

TEST OF MOTOR-GENERATOR

by

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INTRODUCTION

This thesis is written about a motor generator set. The generator is a 1-3-6 phase alternating current generator with the following specifications:

5 K.V.A.	60 Cycle
110/220 volts	1200 R.P.M.
26/13 amperes	
Separate Exciter	
Exciting current 5 amperes.	
Exciting voltage 110 volts.	
S. O. 64 C ' 107	
Serial Number 4790449	

The generator is driven by a direct current motor of type SK.

7.5 H. P.	Style Number 646106
115 volts	Serial Number 4790451
53 amperes	
900/1200 R.P.M.	

The motor generator set is located in the electric laboratory, and is used there to supply currents for different kinds of experiments. The object of this test was not to make any unknown discoveries in the electrical field, but merely to determine some of the characteristics of the generator that might be of future use. The data were obtained by actual test and tabulated as given in the data division. From these data the calculations were made and the results are as given by the curves or data.

SATURATION CURVE

The no-load saturation curve is a curve plotted with terminal volts as ordinate and field current as abscissae. The values of the voltage and current are obtained at no-load. This curve gives some of the characteristics of the alternator and from this, information is obtained which otherwise would require considerable work. For instance, the voltage which corresponds to the armature short-circuited current are estimated from this curve, as explained under the heading of short-circuit curve.

To obtain data for the no-load saturation curve it is necessary to obtain accurate values of field current and terminal volts at no-load. This is gotten by placing an accurate ammeter in the field circuit, and since the phase voltages may not be exactly the same, it is advisable to take the voltage between each of the terminals and use the average of the three. The curve is plotted with the field current against the terminal voltage as shown by curve (a) "Figure 1".

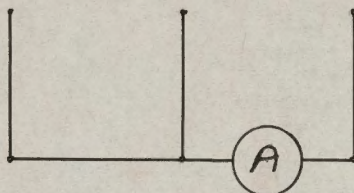
WESTINGHOUSE
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ZERO POWER FACTOR SATURATION CURVE

The zero power factor saturation curve is gotten by drawing a curve parallel to the no-load saturation curve and through the point "B". "B" is gotten by dropping a perpendicular from the short-circuit curve at the point "E", which is at the rated current of twenty-six amperes. This gives the zero power factor curve for rated armature current as shown by curve "C". If it is desired to obtain the zero power factor curve for any other armature current it is only necessary to drop a perpendicular from a point on the short-circuit curve corresponding to the desired current, to the line "OA" and through this point draw the curve.

SHORT-CIRCUIT CURVE

The short-circuit curve values are obtained by short-circuiting the terminals of the alternator through star connected ammeters. Since the line currents were the same only one ammeter was used. The connection is shown by the diagram.



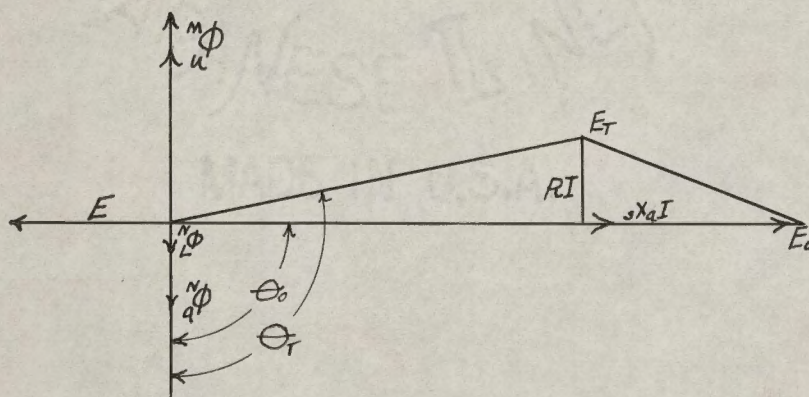
By varying the field current the short-circuited armature current was varied up to 200% of normal rated value. For this particular machine the rated armature current is 26 amperes, thus the readings were taken up to 60 amperes. These values of the current were multiplied by $\sqrt{3}$ in order to get the equivalent single phase values. The short-circuit curve is plotted with the field current as abscissae, and the corresponding equivalent single phase armature current as ordinate, as shown by curve (b) "Figure 1".

The voltage which corresponds to the short-circuited armature current is read from the no-load saturation curve. Knowing the corresponding field current we may obtain the voltage directly from the saturation curve.

SYNCHRONOUS REACTANCE

The armature reaction and reactance drop are proportional to the armature current, and the voltage consumed by both are in time phase for all power factors. One equivalent reactance may represent both factors and this is called the synchronous reactance sX_a . The data for the synchronous reactance are obtained in the same manner as the short-circuit values in the preceding paragraph, and are used in calculating the result.

Since the reactance curve is a curve plotted with armature current as abscissae and the corresponding terminal volts as ordinate, it is necessary to use the saturation curve. The corresponding terminal volts are gotten by reading the volts which correspond to the field current on the saturation curve. The reactance curve is shown by (d) "Figure 1", and is nearly a straight line drooping slightly as the saturation point of the iron is approached. Since the power factor is nearly zero under short-circuit conditions the vector relations are as shown.



The voltage taken by the resistance is small and almost in time quadrature with the induced voltage, therefore, the voltage consumed by the synchronous reactance is practically equal to the total voltage. For the reactance $E_0 = I_a Z = I \sqrt{r^2 + sX_a^2}$ and

$$Z^2 = r^2 + sX_a^2 .$$

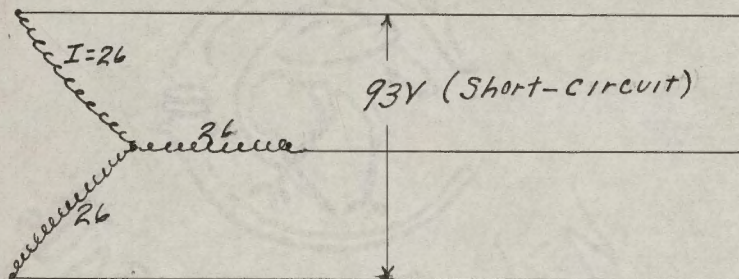
Since the armature resistance is

small $Z = sX_a$, then

$$E_0 = I_a Z = I_a sX_s$$

or $sX_a = E_0/I_a$ approximately. This value is usually larger than that when the alternator is operating under full load, also the synchronous reactance and hence the synchronous impedance vary with the load.

Considering the following diagram, we may obtain X the equivalent reactance.



$R_a = .1$ per phase.

Since R_a is so small we may consider $X = Z = \frac{E_t}{I}$

$$Z = \frac{93}{3 \times 26} = \frac{93}{1.73 \times 26} = 2.061$$

$X = 2.061$ (Equivalent Single Phase).

ARMATURE RESISTANCE

This is determined by passing a direct current through the armature circuit taking readings of the voltage and the current. Then by the equation $E = RI$ or $R = \frac{E}{I}$ which is the resistance between two terminals. The equivalent single phase $R = \frac{R}{2}$ having R and X , the RI and XI drop may be calculated. These are plotted against the equivalent single phase armature current as shown by the curves in "Figure 2".

GRAVES



JAPANESE LINE

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DATA FOR SATURATION CURVE

E _t				
A B	B C	A C	I _f	E _t av.
4.0	3.95	4.0	0	3.98
11.9	11.82	11.9	.2	11.85
28.0	28.0	28.0	.5	28.0
52.8	52.8	54.0	1.0	53.4
73.0	73.0	73.0	1.5	73.0
90.6	90.6	91.0	2.0	90.8
104.2	103.9	104.8	2.5	104.3
117.3	117.1	118.0	3.0	117.7
124.3	124.3	124.5	3.49	124.4
133.1	132.5	133.7	4.0	133.1
138.0	138.0	138.2	4.5	138.1
142.0	142.5	142.2	5.0	142.3
147.0	146.0	147.0	5.5	146.5
150.0	150.0	150.5	6.1	154.0
157.0	156.5	157.0	7.05	156.8
160.0	160.0	160.0	7.5	160.0

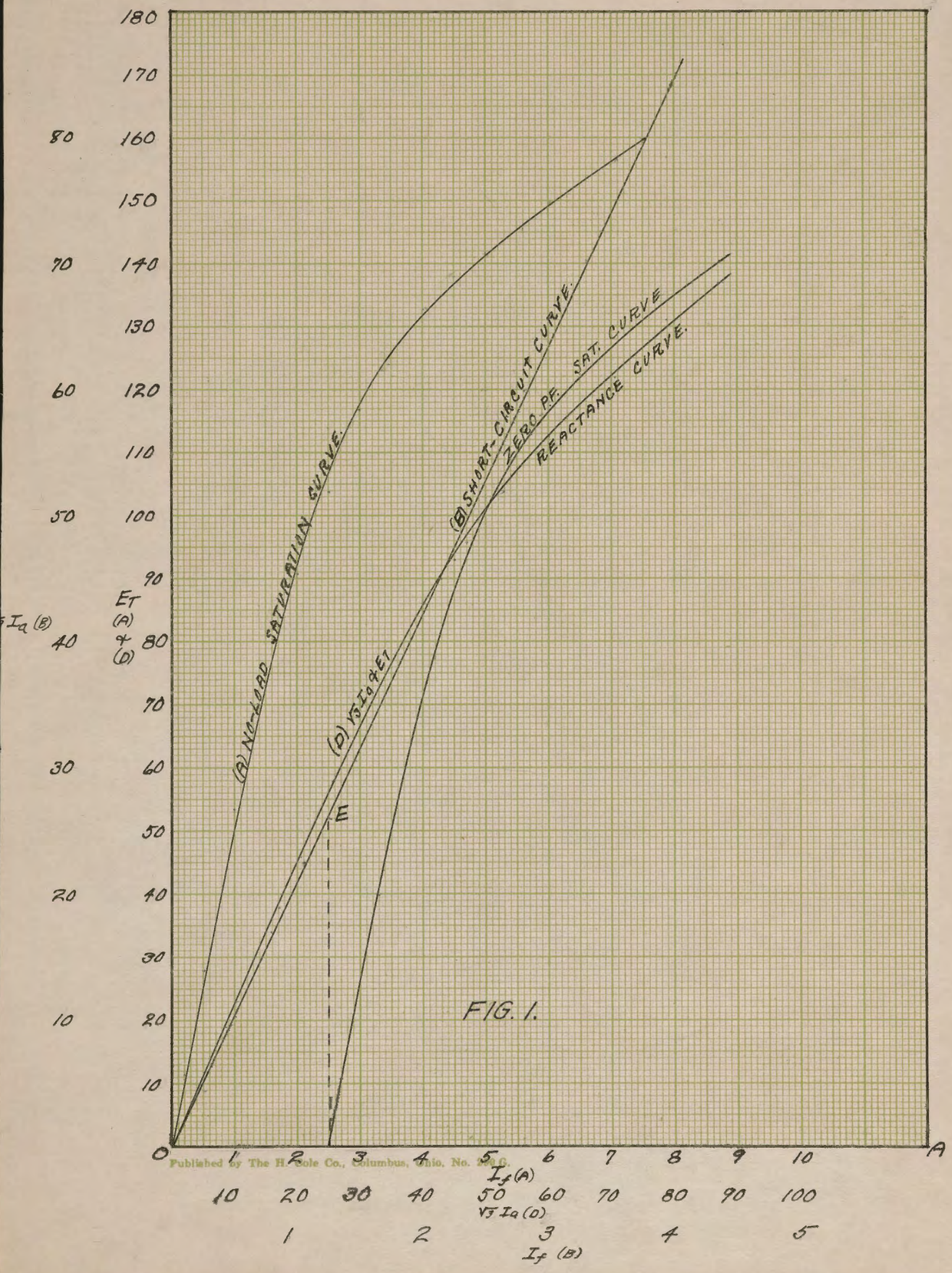
DATA FOR SHORT-CIRCUIT CURVE

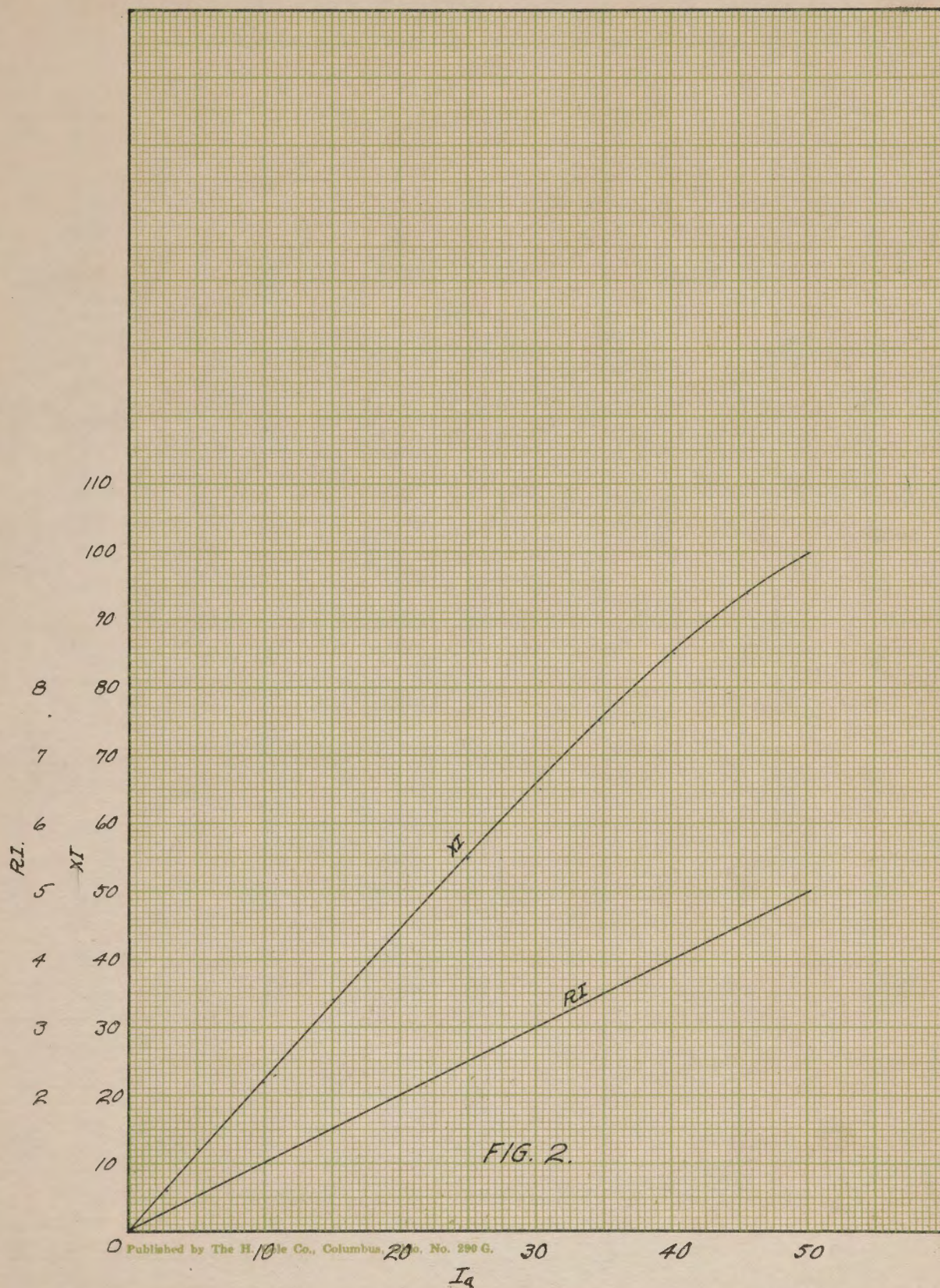
I_f	I_a	$\sqrt{3} I_a$	Corres- ponding V	XI
0.0	.75	1.295	0.0	.5
.2	2.95	5.10	9.0	6.0
.4	5.00	8.65	19.0	12.0
.49	6.05	10.48	23.0	14.0
.78	9.92	17.15	38.0	22.0
.92	12.00	20.80	46.0	27.0
1.20	15.00	25.95	58.0	34.0
1.42	17.00	29.40	68.0	38.0
1.82	22.6	39.05	84.0	50.0
2.00	25.0	43.30	90.0	55.0
2.09	26.0	45.00	93.0	58.0
2.18	27.0	46.70	96.0	60.0
2.41	30.5	52.70	104.0	65.0
2.80	34.7	60.00	113.0	75.0
3.30	40.7	70.50	122.0	85.0
3.98	45.6	78.90	131.0	94.0
4.40	50.5	87.40	137.0	110.0

DATA FOR ARMATURE RESISTANCE

I	E	R
2.1	.40	.190
3.0	.60	.205
3.9	.80	.205
4.5	.88	.195
5.0	1.00	.205
Av. R = .200		

$$R = .2/2 = .1 \text{ per phase}$$





REGULATION

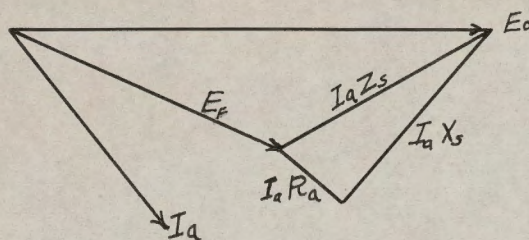
Regulation of an alternator means the per cent increase in voltage when full load is thrown off the machine while keeping the frequency and field excitation constant. The regulation of an alternator depends upon the power factor of the load, and hence the power factor should always be included in the statement of the regulation of the alternator.

There are three main ways to determine the regulation of an alternator as:

1. By the synchronous impedance method.
11. By the A. I. E. E. method.
111. By the magnetomotive force method.

The advantages and disadvantages of each of the three methods will be given in the following paragraphs.

1. The synchronous impedance method is valuable in cases where it is impossible to fully load the alternator due to its size or other reasons. The regulation of an alternator depends upon three things: (1) armature leakage reactance, (2) the apparent or effective armature resistance, (3) armature reaction. The effective resistance of a circuit to an alternating current is greater than to direct current because of (1) eddy-current losses set up in the conductors of the circuit, (2) eddy-current losses set up by the current in any adjacent conducting material, (3) hysteresis losses produced by the current in adjacent iron. The effective resistance of a circuit is equal to the total power loss in the circuit caused by the current, divided by the square of the current. The local eddy current losses and hysteresis losses effect regulation by increasing the apparent armature resistance. If the effective armature resistance is used the above effect may be taken into account. Considering the vector diagram, "Figure 3", E_f is the phase voltage and I_a is the armature current lagging behind the phase voltage.



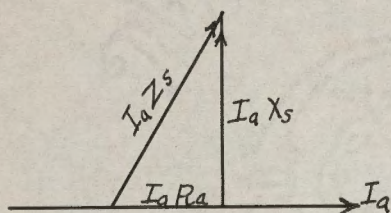
"Figure 3"

The vector $I_a Z_s$ is the electromotive force necessary to overcome the synchronous impedance drop of the armature. Then we have

$$I_a Z_s = \sqrt{(I_a R_a)^2 + (I_a X_s)^2} \quad \text{or} \quad Z_s = \sqrt{(R_a)^2 + (X_s)^2}$$

and since R_a is small compared with Z_s we may consider $X_s = Z_s$ approximately.

In the case of the short circuited alternative E becomes Zero and "Figure 3" changes to "Figure 4" in which E_0 is equal numerically to the synchronous



"Figure 4"

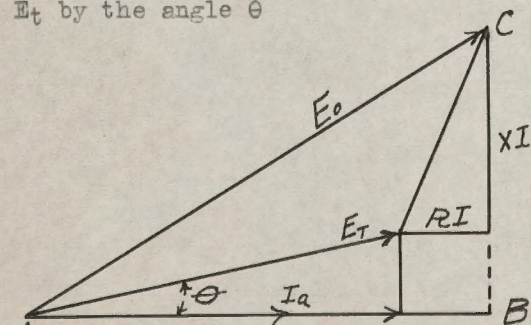
impedance drop $I_a Z_s$ in the armature. E_0 being the voltage found on the open circuit.

$$E_0 = I_a Z_s \quad Z_s = E_0 / I_a.$$

The numerical value of the regulation is found by the equation $\frac{E_0 - E_t}{E_t} \times 100$

where E_0 is the voltage when the load is thrown off the machine and E_t is the terminal voltage with the load on.

"Figure 5" shows the method for calculating E_0 when I_a is lagging E_t by the angle θ



"Figure 5"

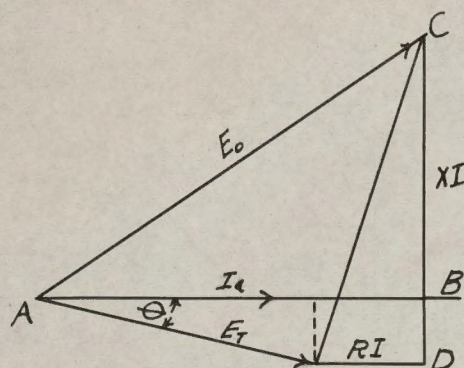
$$E_0 = \sqrt{AB^2 + BC^2}$$

$$AB = E_t \cos \theta + RI$$

$$BC = E_t \sin \theta + XI$$

$$E_0 = \sqrt{(E_t \cos \theta + RI)^2 + (E_t \sin \theta + XI)^2}$$

"Figure 6" represents the method for calculating E_o when I_a is leading E_t by the angle θ



"Figure 6"

$$E_o = \sqrt{AB^2 + BC^2}$$

$$AB = E_t \cos \theta + RI$$

$$BC = XI - E_t \sin \theta$$

$$BD = E_t \sin \theta$$

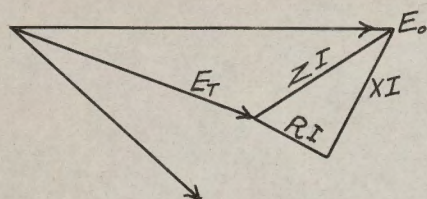
$$E_o = \sqrt{(E_t \cos \theta + RI)^2 + (XI - E_t \sin \theta)^2}$$

For unity power factor E_o is calculated as above except the angle θ is zero. Thus

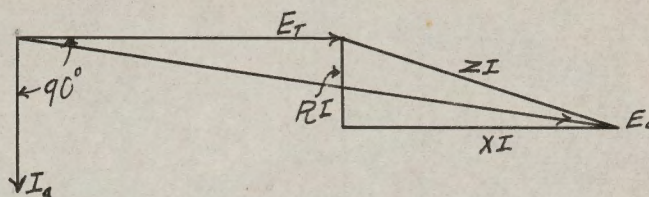
$$E_o = \sqrt{(E_t + RI)^2 + (XI)^2}$$

The above method is used in this thesis and the values are as given by the data sheet.

II. The A. I. E. E. method is a modification of the synchronous impedance method. In the synchronous impedance method the impedance is taken with the generator operating short-circuited, and under these conditions the saturation is lower than under operating conditions, consequently the value of the synchronous impedance is much too large for normal operating saturation. In the A. I. E. E. method the zero power factor curve is used. This curve may be gotten by loading the alternator with a synchronous motor or by estimation as described under zero power factor saturation curve. Consider "Figure 7" the vector diagram for an alternator in which all quantities are per phase. If the power factor be zero, the current will lag 90° behind E_t , and the diagram becomes as "Figure 8" in which the resistance drop $I_a R$ has little effect and $E_o - E_t = X_s I_a$ approximately. E_t is the terminal voltage produced by I_f at zero power factor. E_o is open circuit



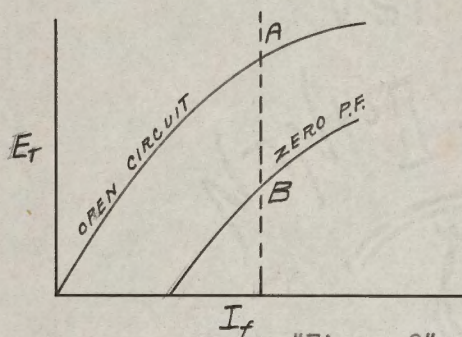
"Figure 7"



"Figure 8"

phase voltage corresponding to I_f . We have
$$X_s = \frac{E_o - E_t}{I_a}$$

Referring to the open-circuit and zero power factors saturation curves, the



"Figure 9"

distance AB corresponding to some $X_s I_a$ the synchronous reactance drop which corresponds to the saturation produced by that excitation I_f , or

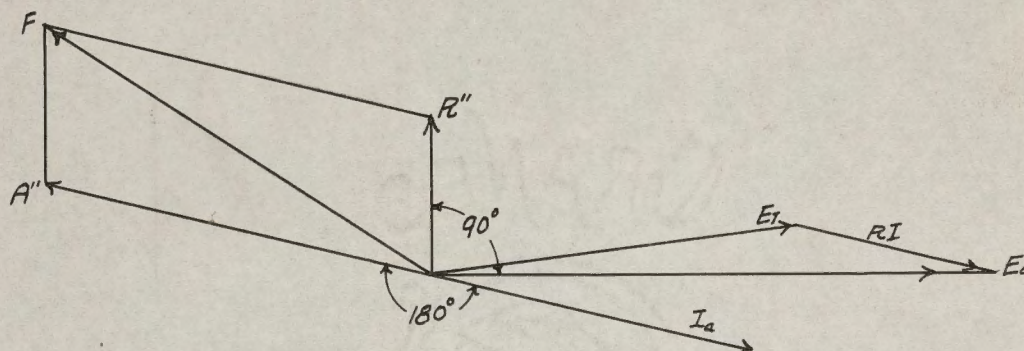
$$X_s = \frac{AB}{I_a}$$

Having X_s the regulation may be calculated as

described before.

III. In the magnetomotive force method an equivalent armature reaction replaces the effect of the real armature leakage reactance. This is an opposite substitution to that of the synchronous impedance method in which the effect of the armature reaction is replaced by an equivalent armature reactance, which is added to the real armature reactance. Two things are involved in this method: (1) "The determination of the amount of field current necessary to generate a voltage equal to that of the reactance drop plus the voltage generated by the armature reaction flux." (2) "The vector addition of this field current to that necessary to induce a voltage equal to the terminal voltage plus the RI drop in the armature." The resultant of the

two fields and the corresponding voltage on the open-circuit curve gives the no-load voltage. The effect of armature resistance is negligible on short-circuit compared with the effect of armature reaction and reactance. Since the armature reaction is in phase with the current, the field will be 180° from the current. "Figure 10" gives a vector representation of the addition of the RI drop to E_t which gives a fictitious induced voltage E_o .



"Figure 10"

The field R'' corresponding to E_o on the saturation curve is 90° ahead of it. The current and the terminal voltage E_t must be known or assumed. E_o may be determined since R_a is known and RI is in phase with I_a . R'' is determined from saturation curve, and A' the field current is taken from the short-circuit curve and corresponds to the armature current I_a . The vector sum of A' and R'' give F and the voltage which corresponds to this is the voltage from which the impedance may be calculated. The results obtained by this method may be erroneous since several assumptions have to be made. However, some of the errors tend to cancel others and this method is used when it is impossible to use the A. I. E. E. method.

"Figure 11" gives a diagram for finding the no-load voltage. E_o for any load current at any power factor, at rated terminal voltage E_t . By this we have θ = angle of the power factor, E_t the terminal volts and E_o the desired no-load voltage. For unity power factor with I_a along OD, E_o the open-circuit voltage is the vector sum of E_t the terminal voltage, $R_a I$ and

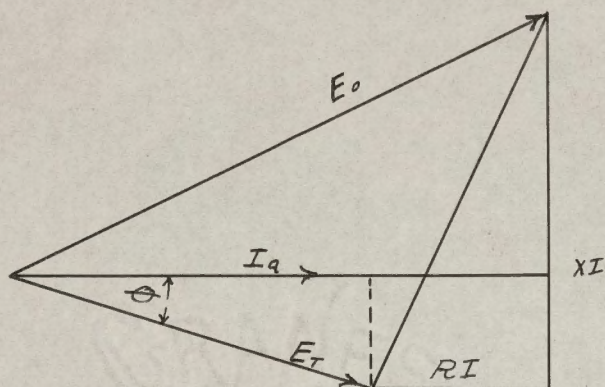
sX_aI_a as shown. The curve B'B H is found by varying the power factor, but keeping the terminal voltage and armature current constant. This gives a circle the loci of E_o with C as the center and E_t as the radius. As an example, let $\theta = 30^\circ$, then $P.F. = \cos \theta = .866$ and $E_t = OA'$, then B shifts to B' and $E_o = OB$.

"Figure 12" is a curve plotted with no-load voltage against the power factor for rated terminal voltage at rated current. The power factor is variable, taking angles every 10° on "Figure 11", and determining E_o as explained above. Plotting the power factor as abscissae and E_o as ordinate the curve is given as shown.

"Figure 13" shows curves plotted with no-load voltage against load current for rated terminal voltage at unity, .5 lagging and .5 leading power factors. (a) is with .5 leading, (b) is with unity, and (c) is with .5 lagging power factors.

"Figure 14" is the regulation curve of the alternator for all power factors.

.5 LAGGING POWER FACTOR



$$I = 26$$

$$R = .1$$

$$\cos \theta = .5, \sin \theta = .866$$

$$X = 2.061$$

$$RI = 2.6$$

$$E_t = 110/1.73 = 63.6$$

$$XI = 53.6$$

$$\begin{aligned} E_0 &= \sqrt{(E_t \cos \theta + RI)^2 + (XI - E_t \sin \theta)^2} \\ &= \sqrt{(63.6 \times .5 + 2.6)^2 + (53.6 - 63.6 \times .866)^2} \\ &= \sqrt{(34.4)^2 + (1.64)^2} = \sqrt{1,182 + 2.7} = \sqrt{1,184.7} \end{aligned}$$

$$E_0 = 34.45$$

$$\text{Regulation} = \frac{34.45 - 63.6}{63.6} = 45.7\%$$

$$\text{If } I = 5, \quad E_0 = 55.0$$

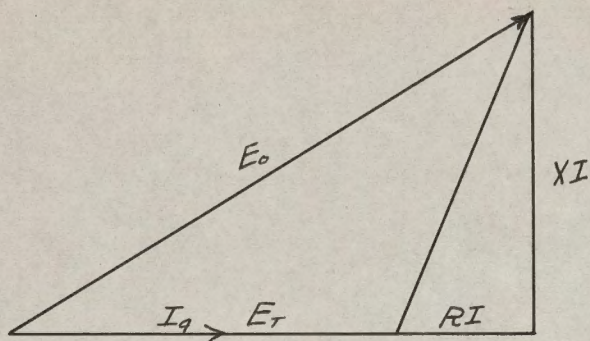
$$I = 10, \quad E_0 = 47.5$$

$$I = 15, \quad E_0 = 41.3$$

$$I = 20, \quad E_0 = 37.5$$

$$I = 26, \quad E_0 = 34.45$$

UNITY POWER FACTOR



$$E_t = 110/1.73 = 63.6 \text{ Volts}$$

$$X = 2.061$$

$$R = .1$$

$$RI = .1 \times 26 = 2.6$$

$$XI = 2.061 \times 26 = 53.6$$

$$E_o = \sqrt{(E_t + RI)^2 + (XI)^2} = \sqrt{(66.2)^2 + (53.6)^2} = \sqrt{4,350 + 2,870}$$

$$= \sqrt{7,220} = 85.3 \text{ volts}$$

$$\text{Regulation} = \frac{85.3 - 63.6}{63.6} = 34.1\%$$

$$\text{If } I = 5, \quad E_o = 65.1$$

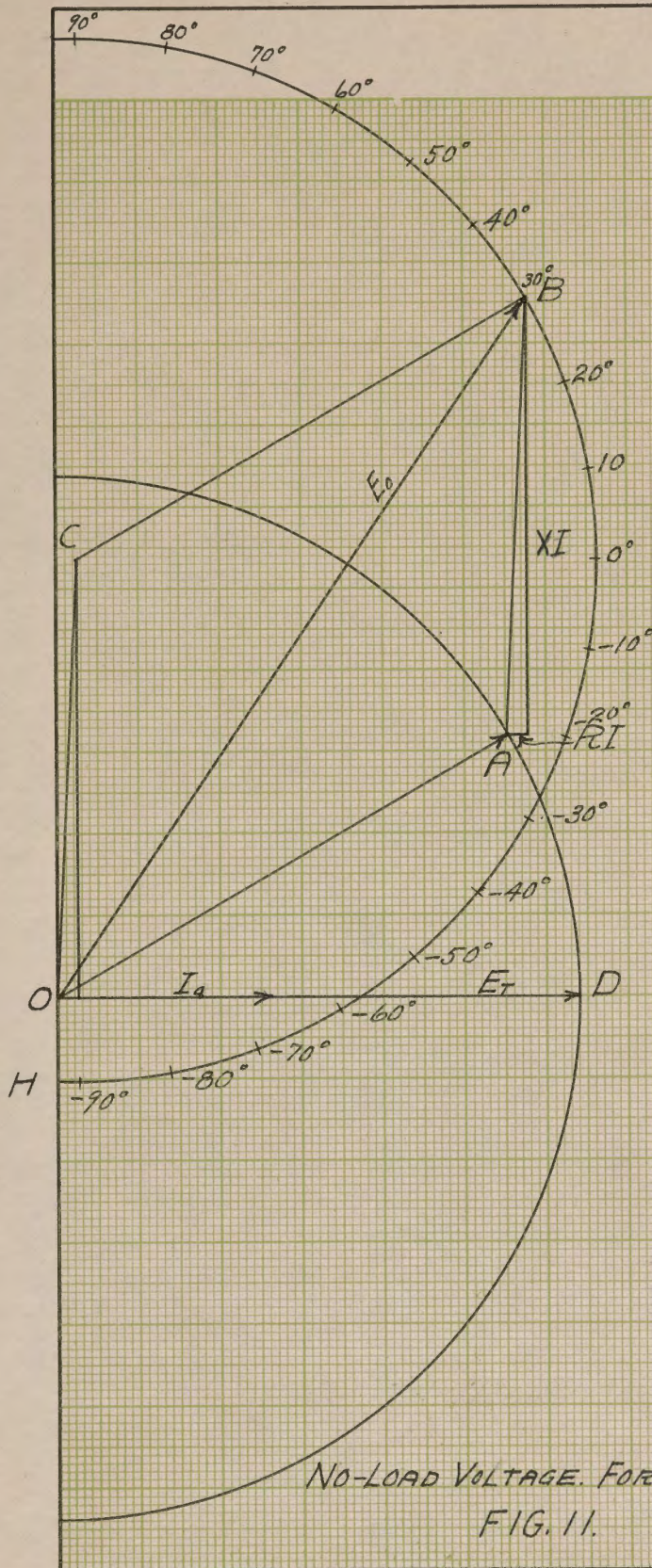
$$I = 10, \quad E_o = 67.8$$

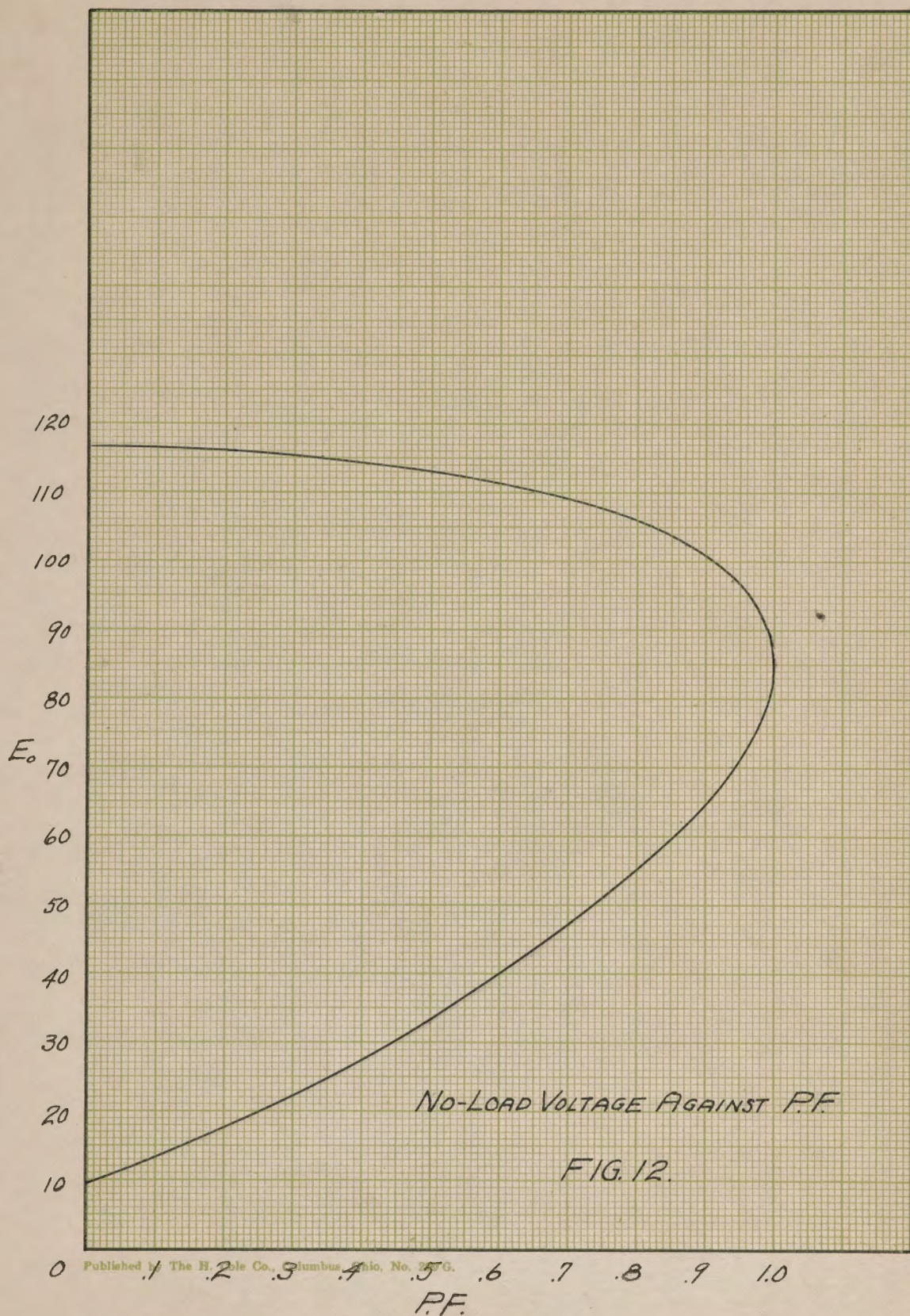
$$I = 15, \quad E_o = 71.8$$

$$I = 20, \quad E_o = 77.5$$

$$I = 26, \quad E_o = 85.3$$

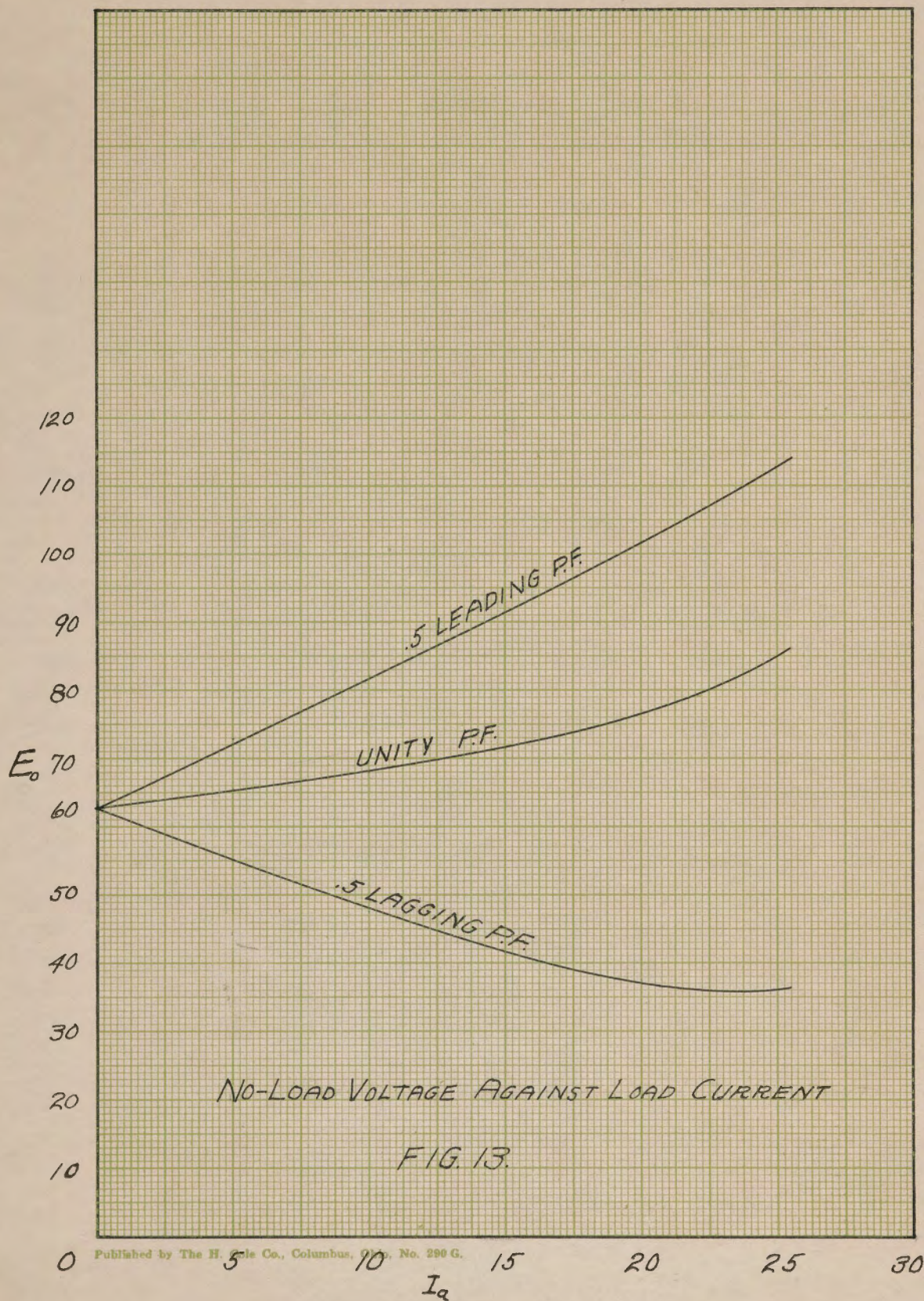
LEADING I		LAGGING I		
θ	E_o	θ	E_o	P.F.
0°	85.0	0°	85.0	1.0000
10	91.5	10	78.0	.9848
20	97.5	20	70.0	.9397
30	102.0	30	62.0	.866
40	107.0	40	53.0	.766
50	110.0	50	43.5	.6428
60	113.0	60	34.0	.5000
70	115.0	70	25.0	.3420
80	116.0	80	16.0	.1736
90	116.5	90	10.0	0.0000





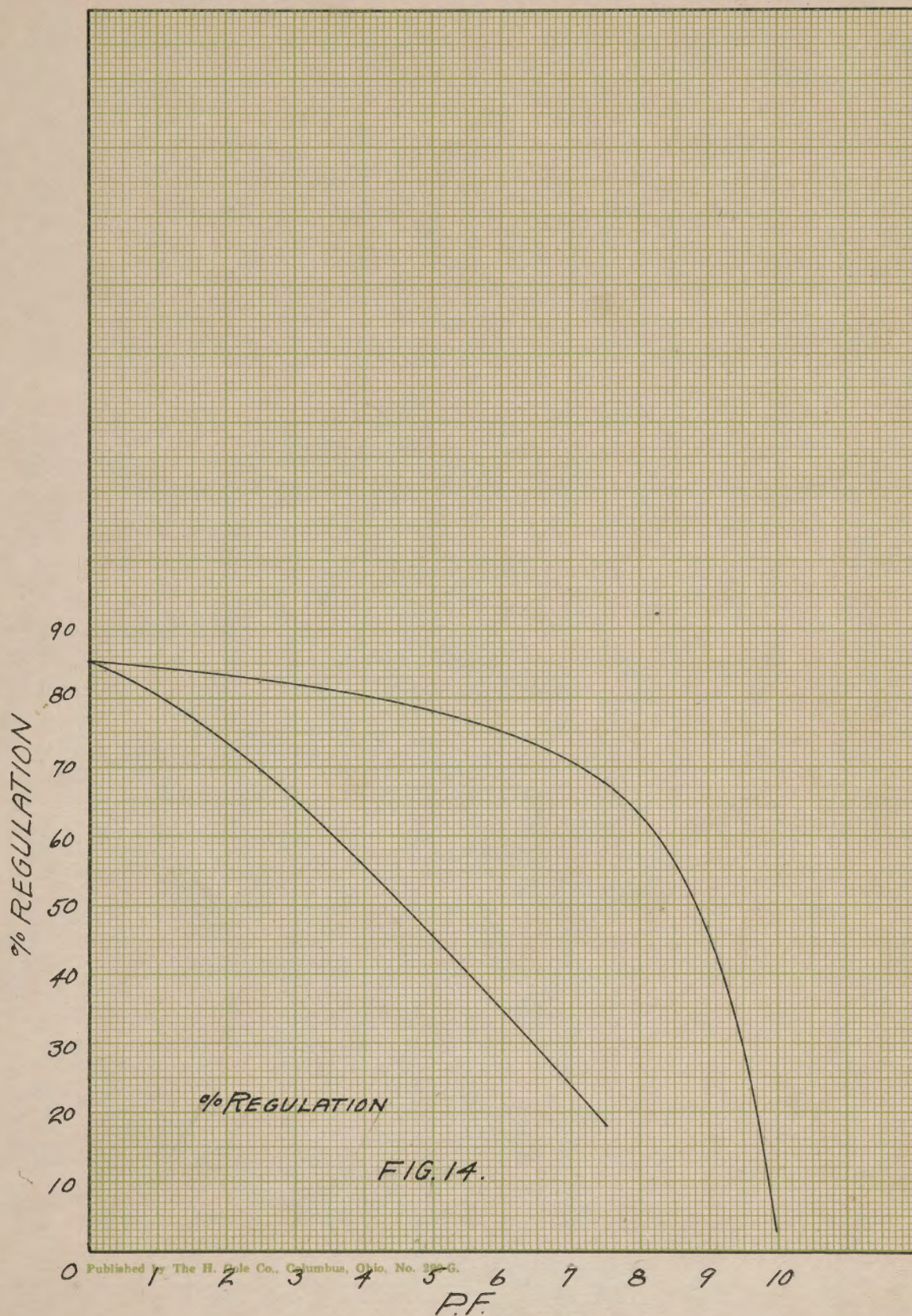
NO-LOAD VOLTAGE AGAINST P.F.

FIG. 12.



NO-LOAD VOLTAGE AGAINST LOAD CURRENT

FIG. 13.



POWER REQUIRED TO RUN THE ALTERNATOR

The alternator is direct connected to a D. C. motor. A certain amount of power is required to run the D. C. motor, but this power is increased due to the load of the alternator. Since the saturation curve was taken for the alternator at no-load it is desired to find the power required to run the alternator at no-load. This power was found by first running the M. G. set at no-load and by use of an ammeter and a voltmeter determine the power, then the two machines were disconnected and the power required to run the motor at no-load was found as above. The difference of the two powers gives the power required to run the alternator.

D A T A

$E_{d.c.}$	$I_{d.c.}$	P_{watts}	P_{2watts}	$P_1 - P_2$ Watts	I_f
112.00	7.50	840		294	5
112.5	4.85		546		5

$$\text{Power} = E I$$

$$P_1 = 112 \times 7.5 = 840$$

$$P_2 = 112.5 \times 4.85 = 546$$

$$P_o = P_1 - P_2 = 840 - 546 = 294 \text{ Watts}$$

BIBLIOGRAPHY

Alternating Current Magnusson

Laboratory Experiments Ricker and Tucker

Testing of Electro Magnetic Machinery Swenson and Frankenfield.

A P P R O V A L.

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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Electrical Engineering