be used as the synchronous motor is brought up to synchronous speed and having the same voltage as the alternator which is to drive the synchronous motor and exactly opposite in phase. One way of knowing when the two machines are in phase is by use of synchronizing lamps. These lamps, one in each phase, are placed over the three-pole switch as shown in diagram of connections. The lamps will first be bright and then dark and as the two machines are nearing synchronism the pulsations of the lamps will be slower and there will be several seconds of darkness each time until they are exactly in phase. When this occurs the switch in the main circuit should be closed and the prime mover of the synchronous motor is cut off.

This method is used in paralleling of alternators but not so much in starting of synchronous motors.

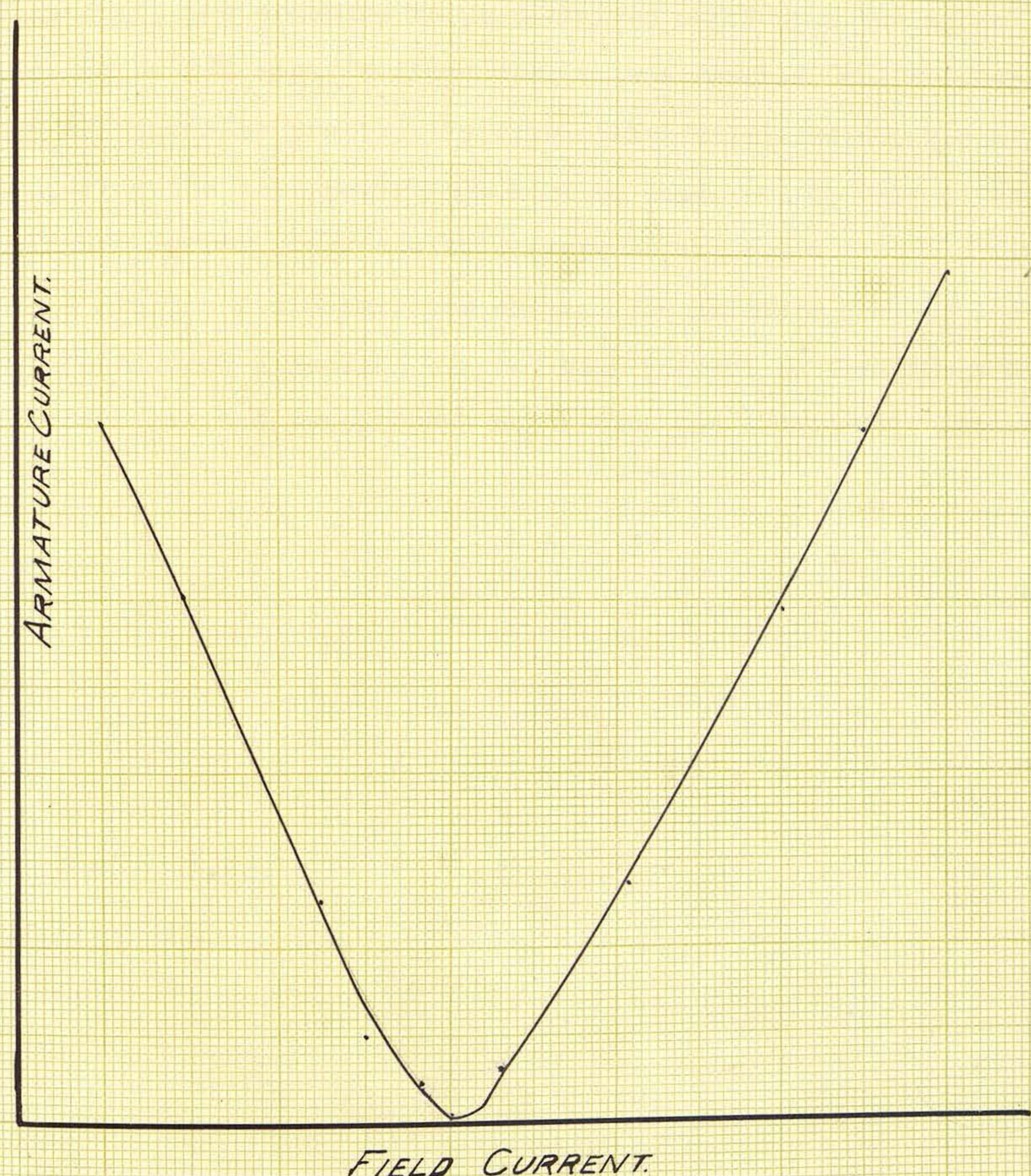
Another method is the partial voltage method. In this the d.c. field of the synchronous motor is opened and the voltage of the driving alternator is lowered to about one-half normal and when the switch in the main circuit is closed, the machine will start as an induction motor, and when it has reached full speed the field circuit is closed. The voltage is brought up to normal gradually after starting. In this method as in the first, the motor is started at practically no-load, e.i. only such load as is necessary in starting, as a generator on the same shaft or one directly belted.

A third method is to close switch in main circuit, open the field on the motor and as the alternator is started the motor will pick up as an induction motor, and when the alternator has reached full speed, so has the motor and the field circuit of the motor is closed. In starting a synchronous motor as an induction motor, the armature current is large, taking about 200% of no-load current as a synchronous motor. When the d.c. field circuit is closed the armature current at once comes down to a lower value depending upon the strength of field current used in the synchronous motor.

Considerable care must be exercised in the use of synchronous motors, and their best condition is where the load is quite steady, otherwise they introduce inductive effects on the line that are quite troublesome. The field of such a motor can be adjusted for a particular load, so there will be neither leading nor lagging current but unity power-factor. If the load changes, then the power-factor also changes, until the field is readjusted; if the load has been lessened the current will lead, and if it increases the current will lag.

Data for Vee curve, no load.

Amps. Fld. :	Amps. Arm. :	Watts (1) :	Watts (2) :
1.00	29	-1400	1900
1.5	17.5	800	1350
2.0	5.	200	700
2.5	0.0	+ 400	100
3.0	13	1100	-450
3.5	24.5	1750	1050
4.0	34.5	2400	1550
4.5	44.5	3000	2100
5.0	55.	3700	2600
5.5	64.5	4300	3100
6.0	74.	4900	3500
6.5	84.	5600	4000
7.0	93	6200	4400


ARMATURE CURRENT.
FIELD CURRENT.

The "Vee" curve is one showing the relation between the motor armature current and the field current. This curve gives the no-load armature current for any field current between the two limits. Starting with one ampere field current and increasing 0.5 ampere at each step, the armature value decreades until when the point corresponding to 2.5 amperes field current was reached, the armature current had decreased to practically zero, this field current, 2.5 amperes, producing the best power-factor at no-load. Up to this point the armature current lagged with respect to the e m f.

As the field was over excited the armature current increased which produced a leading current with respect to the line e m f. The over excited synchronous motor thus has a condenser action.

Data:--   Curve #1.

A_1	A_2	A_3	Volts	$K.W._1$	$K.W._2$	Cos Ø	D.C.Volts	Amperes
24	24.5	22	110	2.5	-.4	.45	104	10
28	28	25	"	3.2	00	.60	105	19
32.5	33	31	"	4.	+.4	.70	106	27.5
44	46	42	"	4.75	.9	.743	108	34.
46	48.5	44	"	5.5	1.2	.755	107.5	37.
55	58.5	54.5	"	6.9	1.3	.79	106	44.5

Synchronous Motor field excited to 1.5 amperes.

Breakdown point at 68 amperes armature current of motor.

A_1, A_2, and A_3 correspond to the current in the different phases of motor armature.

Cos Ø = % power-factor.

Data:--

Curve #2.

A_1	A_2	A_3	Volts	$K.W._1$	$K.W._2$	Cos ∅	D.C.Volts	Amperes
45	46	45	110	3.6	-1.4	.251	106	00
48	48	48	"	4.	1.	.33	106	6
47	47	47	"	4.4	.5	.438	106.5	14
49	50	49	"	5.	0.0	.53	109	22
51	52	51	"	5.65	+1.1	.685	108.5	31
57	57	57	"	6.55	2.5	.835	109	54
63	63	63	"	7.3	3.9	.934	108.5	69.7
65	65	65	"	7.6	4.5	.977	108	76
69	69	69	"	7.9	5.4	1.000	104	87

Motor field excited to 4.5 amperes.

Speed 1200 r.p.m.

Frequency 60 cycles.

Data:--

Curve #3.

A_1	A_2	A_3	Volts	$K.W._1$	$K.W._2$	Cos Ø	D.C.Volts	Amperes
76	76	76	110	5.6	-2.9	.187		
75	76	75	"	6	2.25	.262	107	000
76	76	76	"	7	1	.435	106	9
79	79	79	"	8	0.0	.532	106	29
83	83	83	"	8.9	+1.3	.645	107	42.5
84	85	84	"	9.3	2.	.703	106	62
87	87	87	"	9.8	2.9	.755	106	69
90	90	90	"	10.2	3.6	.805	104	82

Motor field excited to 6 amperes.

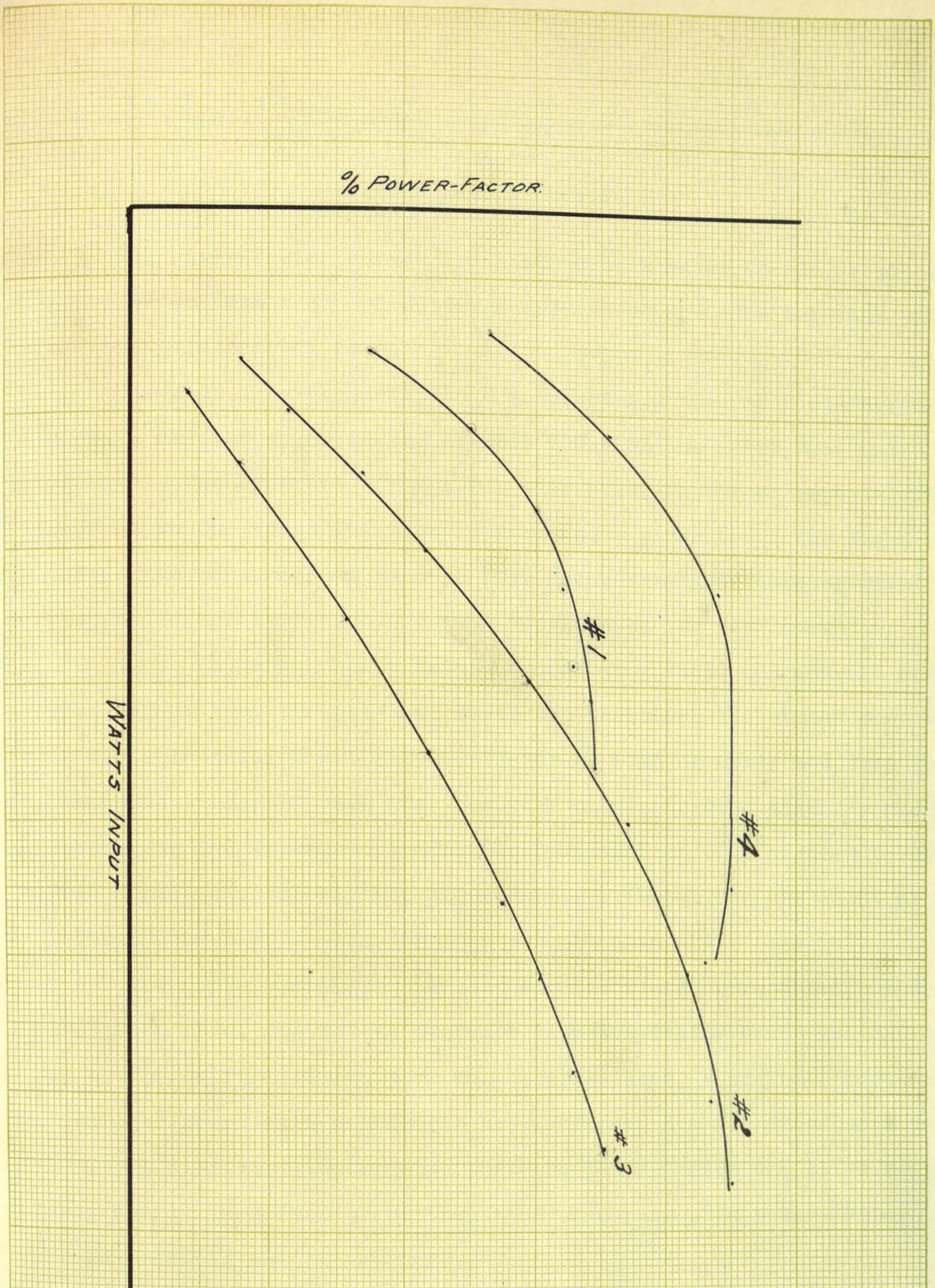
No breakdown point.

Data:--

Curve #4.

A_1	A_2	A_3	Volts	$K.W._1$	$K.W._2$	Cos ϕ	D.C.Volts	Amperes
15	15	15	110	1.7	.1	.631		
22	22	22	"	2.4	.9	.806	104	12.25
25	26	25	"	2.95	1.6	.93	105	23
31	31	30	"	3.41	2.27	.979	106	32.1
37.1	36	35	"	3.9	3.15	1.000	108	42.5
44.5	44	43	"	4.5	4.08	1.000	109	53.7
52	50	51	"	4.9	5.08	1.001	109	65
58	56	55	"	5.05	5.9	.969	109	73.8

Motor field excited to 3 amperes.


% POWER-FACTOR
WATTS INPUT
#1
#4
#2
#3

Power-Factor Curves.

The power-factor curves are plotted with watts in-put as abscissa and % power-factor as ordinates, one curve being taken for each value of the field current used.

Curve #1, corresponding to a value of 1.5 amperes field current shows a maximum power-factor of only 79% when the break down point is reached. The armature current for this power-factor 68 amperes, 69 amperes is the rated full load current as a generator. The field for this curve was under excited so that the current was lagging with respect to the impressed e m f as is shown by the"Vee" curve.

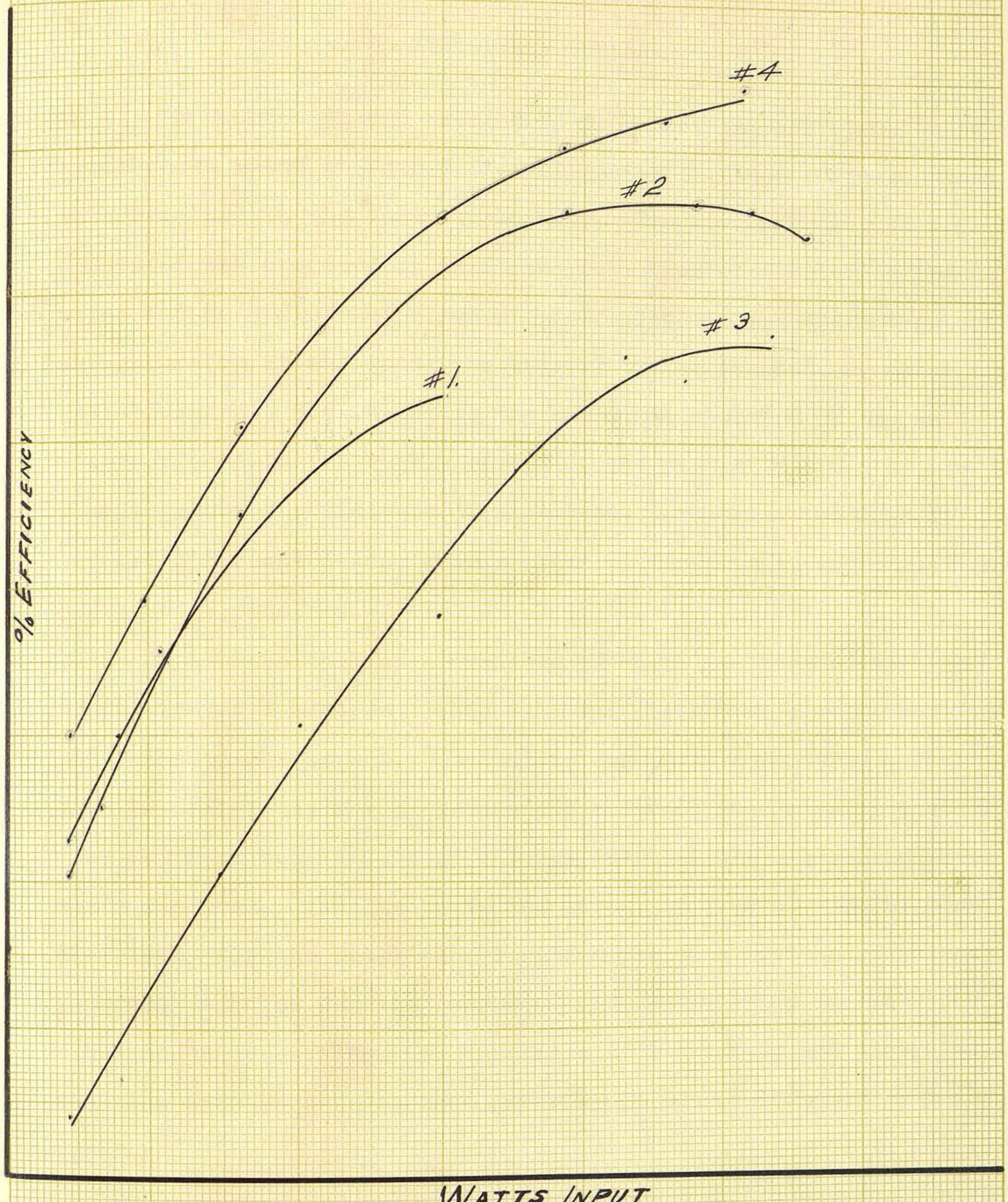
Curve #4, which has a value of 3 amperes field current, is somewhat higher than the previous curve and therefore has higher power-factor. In this we get a power-factor of 100% or unity and from the Vee curve it may be seen that the current was leading slightly with respect to the impressed e m f,this indicated an over excited field. This curve gave the highest power-factor although for one value of input of curve #2 a value of 100% was obtained.

The curve corresponding to 6 amperes field current falls below the other three due to the decrease in power-factor which was caused by the motor field being very much over excited, therefore producing a leading current with respect to the impressed e m f. This curve is nearly a straight line showing that the power-factor and watts input vary nearly in direct proportion to each other. The power-factor would probably not become unity.

The curves taken were for values of 1.5, 3, 4.5 and 6 amperes fie field current. They all resemble a magnetization curve in form. None start at the origin as the lowest value we obtained for power-factor was about 18%. From these curves we would conclude that the best value of field current for operating the machine as a synchronous motor is 3 amperes. This current gives a value of practically unity power-factor, over the greatest range of load.

The curves were obtained by reading the total watts input to the synchronous motor and amperes in each phase. The field current was kept constant at the value desired and the impressed voltage and speed kept constant.

From this equation:- $\cos \phi = \frac{P}{EI\sqrt{3}}$, where P is the sum of the watt-meter readings, E = voltage, I = average current of the 3-phases, and $\cos \phi$ = power-factor, the % power-factor was computed.



EUGENE DIETZGEN CO., CHICAGO.

Efficiency Curves.

The curves on the preceeding page show the efficiencies of the synchronous motor at four different values of field current. They were obtained in the following manner. The Westinghouse, 15 K.W.,D.C. generator was operated by 26 horse-power Crocker-Wheeler calibrated motor and an efficiency curve obtained. By reading the out-put of the generator at any load, the out-put of the synchronous motor could be calculated. The in-put to the motor was measured by two watt-meters placed in the supply circuit. The out-put divided by the in-put gave the efficiency at that load. By taking readings at several different loads, from no-load up to maximum, the efficiency curves were obtained.

It is seen that an efficiency of 92.8% is obtained with an excitation of 3 amperes. This data was checked at a subsequent time and found to be correct. As that is generally considered as too high an efficiency for a synchronous motor of this size, the discrepancy may have been in the efficiency curve of the calibrated motor which was used. If this curve had given, in general, too high an efficiency for the motor, the result would have been an efficiency generally too low for the generator and consequently too high for the synchronous motor. However the shape of the curves and their relative position with respect to each other would not be affected by this error.

A comparison of the four curves shows that for extremely high and extremely low values of exciting current the efficiency is very low, maximum efficiency being obtained with a field current of 3 amps. This is what one would expect from a comparison with the power-factor curves at the above excitations. Three amperes field current gives a power-factor of nearly unity at full load which we will consider as 10 K.W. This should therefore give us maximum efficiency borne out by the efficiency curves. The reason for the decrease of the efficiency with the power-factor is that on low power-factors a considerable amount of wattless current is circulating in the system causing increased I^2R losses in comparison with the energy derived from the watt currents.

Because of this variance of power-factor the efficiency of the motor with 1.5 amperes field current is a maximum at 8 K.W., the point of maximum power-factor; while with 6 amperes field current, maximum efficiency is at 14 K.W. because of the higher power-factor with the greater load at this excitation.

We would then conclude that maximum efficiency is obtained when the field is normally excited, a fact which can be proven from theoretical considerations. We also see that an under excited synchronous motor has maximum efficiency at less than full load; and an over excited motor has maximum efficiency above full load.

Owing to our lack of power in the supply circuit we could not determine the efficiencies above full load, but we have evidently reached the point of maximum efficiency in most of our curves.

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