THESIS

ON

Testing a Rotary Converter

Submitted to the Faculty

of the

OREGON AGRICULTURAL COLLEGE.

for the degree of

BACHELOR OF SCIENCE

in

ELECTRICAL ENGINEERING

by

Julius Gordon Wallace Going

June 1, 1910

APPROVED.

Redacted for privacy

Department of Electrical Engineering.

Redacted for privacy

Dean School Engineering.

ROTARY CONVERTER.

The ROTARY CONVERTER or Double Current Generator is a machine for converting alternating current to direct current, or vice versa. The importance that such machines have now assumed in the electrical industry is due to several cuases;

(a) It is necessary, for economic reasons, to use alternating current at high voltages in long-distance transmission. Therefore, rotary converters are required for changing the alternating current into direct current for use in electric railway motors, which must be supplied with direct current from the trolley wire at points at a distance from the power house.

(b) Rotary converters are needed for charging storage batteries in places where the central station supplies, alternating current and inverted rotaries are necessary for factory driving with alternating current motors in cases where direct current only is supplied by central stations.

(c) Direct current is necessary in many chemical and electrometallurgical industries such as electrolytic reduction of aluminum from its ores, electrolytic refining of copper, etc. If alternating current is generated and transmitted to these establishments it must be converted into direct current before it can be utilized.

In general appearance and construction the rotary converter resembles a direct-current generator very closely. The chief outward difference is the addition of a number of collector rings concentric with the shaft on one side of the armature, and the commutator is very much larger than in the ordinary direct-current generator. Another point of difference is in the relative dimensions of the magnetic cores, which are smaller than would be usual or desirable in the ordinary direct-current generator.

Under the usual conditions of running the armature is driven, as in a simple synchronous motor, by alternating current supplied to the collector rings from an external source. While so revolving direct current can be taken from the brushes bearing upon the commutator.

The current in the armature of a rotary converter may be thought of as the difference between the inflowing alternating current and the outflowing direct current. The average value of the current in a given armature conductor is therefore smaller in value than in a corresponding direct-current generator, and the heating effect is correspondingly less. Furthermore the magnetizing action of the inflowing alternating current upon the armature is about completely neutralized by the magnetizing action of the outflowing direct current. Therefore a larger number of smaller conductors may be wound upon a given armature core, if the armature is to be used for a rotary converter, than would be permissible if the armature were to be used for a direct-current generator. That is, the allowable power output of a machine of given size is not limited to so small a value if the machine is to be used as a polyphase rotary converter, as it would be if the machine were to be used as a direct current generator. The machine under test is rated as a 10 K.W. Double Current Generator. If used as a 3 phase rotary convertor its' output would be 1.32 x 10 = 13.2 K.W. For six phase it would be 1.92 x 10 - 19.2 K.W. or nearly double its rated capacity as a direct-current generator.

The names Double Current Generator and Rotary Converter apply to the same machine. The essential difference in operation is, however, that in the former the direct current and alternating current are not in opposition as in the latter, but in the same direction, and the resultant armature polarization is thus the sum of the armature polarization of the direct and alternating currents. Also in the double current generator, since there is no opposition of currents, the heating of the armature due to its resistance depends upon the sum of the two currents; that is, upon the total load on the machine. Hence, the output of the double current generator is limited by the current heating of the armature, and by the field distortion due to armature reaction, in the same way as in a direct current generator or alternator, and is consequently much less than that of a converter. Compared with the direct current generator, the field of the double current generator must be such as to give a much greater stability of voltage, owing to the strong demagnetizing effect which may be exerted by lagging currents on the alternating side, and may cause the machine to lose its excitation all together. For this reason it is frequently preferable to seperately excite double current generators.

The double current generator is a machine driven by mechanical power and producing both direct and alternating currents from the same armature. In some power plants it is frequently advisable to use this type of machine, using the direct current for local lighting and power and the alternating current for outlying districts and also for feeding constant current transformers for arc-lighting circuits. Double current generators can also be used to supply more power into the alternating circuit than is given by their prime mover, by receiving power from the direct current side; This is a great advantage in central stations for in the day time, or during hours of light load, the storage batteries could be charged from the direct current side and this stored energy utilized during the peak load in both direct and alternating systems.

Starting.

The polyphase converter is self-starting from rest. The E.M.F. between the commutator brushes is alternating in starting, with the frequency of slip below synchronism. Thus a direct current voltmeter or incandescent lamps connected across the commutator brushes indicate by their beats, the approach of the converter to synchronism. The field circuit should be opened at starting for if the field were excited the machine voltage would be added to the line voltage at certain instants thus causing excessive rushes of current.

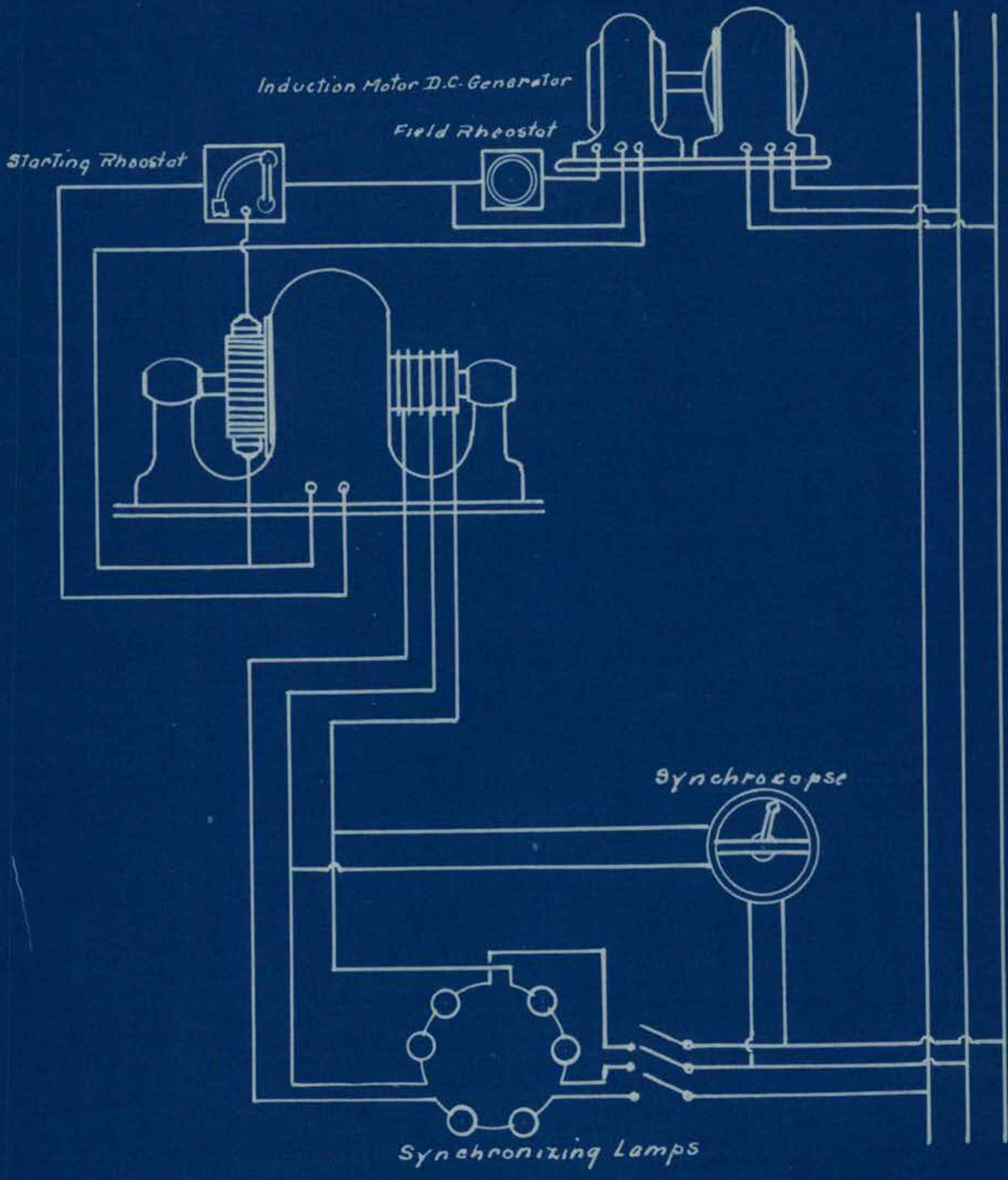
Starting test.

We first started the rotary by inherent induction motor action. This is essentially a hysteresis effect and entirely so in machines with laminated field poles, while in machines with solid magnet poles, induced currents in the latter contribute to the starting torque, but at the same time reduce the magnetic starting flux by their demagnetizing effect. This action is necessarily very weak and the current taken by the 10 K.W. rotary at the starting was 210 amperes the voltage being 35 volts. By using an auto-starter the current drawn from a 110 volt 3 phase line would be $\frac{35}{110} \times 210 = 61.7$ amperes

At the moment of starting, the field circuit of the rotary is in the position of a secondary to the armature circuit as primary; and since in general the number of field turns is very much larger than the number of armature turns, excessive E.M.F's may be induced in the field. In order to determine the voltage across the field terminals at starting, a ten to one potential transformer was connected in the field circuit and a voltmeter across its' secondary. By this method the voltage induced in the field at starting was found to be 10 x 47 = 470 volts. Although this voltage may seem trifling, yet, when one considers larger machines, say those having capacities of 100 K.W. or more, these E.M.F's may reach from 4000 to 6000 volts or more and have to be taken care of by breaking the field circuit into sections.

As synchronism was approached the ammeter needle gradually swung back until it registered but 15 amperes. The field circuit was then closed and the starting switch pulled to the running position. The field excitation was next adjusted to give unity power factor at which the no load current was 7 amperes.

The rotary converter was next started from the direct current side and synchronized with the A.C. supply. The exact point when synchronism was reached was determined by synchronizing lamps and also by the synchroscope. The field of the converter was adjusted to give about the same voltage as the line, also the phase rotation was determined before throwing the machine in parallel with the line. This method serves very well where the d.c.



Synchronizing

voltage is constant but in railway work where there is always more or less fluctuation of load, it is frequently preferable to run the converter up to or beyond synchronism by direct current; then cut off the direct current, open the field, and connect it to the alternating system, thus bringing it into step by alternating current. This method was tried and the rotary was brought into synchronism in much less time than was required by the above method

Ratio of Voltages and Currents.

Since the rotary converter differs from a direct current machine only by the addition of the collector rings, it is obvious that there must exist some relation between the alternating and direct current voltage. In order to get this ratio, we must assume a sine wave which is practically true, due to the multi-tooth distributed winding. Take, first, the single phase converter. The maximum alternating voltage between opposite collector rings is equal to the direct current electro-motive-force E, and since the effective value of the alternating E.M.F. is $E_1 = \frac{E}{\sqrt{2}}$, the ratio of voltages in a single phase converter $E : E :: 1 : \sqrt{2}$.

By tapping the armature winding at three equidistant points it can be shown mathematically and proved experimentally that the ratio of A. C. to d. c voltage is as $\sqrt{3} : 2\sqrt{2}$ or $E_3 = .615\ E$.

For any number of rings, the voltage between two adjacent collector rings can be expressed as follows.

$$E_n = 2\ E,\ \sin \frac{\pi}{n} - \frac{E \sin \frac{\pi}{n}}{\sqrt{2}}$$

Also the value of line current is

$$I_n = \frac{\sqrt{2}\ I}{n \times \sin \frac{\pi}{n}}$$

Where—

I_n = line current in an n phase system.

I = value of direct current.

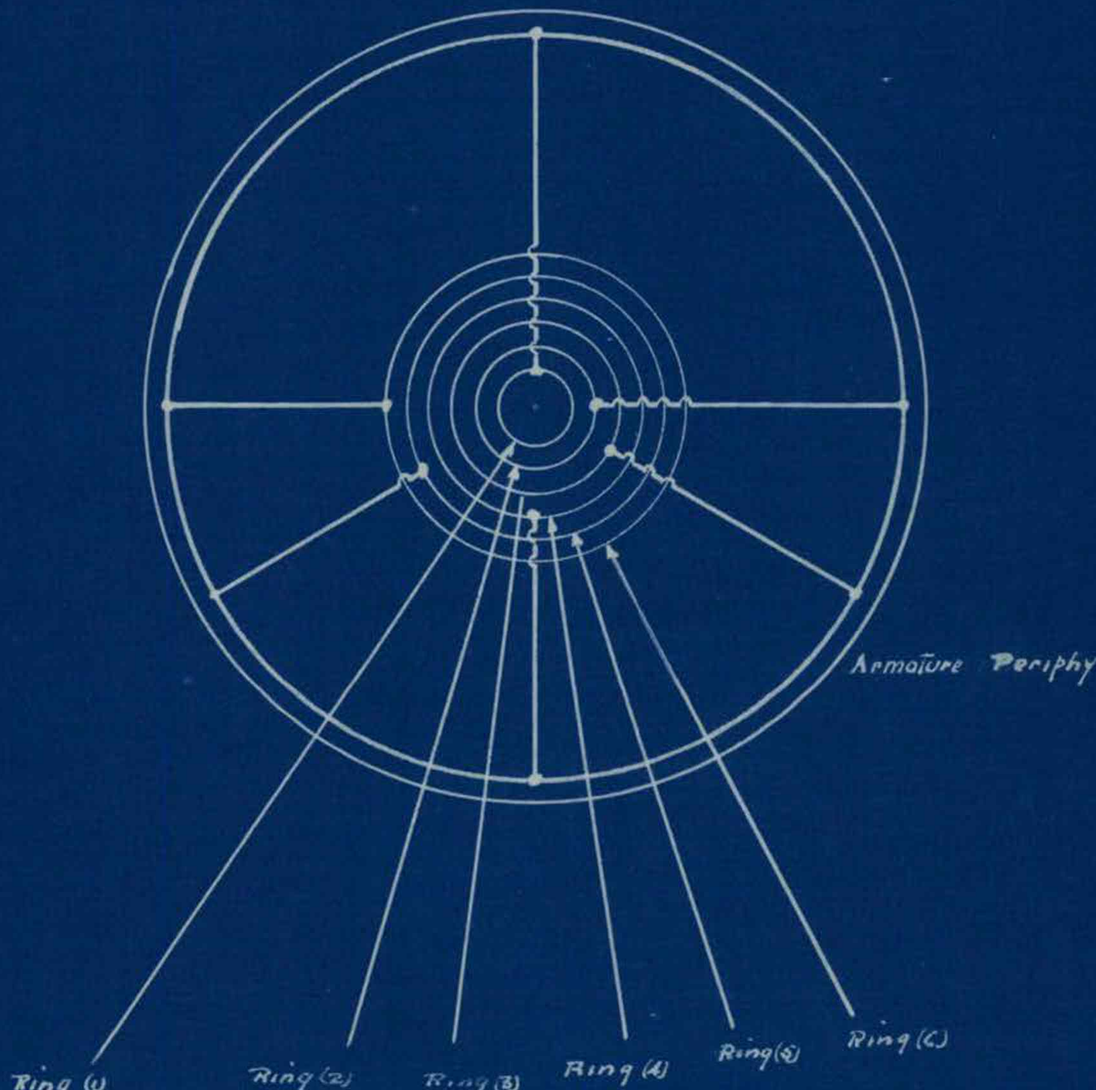
n = number of phases.

Ratio of Voltage Test.

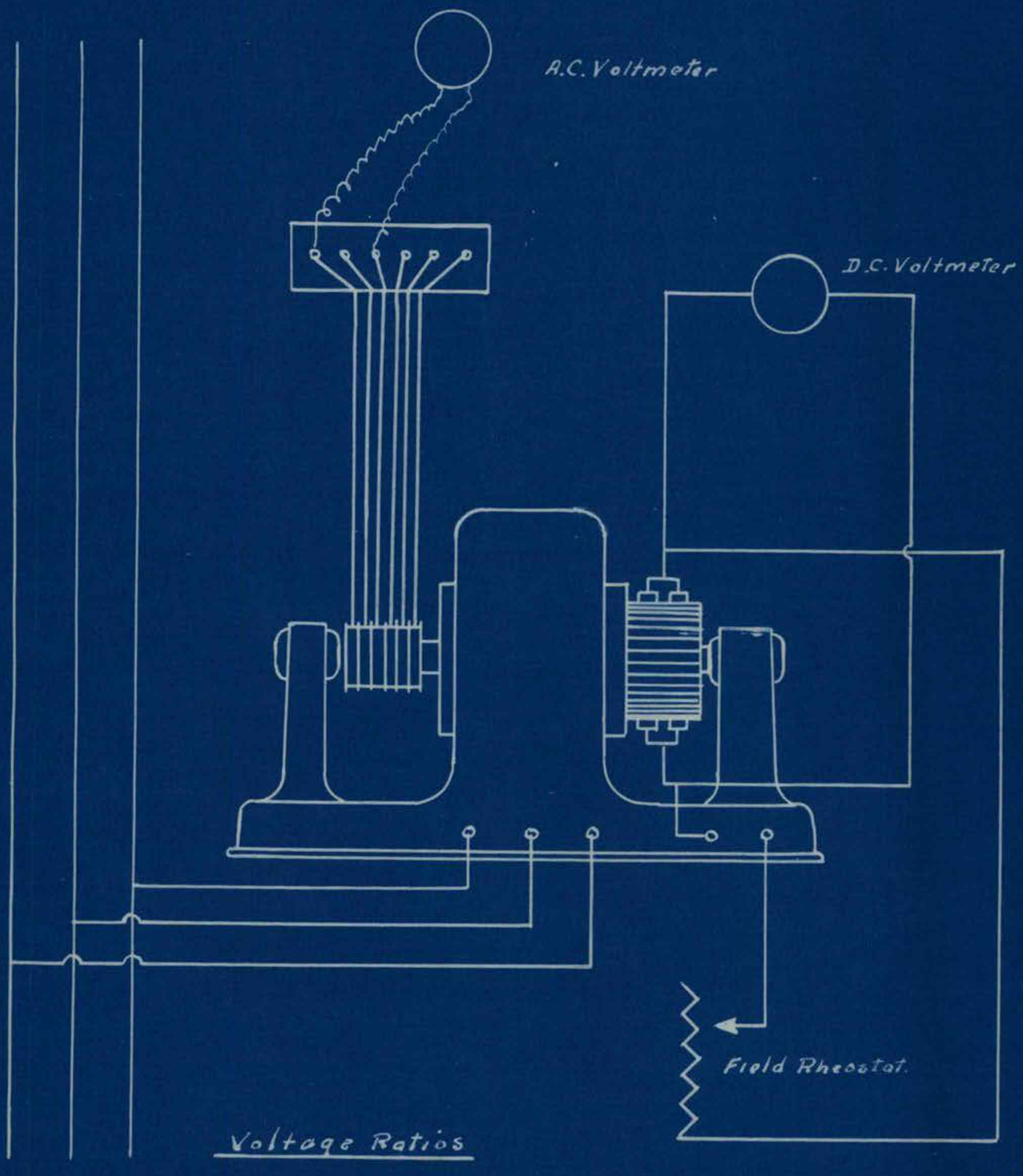
To prove the above theory the ratio of A.C. voltage to D.C. voltage was tested for every possible combination. Since there were six rings on the alternating side $\frac{N(n-1)}{2} = \frac{6(6-1)}{2} = 15$ combinations. Therefore fifteen combination of voltage ratios were taken as given in the following table.

Data obtained in Ratio of Voltage Test.

	Lagging Power Factor		Leading Power Factor		Unity Power Factor		
Rings	DCVolts	ACVolts	DCVolts	ACVolts	DCVolts	ACVolts	Phase
1—2	180	91	200	100	195	97	from 4
1—3	"	109	"	123	"	121	" 3
1—4	"	130	"	143	"	140	" 1
1—5	"	114	"	122	"	120	" 3
1—6	"	39	"	100	"	98	" 4
2--3	"	32	"	37	"	37	" 12
2--4	"	93	"	100	"	98	" 4
2--5	"	126	"	135	"	132	" 2.4
2--6	"	128	"	140	"	137	" 1
3--4	"	65	"	70	"	69	" 6
3--5	"	110	"	121	"	119	" 3
3--6	"	126	"	136	"	132	" 2.4
4--5	"	65	"	71	"	68	" 6
4--6	"	92.5	"	100	"	98	" 4
5--6	"	36	"	137	"	37	" 12



Connections of Slip Rings to Armature Periphy



Voltage Ratios

The readings were taken with unity power factor and also with leading and lagging currents. As shown by the data the variation of power factor had no effect on the ratio of voltage. However the compounding effect was quite evident with leading currents. This experiment shows that the ratio of voltages in a rotary converter is approximately constant for all conditions. The shape of the alternating current wave may vary to some extent this ratio but there was no apparatus on hand to investigate this phenomena.

Saturation Curves.

The saturation curve or excitation characteristic is the curve giving the induced voltage (terminal voltage at open circuit) at normal speed as a function of the amperes in field winding. These curves are of the same general shape as the magnetic induction curves with the exception that the knee is not so sharp, due to the different parts of the magnetic circuit reaching saturation successively. These curves are valuable because they give directly the value of field current necessary to induce any given voltage. Thus if a machine needs a compound winding we must look to this curve to find the number of additional ampere-turns to be wound on. Direct current generators are usually operated at a point of the saturation curve above the bend, that is, at a point where the terminal voltage increases considerably less than proportionally to the field excitation. This is necessary in direct current generators (self exciting) to secure stability of voltage.

Test for excitation characteristic.

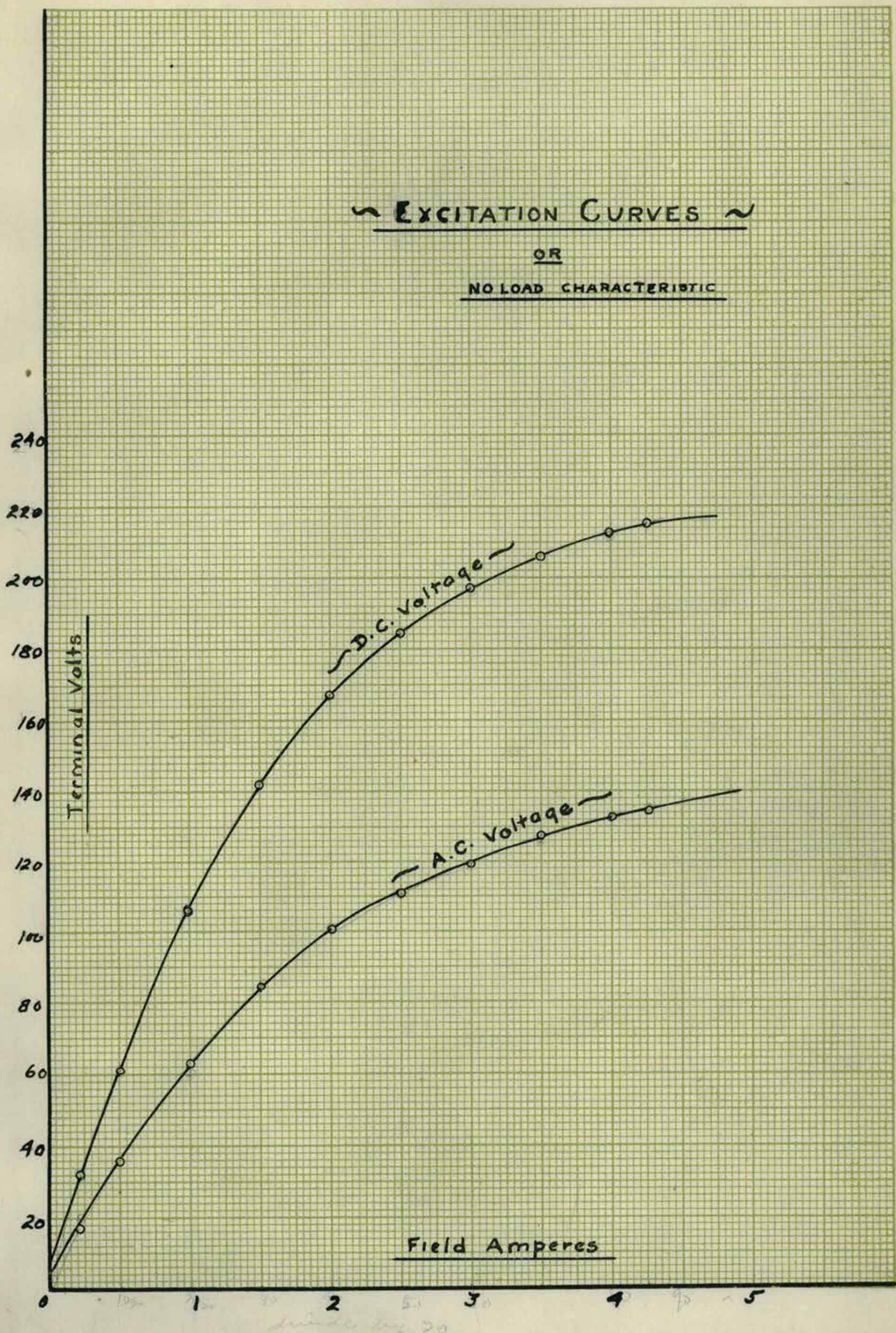
The machine was belted to a direct current motor, the speed of which could be adjusted by varying it's field strength and also the applied voltage. The Rotary was run at an approximately constant speed of 1800 R.p.m. and readings of voltage taken on both A.C. and D.C. sides for various values of field current. From the data obtained, saturation curves were plotted for both A.C. and D.C. sides, field amperes being taken as abscissae and volts as ordinates.

Load Characteristic.

The curve giving terminal volts as function of current output is called the load characteristic. It is important to know the variation of voltage in a rotary converter as well as in the direct current generator. By taking into account the drop on the line side of the rotary any change in the ratio of voltages with varying load may be determined.

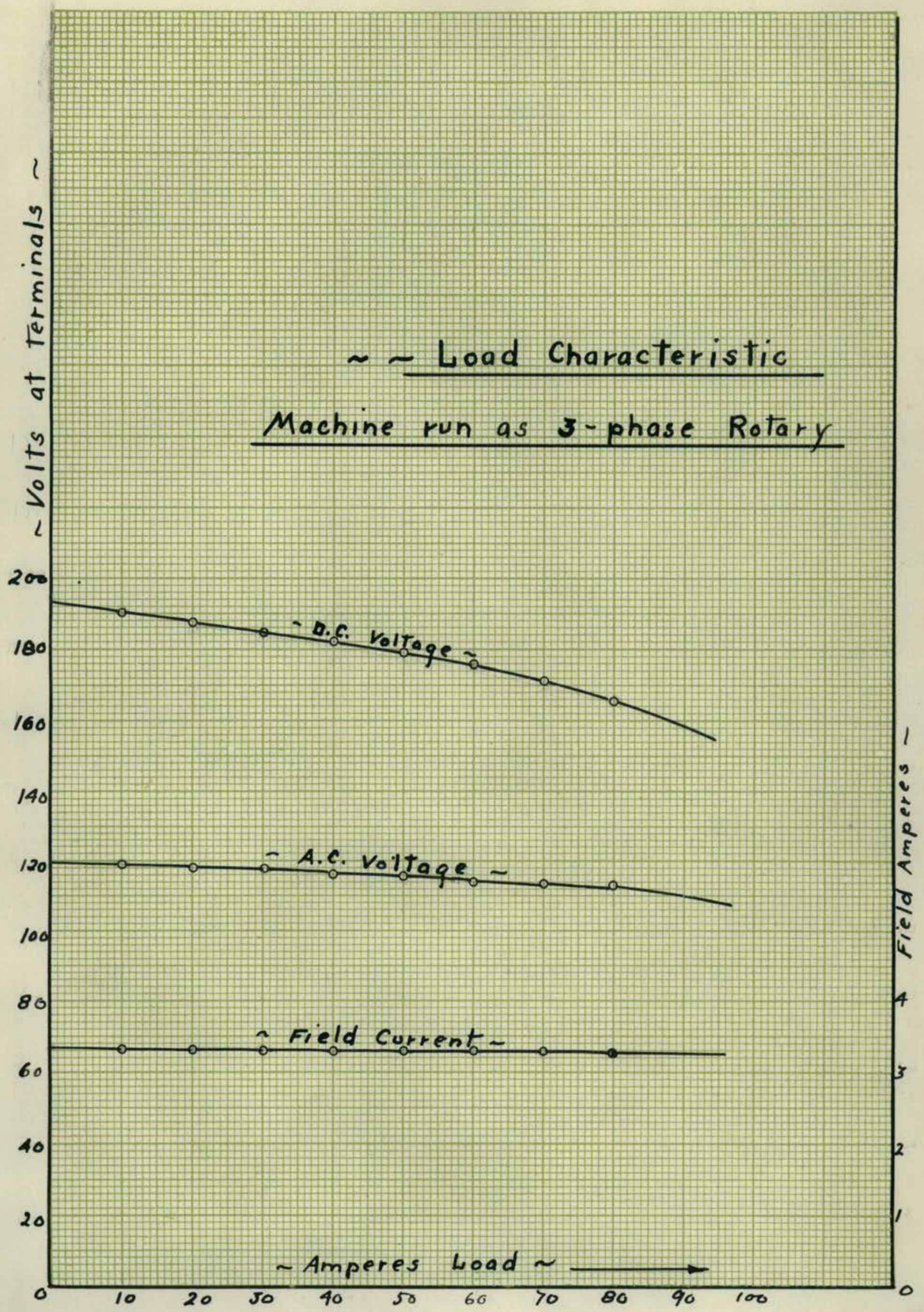
Test for Load Characteristic.

The machine was run as a three phase rotary and loaded on a waterbox. The applied A.C. voltage at no load was about 120 volts thus giving a voltage across the brushes of 120 ÷ .612 = 197 volts. First adjusted the field


~ EXCITATION CURVES ~
OR
NO LOAD CHARACTERISTIC
~D.C. Voltage~
~A.C. Voltage~
Terminal Volts
Field Amperes
240
220
200
180
160
140
120
100
80
60
40
20
0
1
2
3
4
5

Data obtained for No-load Characteristic.

A. C. Volts 3 phase	D. C. Volts.	Field amperes.
20	33	.2
37	61	.5
60	106	1
86.5	142.5	1.5
101.5	167	2
110.5	184.5	2.5
119	197	3
125	206	3.5
133	221	4
135	226.5	4.25


~ ~ Load Characteristic
Machine run as 3-phase Rotary
~ Volts at Terminals ~
~ D.C. Voltage ~
~ A.C. Voltage ~
~ Field Current ~
Field Amperes ~
~ Amperes Load ~
200
180
160
140
120
100
80
60
40
20
0
10
20
30
40
50
60
70
80
90
100
4
3
2
1
0

Data for Load-Characteristic.

Volts.		Amps.	
A. C.	D. C.	Field.	Load (d.c.)
120	194.5	3.28	0
119	191	3.2	10
118	185	3.15	20
117	183	3.05	30
116	177	2.98	40
114.5	176	2.92	50
114	175	2.88	60
113.5	169	2.82	70
113	166	2.77	80

excitation to give unity power factor at no load. The load was then varied by steps of 10 amperes readings being taken, at each step, of voltage applied to rings, voltage across brushes, amperes in field and amperes of load. Curves were d.c. voltage and field amperes as ordinates against load amperes as abscissae. In this plot, the curves of A.C. voltage and D.C voltage should be at a constant distance from each other and any variation therefrom would indicate a change in the ratio of voltage of the converter.

V Curves or Phase Characteristics of Synchronous Motor.

By varying the field excitation of the synchronous motor the current can be made lagging of leading at will, and the synchronous motor thus offers the simplest means of producing out of phase or wattless currents for controlling the voltage in transmission lines, compensating for wattless currents of induction motors, etc. Synchronous machines used merely for supplying wattless currents that is, synchronous motors or generators running light, with over-excited or under-excited field, are called compensators or "rotary condensers".

V - curves, or phase characteristics of the synchronous motor, are curves which show the relation existing between the armature current and field current at constant load and constant applied E.M.F. on such a curve there is a certain field excitation which gives minimum current, a lesser excitation gives lagging current, a greater excitation leading current. The higher the synchronous reactance of the armature, the flatter are the phase characteristics; that is, the less sensitive is the synchronous motor for a change of field excitation or of impressed E.M.F.

Test for V - curves.

The machine was run as a simple phase synchronous motor. Two rheostats were connected in series with field circuit to permit of wide variation in field excitation. A power factor meter was also connected in to show the effect of variable field excitation. The first readings were taken with motor running light. The machine would not take a leading current, running light, on account of severe hunting action. Therefore readings for lagging current, only, were taken and in plotting the V - curve for this load, it was assumed that the curve was symetrical. The rotary was next belted to a D.C. generator in order to obtain V - curves under load. As the converter would not start up under load from the A.C. side, we used a double throw switch, as shown in the diagram, bringing the machine above synchronism and then throwing it onto the line with field unexcited. When the ammeter reading showed that the motor was in step with the supply mains, the field switch was closed and the double throw switch

Data for V - curves.

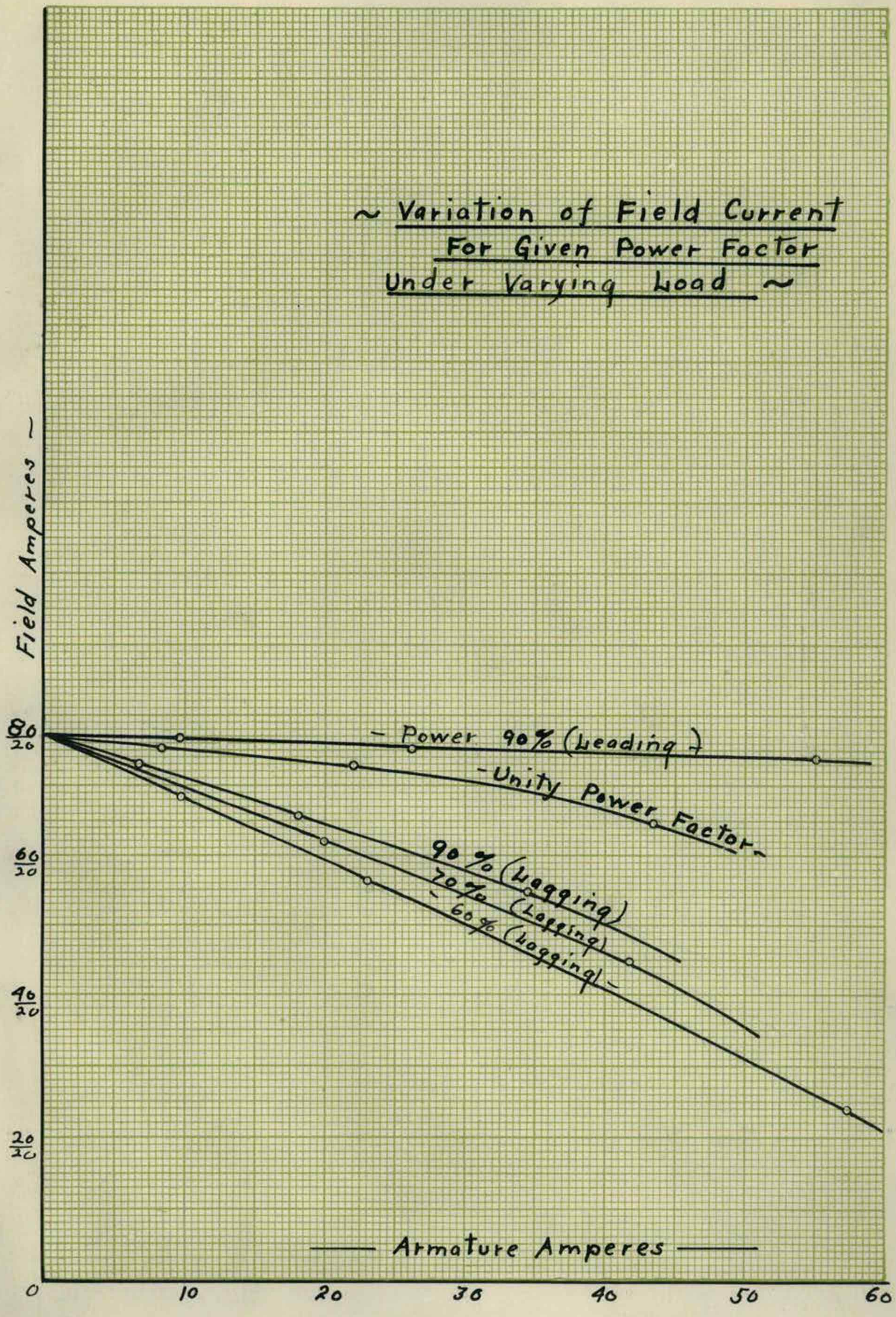
Armature Amps.	Field Amps.	% Power Factor.
	— Unloaded —	
7	3.65	100
40	2.35	30 lag
27	2.75	40 "
Running Generator Unexcited.		
18	3.27	100
57.5	1.7	35
48	2	37.5
36.8	2.35	45
27.5	2.75	60
22.5	2.85	75
20	3.1	90
18	3.25	100
22.5	3.5	-90
27	3.75	-78
37.5	4	-60
47.5	4.5	-75
56	5	-37

Continued Data for V - Curves.

Running Generator Excited.

Armature Amps.	Field Amps.	Power Factor.
90	.9	60
61	1.55	70
49	1.95	80
42	2.25	90
34.8	2.75	100
44.4	3.25	-90
54	3.7	-75
63	3.9	-65
84	4.6	-50


~ V- Curves for ~
Machine Run as Single Phase
Synchronous Motor
Armature Amperes.
Field Amperes →
Heavy Load
Unity Power Factor
Light Load
Machine Unloaded
60
50
40
30
20
10
0
1
2
3
4
5


~ Variation of Field Current
For Given Power Factor
Under Varying Load ~
Field Amperes
Armature Amperes
- Power 90% (Leading)
- Unity Power Factor
90% (Lagging)
70% (Lagging)
60% (Lagging)
80/20
60/20
40/20
20/20
0
10
20
30
40
50
60

on the D.C. generator was thrown to the water box side. Readings were taken of armature amperes, field amperes and power factor with D.C. machine unexcited, and the same readings repeated with heavier load namely with field excited. We tried to load generator on water box but the load current was so great that the range of wattless currents was limited to a very small value. However three curves are sufficient for the purpose in mind.

Efficiency.

In this machine, efficiency may be determined for quite a few combinations, viz:- as a single phase rotary as a three phase rotary, as a direct or alternating current motor or as a direct or alternating generator. It is obvious that the machine will have its highest efficiency when operated as a three phase rotary converter for, in this case, the direct and alternating currents neutralize each other and, for any given output the corresponding I^2R loss in the armature will be smaller than when operated by any of the other methods.

Regarding efficiency, it is interesting to compare the converter with the synchronous-motor-generator set. The efficiency of the stationary transformer of large sizes varies from 97% to 98% with an average of 97.5%. That of the converter or synchronous motor varies between 90% and 94%, with 93% as average, and that of the direct generator between 90% and 94% with 92% as average. Thus the converter with its stepdown transformers will give an average efficiency of 90.7%, a direct current generator driven by synchronous motor with step-down transformers an efficiency of 83.4%, without step-down transformers an efficiency of 85.6%. Hence the converter is more efficient.

Efficiency from Losses.

The efficiency of electrical machines is usually so high that a direct determination by measuring the mechanical power and the electric power is less reliable than the method of adding losses, and the latter is therefore commonly used.

The losses consist of;

1. Resistance loss in armature.
2. Resistance loss in field.
3. Hysteresis and eddy current loss in magnetic circuit.
4. Friction and windage loss.
5. Eddy currents or hysteresis due to the current flowing in the armature under load.

In determining the efficiency from losses, it is necessary to determine the stray power loss. This term includes all losses which cannot be satisfactorily calculated from simple data. These losses are —

(1) Eddy current and hysteresis losses, chiefly in the

armature core, due to the reversals of magnetization as the armature rotates.

(2) Air friction loss, or windage, as it is called, due to the fun-like action of the rotating of the rotating armature.

(3) Friction losses in bearings and at brushes.

These losses cannot be separately measured with accuracy. The stray power loss which is the sum of these losses can, however, be quite accurately determined for a given machine by an experiment test. When this loss has been determined for a given speed and a given voltage, it is easy to calculate the true efficiency of the dynamo for a specified output of power at a given speed and voltage, the resistance of the various windings being known. This calculation is based on the equation

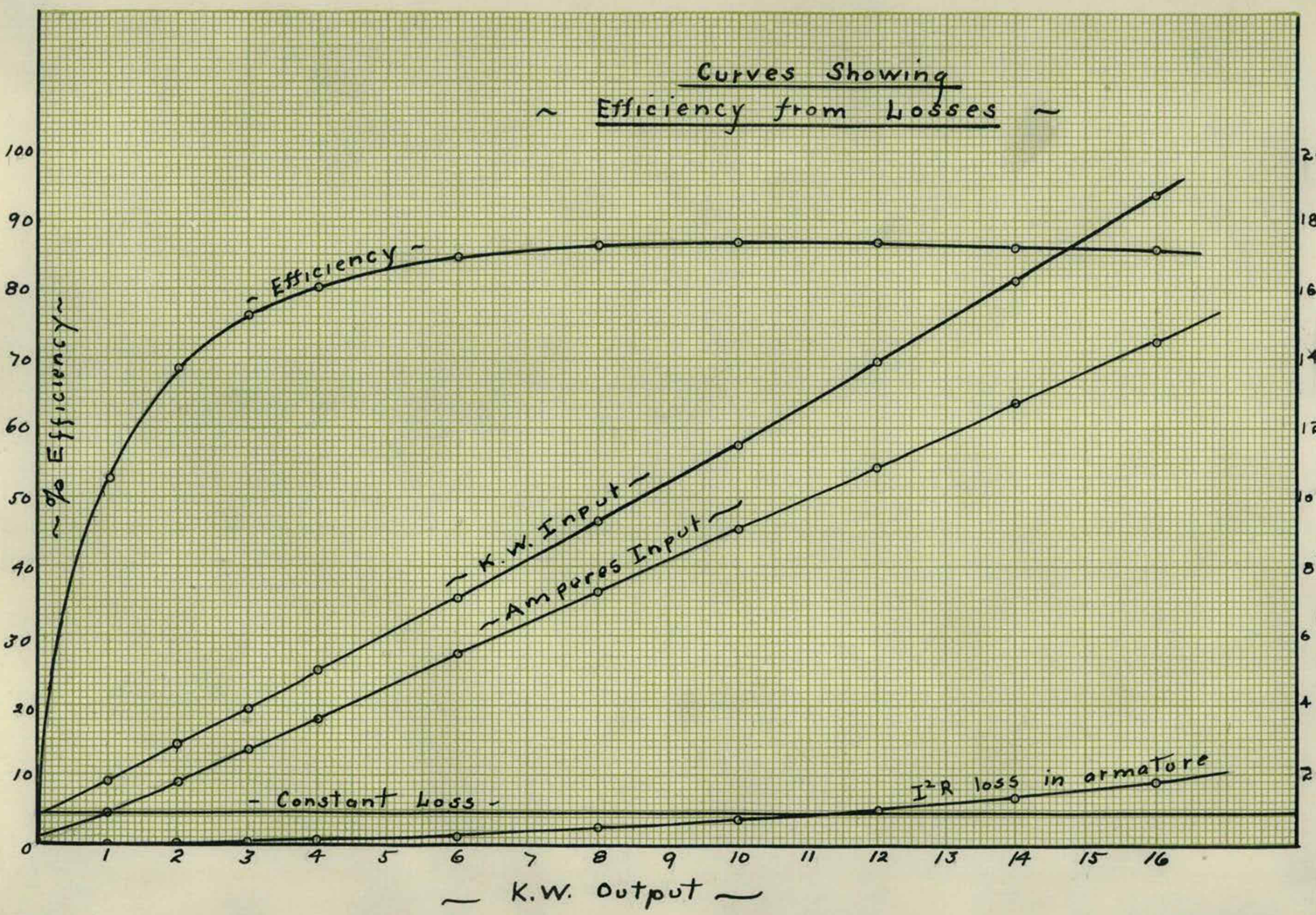
$$\text{Efficiency} = \frac{\text{Power Output}}{\text{Power output - losses}}.$$

Test to determine Efficiency from Losses.

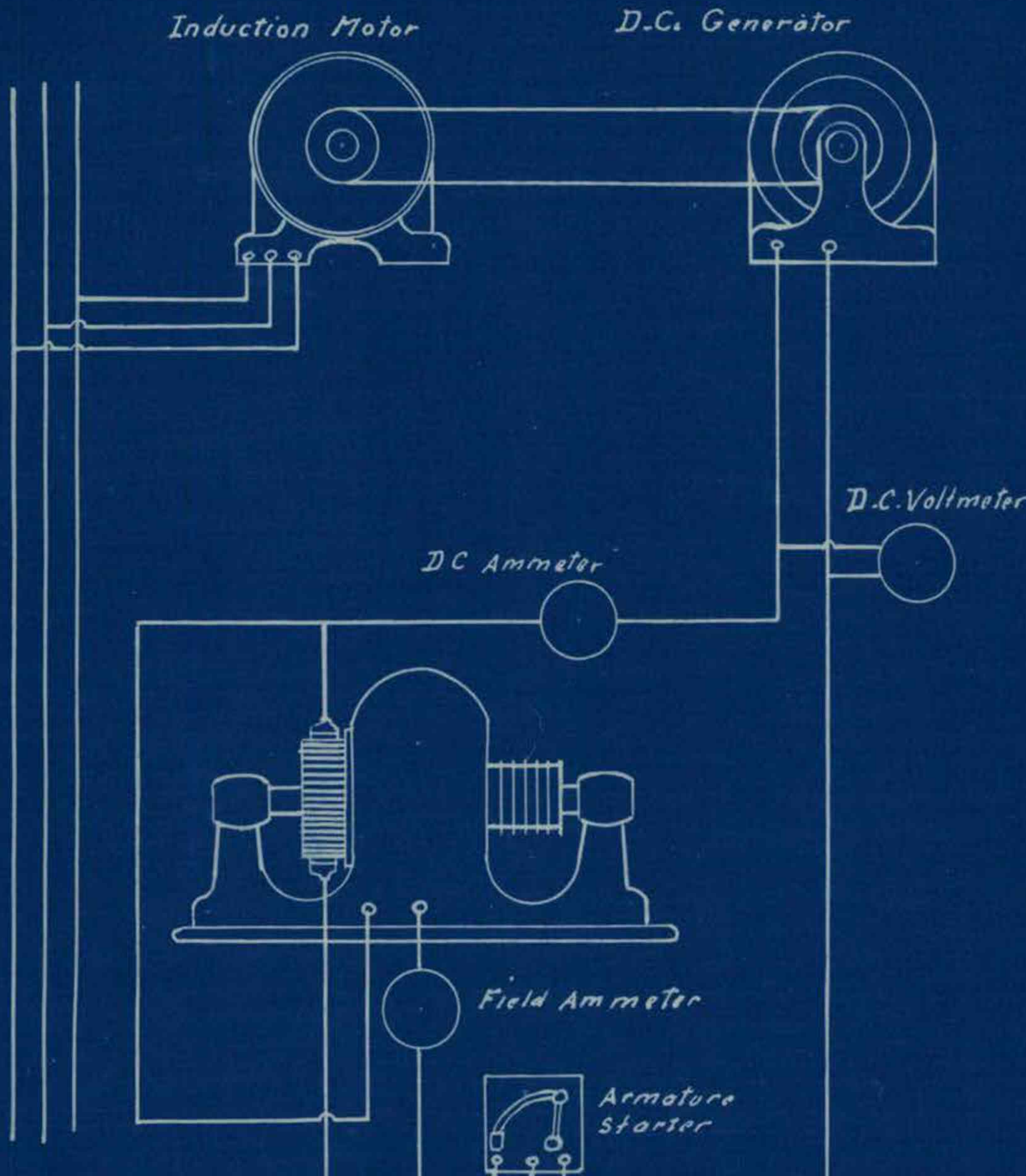
We first determined the stray power loss at several different speeds with constant field excitation. In order to do this the rotary was run as a direct current motor and the input noted for each speed. This power exceeds the stray power loss S by a very saml1 amount, which for all practical purposes, may be neglected. Next measured the armature resistnnce by drop of potential method. The efficiency and losses were plotted as ordinates to power output as abscissae. The following calculation show the

Data for Stray Power Loss.

Volts	Arm. Amps.	Field Amps.	Speed
110	7	1	1800
110	7	constant	1800
120	6.75	"	1950
130	6.5	"	2000
110	7	"	1800
100	6.75	"	1700
90	6.5	"	1620



Curves Showing
~ Efficiency from Losses ~
~ % Efficiency ~
~ K.W. Input ~ Amperes
~ Efficiency ~
~ K.W. Input ~
~ Amperes Input ~
- Constant Loss -
I^2R loss in armature
~ K.W. Output ~
0
10
20
30
40
50
60
70
80
90
100
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
2
4
6
8
10
12
14
16
18
20



Efficiency from Losses

method adopted for finding the efficiency at any output. Take say, full load or 10 K.W. output -

Res. of Armature = .085 ohm.

(a) Armature current at this output = 10,000 ÷ 110 = 91 Amperes.

(B) Armature loss = 91^2 x .085 = 705 watts.

(c) Field loss = EI = 110 x 1 = 110 watts.

(d) Stray power loss = 770 watts.

Total loss at 10 K.W. output = 1585 watts.

$$\text{Efficiency} = \frac{10,000}{10,000 - 1585} = 86.5\%$$

Efficiency as Single Phase.

Rotary Converter.

In this experiment we åndeavored to obtain the efficiency of the machine operating as a single phase converter, that is, the amount of power which must be sacrificed in order to transform alternating current into direct current. First brought the machine up to speed three phase. Loaded the direct current side on a water-box through an ammeter. The rotary would not run constantly single phase on account of severe hunting action and consequently pulling out of step in short time. Therefore we ran the machine three phase and, after adjusting the load to the desired value, pulled out one phase taking quick readings of watts input, amperes output, volts across brushes and amperes in field. These readings were repeated for several different direct current loads. The efficiency was determined as the ratio

Data for Efficiency Curve.

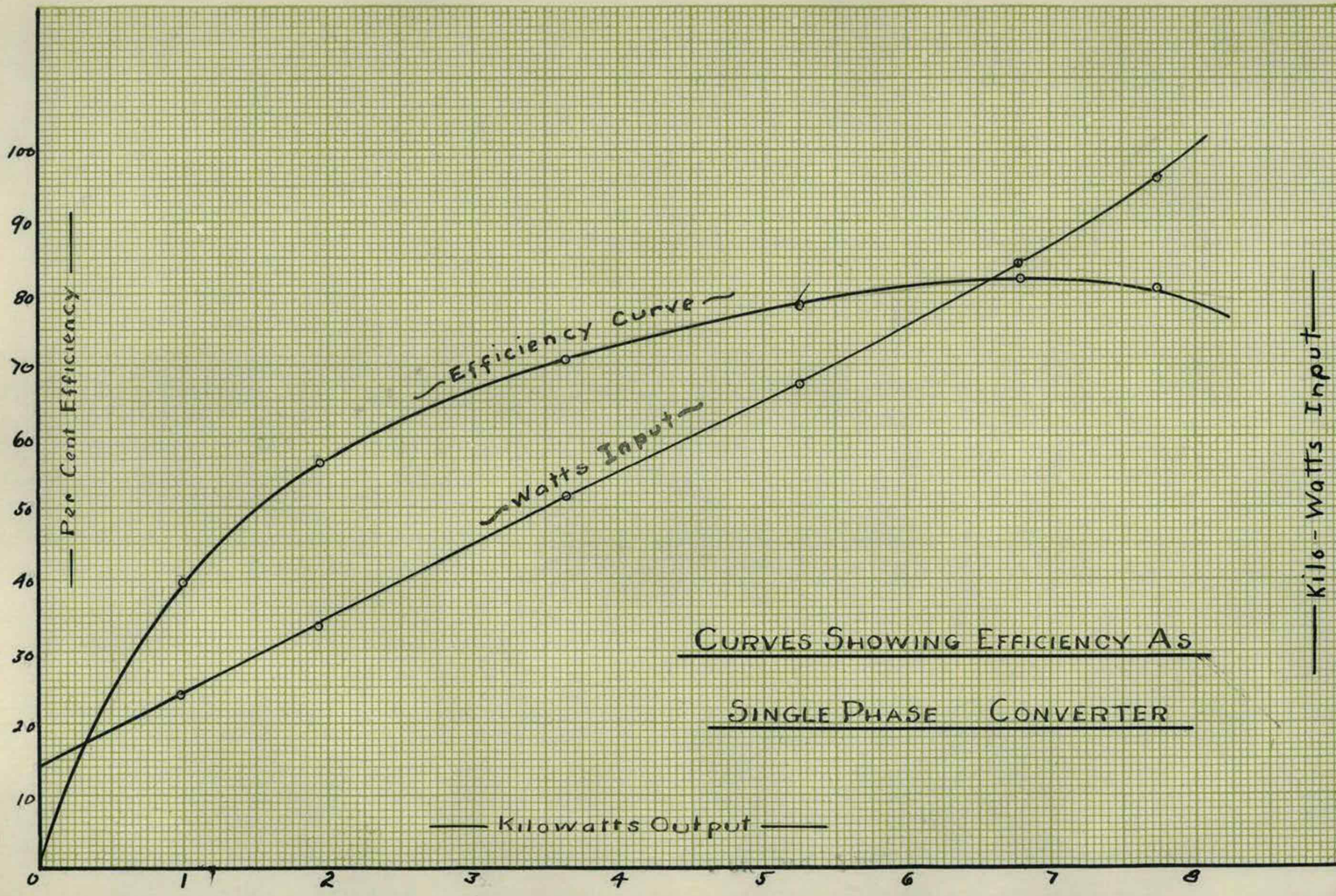
Output Watts.	Current Amps.	I^2R loss	Constant loss	input	% Efficiency
1000	9.1	7.05	880	1887	53
2000	18.2	28	"	2908	68.7
3000	27.2	63	"	3943	76
4000	36.2	112	"	4992	80.2
6000	54.5	252	"	7132	84.2
8000	72.75	450	"	9330	85.8
10000	91	705	"	11585	86.5
12000	109	1010	"	13890	86.5
14000	127	1380	"	16260	86.2
16000	145.5	1800	"	18680	85.75

Data for Efficiency as Single Phase Rotary.

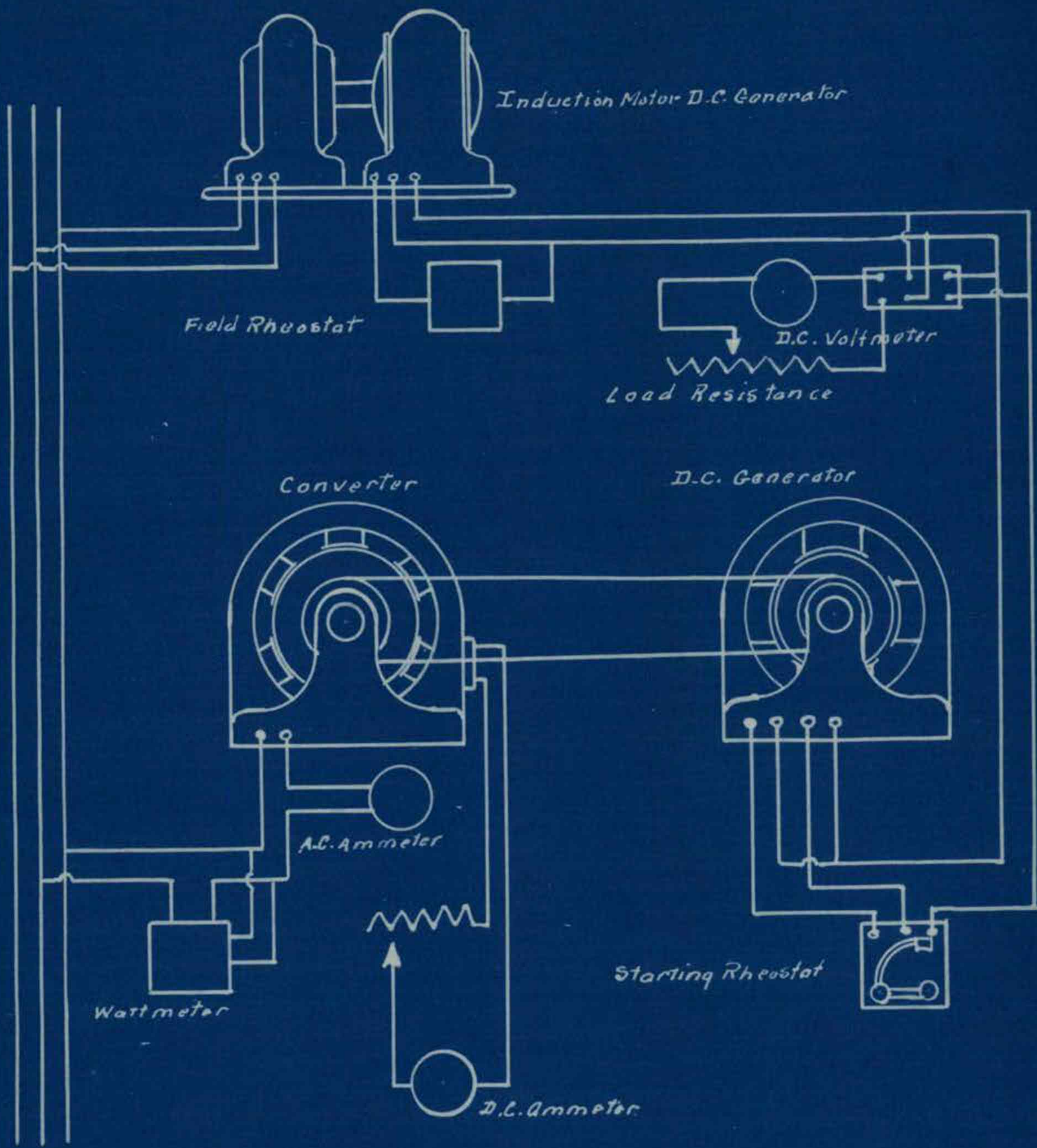
D. C. Volts	Load (d.c.) Amps.	Field Amps	A. C. Watts.
194	5	3.3	2400
192	10	3.25	3360
182	20	3.2	5160
175	30	3.1	6720
170	40	3.05	8400
165	47	3	9600

Data for Efficiency Curve.

Output.	Input	% Efficiency.
970	2400	40.4
1920	3360	57
3640	5160	70.5
5250	6720	78.25
6800	8400	82
7750	9600	80.75



Curves Showing Efficiency As
Single Phase Converter
Efficiency Curve
Watts Input
Per Cent Efficiency
Kilo-Watts Input
Kilowatts Output
100
90
80
70
60
50
40
30
20
10
0
1
2
3
4
5
6
7
8



Efficiency from Loads for Single Phase

of direct current output to alternating current input. The following calculation shows the method of finding efficiency at any output — Take the point where the water-box load was 47 amperes Then —

Output = 47 x 165 = 7,750 watts.

Input = 9,600

Efficiency = $\frac{7750}{9600}$ = 81%.

This efficiency is rather low due to the fact that the machine was run above normal voltage, D.C. E.M.F. being in the neighborhood of 200 volts which necessitated a large field current to give unity power. Also the excess direct current voltage had to be absorbed by a field rheastat and the loss in this could hardly be charged to the machine.

Efficiency as Three Phase.

Rotary Converter.

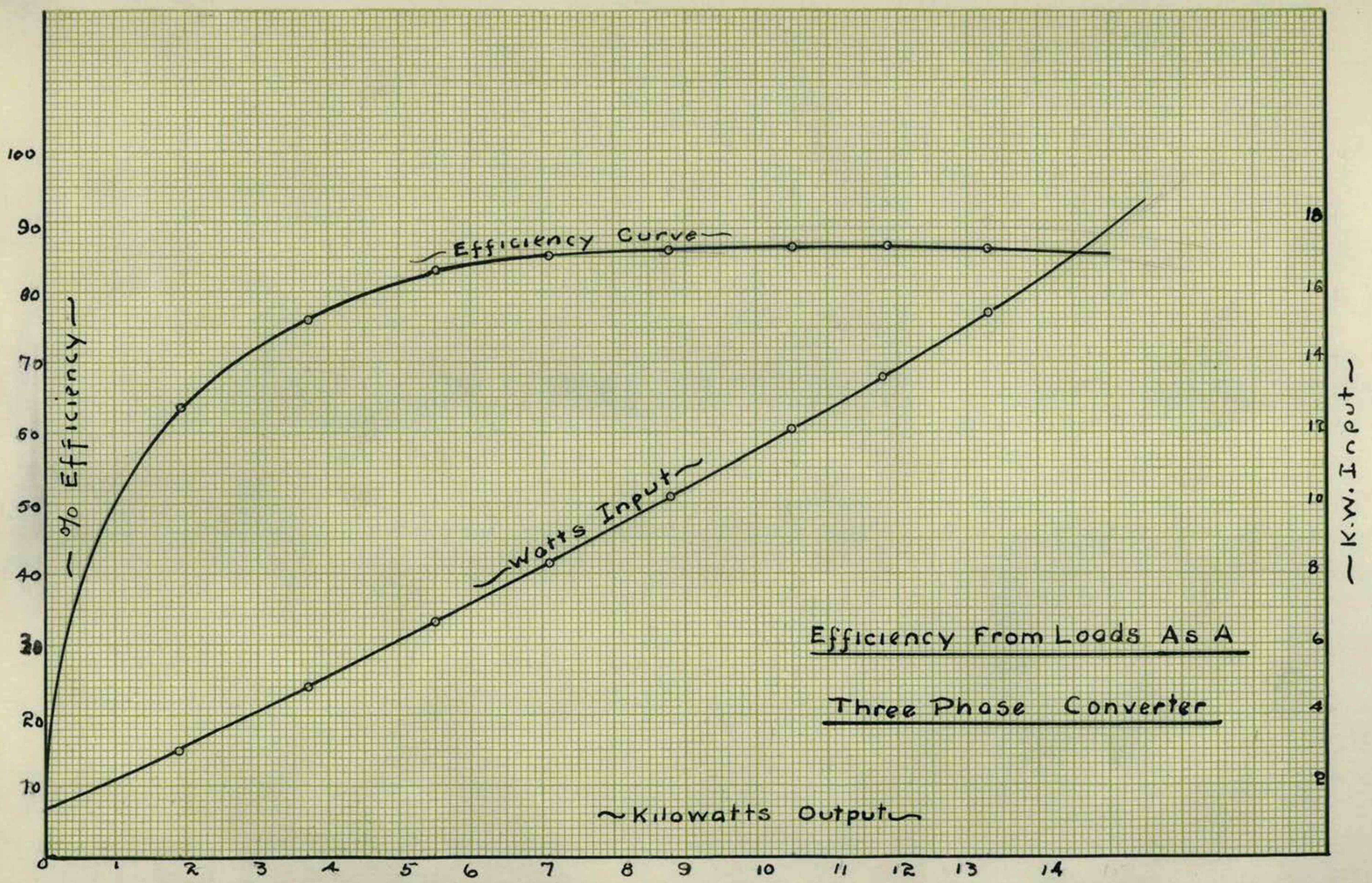
This experiment, although similar in principle to the last, was taken to show that the three phase converter is more efficient than the same machine operated single phase. The machine was run three phase, power being measured on the alternating current side by means of wattmeter in connection with a polyphase board and on the direct current side by a voltmeter and ammeter. The amperes output on the direct current side were varied by means of a water box. The total alternating current input was found by taking the algebraic sum of the two wattmeter readings. The output in watts of direct current was calculated as the

Data for Efficiency 3 - Phase.

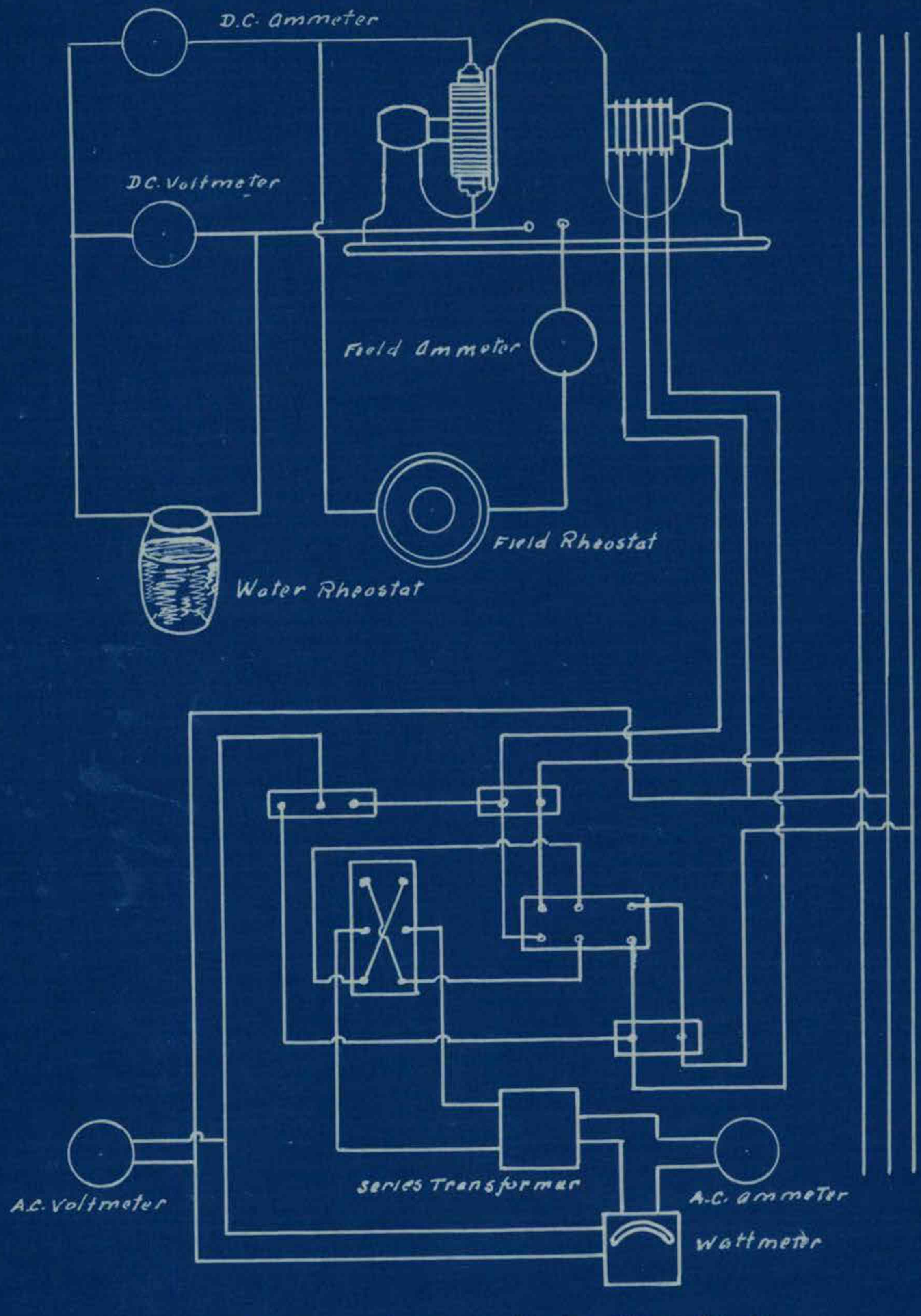
D. C.			A. C.		
Volts	Lead Amps	Field Amps	Volts	Watts ÷ 12 Phase A.	Phase B.
194.5	0	3.28	120	50	55
191	10	3.2	119	120	130
185	20	3.15	118	175	230
183	30	3.05	117	230	320
177	40	2.98	116	300	395
176	50	2.92	114.5	370	480
175	60	2.88	114	408	600
169	70	2.82	113.5	483	650
166	80	2.77	113	533	750

Data for Construction of Efficiency Curve.

Output	Input	% Efficiency
0	1260	0
1910	3000	63.7
3700	4860	76.2
5490	6600	83.3
7080	8340	85
8800	10200	86.25
10500	12100	86.25
11830	13600	87.2
13280	15400	86.25



Efficiency Curve
Watts Input
% Efficiency
K.W. Input
Kilowatts Output
Efficiency From Loads As A
Three Phase Converter
100
90
80
70
60
50
40
30
20
10
18
16
14
12
10
8
6
4
2
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14



Efficiency from Loads for Three Phase

product of volts and amperes. The efficiency curves were drawn as before, each point being calculated from the relation.

$$\text{Efficiency} = \frac{\text{D.C. output}}{\text{A.C. input}}$$

In the above tests it is seen that rotary converter is more efficient than converting by motor generator action, that the regulation is more constant and that is has greater capacity for overload. Also that a greater range of voltages are possible than with a motor generator set on account of the different combinations with which the armature periphy may be connected. It differs from the shunt motor in that the voltage can be varied only about 5% by manipulation of the field, but this variation of the field current changes the power factor, however.

In summing up the conclusions derived from each experiment the writers feel that there is a good reason for the existance of the converter.

The End.