REWINDING AND TESTING A 15 H.P. D.C. MOTOR

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1906

REWINDING AND TESTING A 15 HP D.C.MOTOR.

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Introduction.

In treating this subject we shall not confine our discussions to the particular motor tested. We shall give a general discussion of the Direct Current motor under the heads of theory, and development. Under tests we shall discuss the particular motor under consideration. The greater part of our work does not appear in writing but in the motor which is operating successfully in the dynamo laboratory.

Although the subject may appear as elementary, it is of the greatest importance. Notwithstanding the growing popularity of the induction motor the time is far distant when it will replace the direct current motor. In fact, the qualities of direct current make it possible to accomplish results with it that can never be hoped for in the A.C. motor.

Yet in the present state of perfection of the D.C. motor, there are still desired improvements. Its efficiency at best is low and a simpler method of variation of speed would satisfy a long felt want.

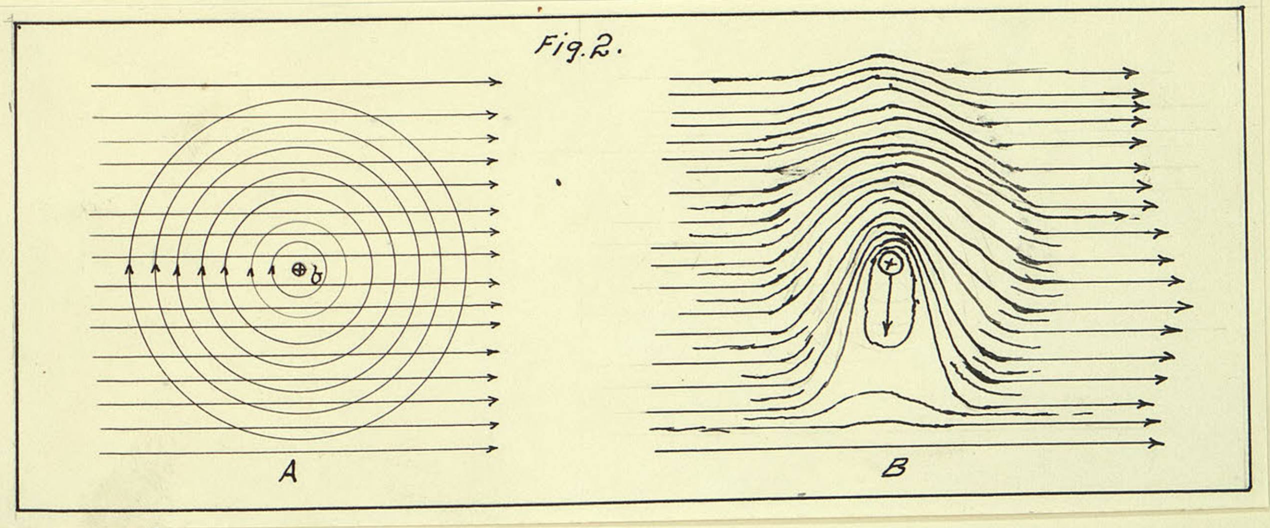
In the present method of power transmission the D.C. motor is half the problem, hence the man who is to solve it cannot understand its principle too well.

Theory.

It is a peculiar fact, that while the principle of the motor, discovered by ampere in 1821 and soon afterward applied in the construction of the galvanometer, it was not until after the dynamo had been fully developed that the motor was discovered. A workman connecting two dynamos in parallel found one of them running without the aid of its prime mover.

The principle discovered by Ampere and upon which the operation of the motor depends is as follows, "If a conductor carrying a current be placed in a magnetic field it will be acted upon by a force tending to move it in a direction at right angles to the line of force and to the axis of the conductor."

Fig. 2.



If a conductor be carrying a current, circular lines of force are produced around it in a clock wise direction when the observer is facing in the direction in which the current is flowing. Suppose such a conductor to be placed in a magnetic field as shown in Fig. 2A. (In this and all subsequent figures the cross-section of a conductor will be marked (+) when the current is flowing into the plane of the paper and (-) when the current is flowing out of the plane of the paper). The existing field is indicated by the straight lines and its direction by the arrow heads, while that produced by the conductor is represented by the circular lines.

The resultant of these two fields is shown by the lines in Fig. 2B, in which a portion of the lines below the conductor have been neutralized by those produced by the current in the conductor and others have sought the easier path above b. This distortion of the field produces a tension in the lines of force which will tend to pull the conductor downward as shown by the arrow. The magnitude of this force may be calculated as follows:

Let H = strength of the field,

l = length of the conductor,

i = the absolute units of current in the conductor.

Now since an erg of work is done by an absolute unit of current cutting a line of force, the work done (dw) where the conductor moves a distance dx will be

$$dw = iHl\,dx$$

But since work is equal to force times space

$$f = \frac{dw}{dx} = iHl \text{ dynes} \qquad (1)$$

If the current be measured in amperes then

$$f = IHl\,10^{-1} \text{ dynes} \qquad (2)$$

If the direction of this force be indicated by its sign it appears from the equation that the direction of the force is reversed by changing the sign of I or H and is unaltered if the sign of both I and H be changed.

Fig. 3.

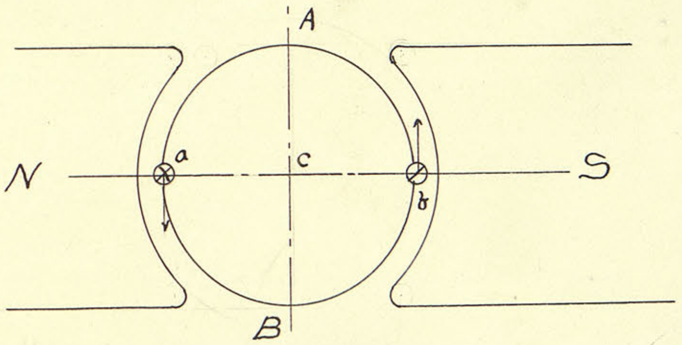


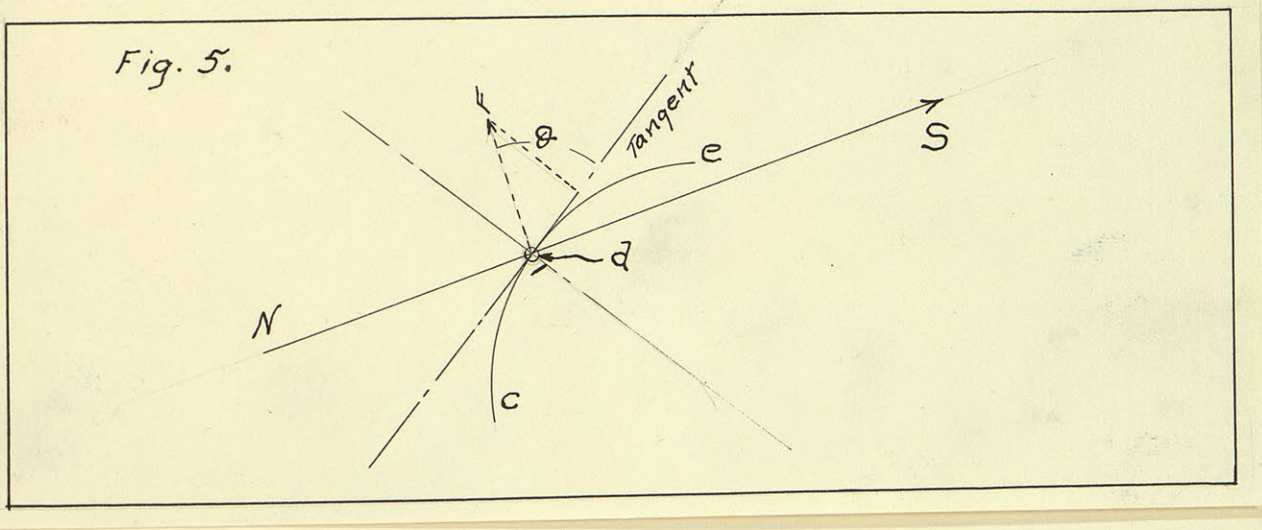
Figure 3 represents a cross section of an armature whose normal plane is A B. On its surface are the conductors a and b. The direction of the current in each is opposite while the sign of H is the same for both hence the forces acting on the two will be of opposite sign and will constitue a couple tending to rotate the armature in the direction indicated by the arrow.

Let the number of conductors distributed equally around the surface of the armature, with their axes at a distance of cm from the axis of the armature, be S and the length of each conductor be l.

The distance between successive conductors, then, will be $\frac{2\pi\gamma}{3}$, (Fig. 4) and the area inclosed by them will be $\frac{2\pi\gamma l}{S}$.

If dN be the number of lines of force entering this area then $\frac{SdN}{2\pi\gamma l}$ will be the intensity of magnetization at this point. In Figure 4, let d be the axis of a conductor on the surface c d e of the armature.

Fig. 5.



Let the direction of the lines of force entering the armature at this point be NS; the angle that the normal (dF) to NS makes with the tangent plane be ϕ.

The force acting on d in the direction dF is

$$df = IHl\ 10^{-1}$$

Substituting the value of

$$H = \frac{SdN}{2\pi\gamma\ l \cos\phi}$$

$$df = \frac{SI\ 10^{-1}\ dN}{2\pi\gamma \cos\phi} \qquad (3)$$

The component of this force tending to produce rotation is that acting in the direction of the tangent and is equal to $d\ \cos\phi$ Hence,

$$d\ t = \frac{SI\ 10^{-1}\ dN}{2\pi\gamma}$$

Integrating, the force acting on one side of the armature

$$= \frac{ISN\ 10^{-1}}{2\pi\gamma}$$

and for the two poles it will be

$$= \frac{I\ SN\ 10^{-1}}{\pi\gamma}$$

For any number of pairs of poles P the force will be

$$= \frac{PI_a\ SN\ 10^{-1}}{\pi\gamma a} \qquad (4)$$

where I_a is the total armature current and a is the number of parallel circuits through the armature.

Since force times radius gives torque the torque t in dyne cm will be

$$t = \frac{PI_a\ SN\ 10^{-1}}{\pi a}$$

In pounds feet it will be

$$T = \frac{PI_a\ SN\ 10^{-1}}{\pi a} \times \frac{10^{-5}}{4.45 \times 2.54 \times 12}$$

$$= \frac{PI_a\ SN\ 10^{-8}}{\pi a \times 13.56} \qquad (5)$$

Now the horse power output is

$$H\ P = \frac{2\pi \times r.p.m.}{33000} \times T \qquad (6)$$

$$= \frac{2\pi \times r.p.m.}{33000} \times \frac{PI_a\ SN\ 10^{-8}}{\pi a \times 13.56}$$

$$= \frac{2PI_a\ SN\ r.p.m. \times 10^{-8}}{a \times 13.56 \times 33000}$$

$$\text{Watts output} = HP \times 746$$

$$= \frac{2P}{a} \times \frac{SN\ r.p.m.}{10^8 \times 60} \times I_a \qquad (7)$$

But when the motor is running it acts in every respect as a generator and generates a back electro motive force C which is

$$e = \frac{2P}{a} \times \frac{SN(r.p.m.)}{10^8 \times 60}$$

Hence the watts output W_o is

$$W_o = I_aC \qquad (8)$$

Equation 7 gives the power expended in rotating the armature and accounts for all of the mechanical power developed, although all of this power does not appear as useful power.

The armature current will undoubtedly be at any time

$$I_a = \frac{E - e}{R_a} \qquad (9)$$

where R_a is the armature resistance.

Therefore the current will be greatest when e is equal to 0, or when the armature is standing and will be zero when C is equal to E. This is impossible since under these conditions we must have speed without torque, equation 10, which would mean no losses whatever, either mechanical or electrical.

Writing equation (5) in the form

$$T = MI_a \tag{10}$$

$$= \frac{ME}{R_a} - \frac{MC}{R_a} \quad \text{in} \quad \text{in which } M = \frac{PSN\ 10^{-8}}{\pi a \times 13.56}$$

Substituting

$$C = \frac{2P}{a} \times \frac{SN \quad \text{r.p.m.}}{10^8 \times 60} = K' \text{ r.p.m.}$$

$$\frac{ME}{R_a} = MK$$

$$T = MK - \frac{MK'}{R_a} \text{ r.p.m.}$$

Solving for r.p.m.

$$\text{r.p.m.} = \frac{K}{K'} - \frac{T^{Ra}}{MK'} \tag{11}$$

This equation shows that the greater the torque the less the speed. Hence if the load on the motor be increased the speed will decrease until the difference between the counter and impressed electro motive force is great enough to allow a sufficient armature current to flow to supply the losses, or to develop a torque equal to the retarding torque. Since the value of

$$\frac{RaT}{MK'} = \frac{a}{2P} \times \frac{10^8 \times 60\ I_a\ Ra}{SN}$$

in which I_a is the only variable. For the maximum value of I_a the value of $\frac{T}{MK'}$ will never be great as compared to $\frac{K}{K'}$. This explains the comparatively small drop in speed of the shunt motor.

Equation (8) gives the output of a motor. That is, the power used in driving the armature together with its load. Since all mechanical losses are output they must be balanced by an equal input loss. Then the mechanical losses (friction, windage, etc.,) may be measured by the input with no load on the motor. These losses are known as the no load losses. The true available output of the motor then is equal to I_aC minus the no load losses.

Or if the output is measured by means of a prony brake as HP then,

$$HP = \frac{I_aC - \text{No load losses}}{746} \qquad (12)$$

If we let the watts lost in the field be W_t, then the input of the motor will be $W_t + I_aE$.

Now since the efficiency is equal to the output divided by the input, we have, representing efficiency by E

$$E = \frac{HP \times 746}{W_t + I_aE}$$

From this equation it may be seen that to increase the efficiency we must decrease the field loss and also the armature losses.

DEVELOPMENT.

The real development of the electric motor began June 3, 1873, when, as before stated, by accident the reversibility of the generator was discovered. M. Fontaine, however, claims that this discovery was not an accident but the result of his labors to prove the reversibility of the Gramme machine and a result that he was expecting.

The efficiency of the motor as it was at that time is not exactly known but was very low. The improvement or development of the motor then has been to increase its efficiency and reduce the cost of construction. The same improvements that have been made in the generator will to a great extent apply to the motor. In the first place, let us look at the losses that occur in a motor and the means taken to reduce them to a minimum.

1. I^2R loss in the armature field and brush contact.
2. Foncault or eddy currents in the armature core and pole peices.
3. Foncault or eddy currents in the armature conductors.
4. Hysteresis in armature core.
5. Friction of bearings and brushes, and air friction.

The I^2R loss in the armature and field can be directly computed when the machine is designed. It is made small by the use of less resistance in the armatures of large machines. If the completed machine shows too great a loss due to commutator connections, brush contacts or brush connections better mechanical construction is used to reduce this loss. In the modern motor these parts are very well designed and it seems difficult to make much improvement in this way.

The method used to reduce foucault currents is to use laminated armature cores. In this case the loss in each disc $= \frac{l^2d}{rd}$. rd being the electrical resistance in the path of the current through the disc and ld the pressure generated in the disc. ld is proportional to the number of revolutions per minute of the armature and to the number of lines of force entering the disc. The latter makes ld proportional to the thickness of the discs, while rd is evidently proportional to the thickness of the disc. Hence, $\frac{ld}{rd}$ is proportional to the cube of the thickness of the discs. As the number of discs in an armature is inversely proportional to the thickness of the discs the total heating due to foucault currents in completely insulated discs is proportional to the square of the thickness of the discs. On account of mechanical considerations it is not best to reduce the thickness of the discs to much less than .015". Hence, if two or more discs make electrical contact the heating is considerable. It was at first the practice to use tissue paper between the discs as insulation but now the black oxide is depended upon by nearly all the manufacturers. It is the practice to leave several air spaces in the armature core. These serve the double purpose of helping to ventilate the core, and if a burr has been made by the lathe tool, thus causing metallic contact between the discs this air space will make a break in it.

Foucault currents in the armature conductors give practically no trouble except where the current is very large, requiring heavy conductors. In machines large enough to require attention in this regard, the conductors are formed by winding several wires in the same coil in parallel or by using bars in parallel. When the rectangular bars are used they are placed in slots on the edge. If placed on the side, currents will flow in the bar due to a difference in the rate of cutting lines of the two edges. If wires are used the coil is given a half twist when crossing the head so as to make all the wires in the coil of the same length. The hysteresis loss in small machines is small but in large armatures may become a serious matter. The loss varies with B, (flux in the iron), and with the quality of the iron of which the core is made. With each different lot of iron B may be determined experimentally. In the best soft iron the loss is likely to lie between .00001 and .00002 watts per cubic centimeter per revolution per minute. This causes a rise in temperature that makes ventilation in large armature cores necessary.

The friction loss depends upon mechanical construction entirely and is reduced to a minimum by finely aligned and well fitted bearings and brushes. The friction loss is best measured by running the machine from a calibrated motor and measuring the power taken to overcome the bearing friction, brush friction, and windage.

The I^2R field loss may be easily calculated when the motor is designed. To reduce leakage the air gap has been reduced and the armature slotted. The slotted armature answers the double purpose of making a shorter path for the flux and of holding the coils in place which is hard to do on the smooth core armature.

Direct current motors are divided into series, shunt and compound machines according to the kind of field winding employed.

The series machine has a field composed of a few turns of heavy conductor through which the entire armature current passes. A motor, when running, generates an electro motive force the same as a generator. This electro motive force opposes the impressed electromotive force and is called "counter electro motive force". The amount of current that flows is proportional to this counter electro motive force. The torque is proportional to the current as shown by the torque curves. Upon starting a series motor the counter electro motive force is zero and increases as the speed increases. We can deduce from this that the torque is inversely proportional to the speed. Hence, a series motor will start under a very heavy load.

The advantages of a series motor are

1. The torque on overload is large. Series motors are therefore well adapted for starting loads with great friction of repose.

2. The cost of the field is considerably less than in the case of the shunt motor, as the number of turns required is very much less.

The disadvantages are

1. The speed varies with the load.

2. If the load is removed the speed becomes dangerously high and the motor may race, or run at a dangerously high speed.

Shunt motors are made with a field composed of many turns of fine wire. The field is in parallel with the armature and only a small current passes through. Their great advantage is that the speed is practically constant at all loads.

The disadvantages are as follows:

1. When the motor is on a constant potential circuit the field current is constant. The torque is proportional then to the armature current and will not start under heavy loads as the series motor will.

2. There is a high potential between the field terminals. Opening the field circuit suddenly causes a large spark and a high potential due to self induction.

3. The field is more expensive both in material and workmanship than the series field.

The compound motor is wound with both a shunt and series field. They are made in two kinds, cumulative wound and differentially wound. The cumulative wound motor has the direction of current the same in the series and shunt fields, which adds the effect of the two. As the speed decreases, and the current increases, it strengthens the field and gives a greater torque. The special use of this motor is where it is frequently started under load and a constant speed is required.

The differentially wound motor has its series turns opposing the shunt turns. As the load increases the increasing armature current strengthens the series field which weakens the total field and speeds up the motor, keeping a constant speed. It is used in clothing mills and places where a small variation of speed is detrimental to the work.

Series motors are used for cars, elevators, hoists, etc., where they must start under a heavy load.

Shunt motors are used where a nearly constant speed is required with a certain allowable variation.

To discuss fully the different designs for every different use would require more than is possible to put in this paper, so we discuss the particular motor upon which our tests were made.

The motor in question is a B.F.Sturtevant Shunt Wound, 15 HP, 220 Volt Motor. It is a four-pole machine, the full load current being 50 amperes.

The shop test showed 1000 R.P.M., with 200 volts, 43 amperes armature current and 1.04 amperes field current. This motor was originally installed to run the fan in the heating system of the Physical Science building. After running for a time it ran at a dangerously high speed and was completely wrecked.

The armature core is laminated iron with ventialting ducts. The armature conductors consist of formed coils. It is a closed coil, two circuit winding. The commutator is composed of 102 bars, while the armature has 51 slots. Each formed coil consists of two coils of two turns each. This gives four ends for each coil which makes 204 ends. One coil is then a dead end one. It simply has its ends taped and fastened down and is of no use except for mechanical balance. The throw of the coils is fourteen.

From the end the commutator connections were carried forward and backward so that a coil spanned one half the commutator less one segment. The end of the next coil is joined in the same place, making a complete closed circuit, each half thus making two circuits.

Tests.

The following tests were made:

A test for grounds,
An insulation test,
Efficiency test,
Torque test,
Heat run.

After the coils were in place a test was made for grounded armature. A 220 volt lamp was placed in series with two terminals, one of which was placed on the commutator and the other on the armature shaft. In this test no ground could be detected. The coils were then soldered to the commutator and the binding wires put on the armature. To put on the binding wires the armature was put in a lathe and the commutator was turned true and the shaft smoothed with emery and oil.

The motor was then assembled and the first ground was discovered accidentally by touching the yoke and commutator at the same time. A test was made with a voltmeter in series with the commutator and shaft and the coil located. The coil was pried out and more carefully insulated. The insulation was found to be broken where the coils were sprung over the end of the armature teeth. Five or six coils were found broken in the corresponding places.

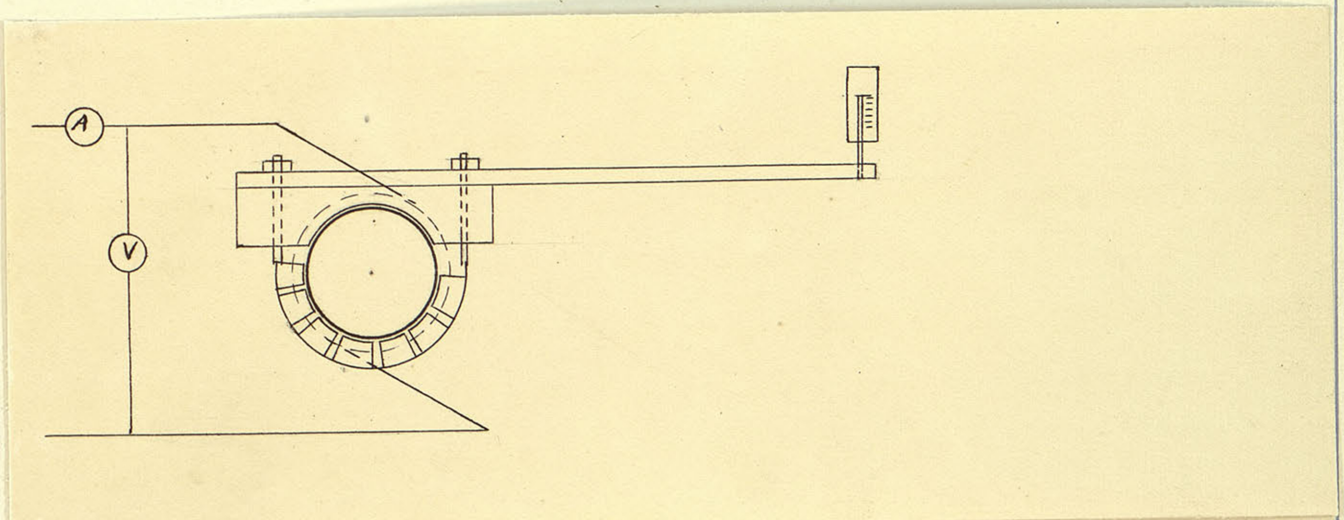
They were each raised up and insulated with tape and fibre. The machine pulled its load with the ground showing that a grounded machine will run and pull its load.

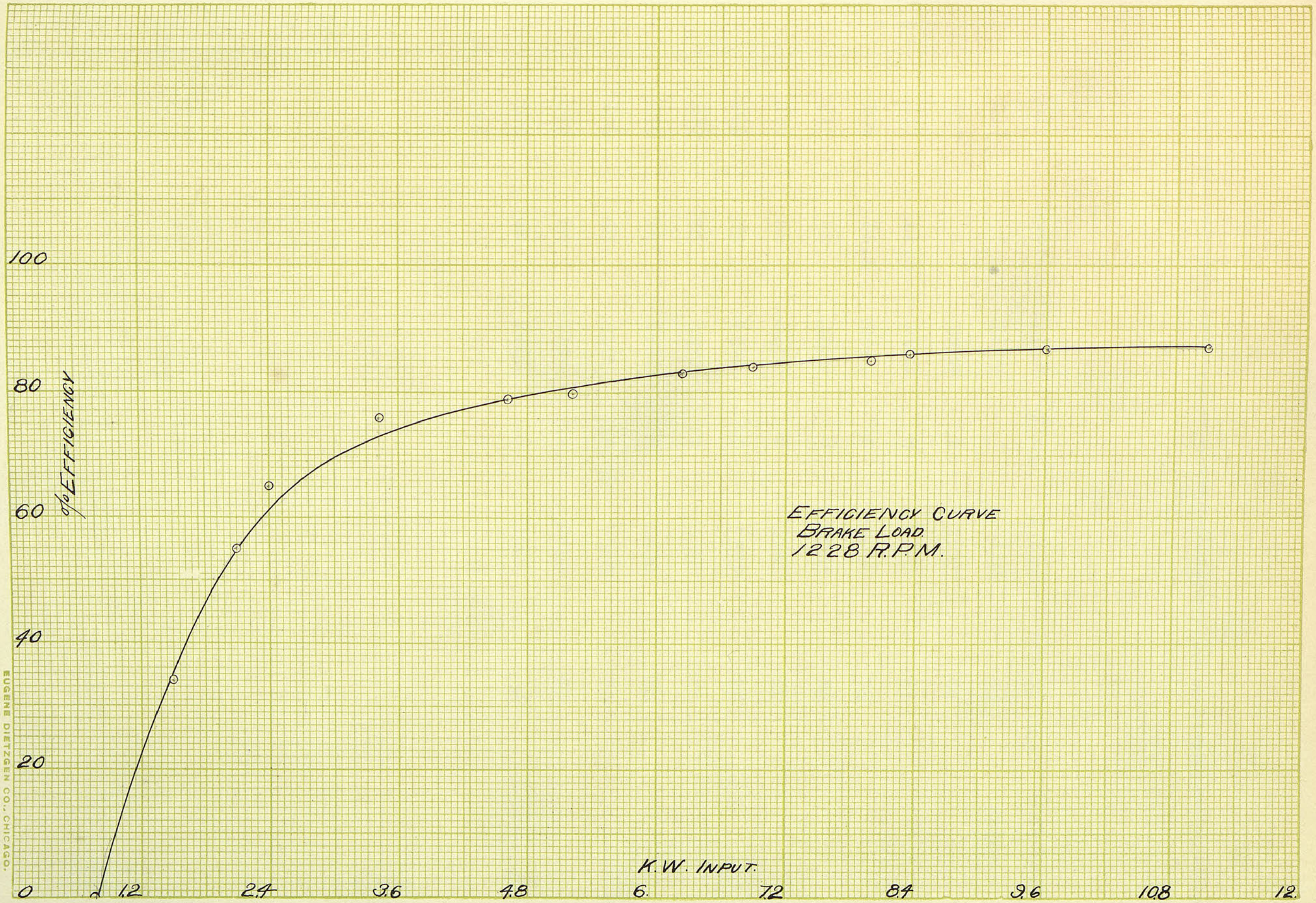
The next test was the efficiency test. In this the main difficulty was with the brake. When the machine was pulling nearly full load or above, the brake became heated very quickly and charred. This gave very unsatisfactory and varying results, as the readings were too high.

We then tried some plumbago and oil on the brake and the results were more satisfactory. The efficiency curve shows an efficiency of

67% at 1/4 load,
81 1/2% at 1/2 load,
86% at 3/4 load,
88% at full load.

Above one half load this is very good.




EFFICIENCY CURVE
BRAKE LOAD.
1228 R.P.M.
% EFFICIENCY
100
80
60
40
20
0
K.W. INPUT.
1.2
2.4
3.6
4.8
6.
7.2
8.4
9.6
108
12.

Volts	Amperes	Input	#Pull	Output	Efficiency	R.P.M.
217	7	1519	1	523	34	1228
212	9	1908	2	1047	55	
211	11.5	2432	3	1570	65	
209	16.5	3448	5	2616	76	
210	22	4620	7	3666	79	
208	25	5200	8	4185	80	
209	30	6270	10	5233	83	
209	33	6897	11	5756	84	
210	38	7980	13	6800	85	
208	40	8320	13.75	7190	86	
206	54	11124	18.5	9670	87	
200	48	9600	16	8360	0	
194	4	776	0	0		

In the factory test the machine ran 1000 revolutions per minute, but since rewinding the fields and armature, it runs 1228 revolutions per minute. The former resistance was 192.3 ohms in the field, now it is 166.6 ohms. This would give a lower speed but other conditions are not the same as they were in their test.

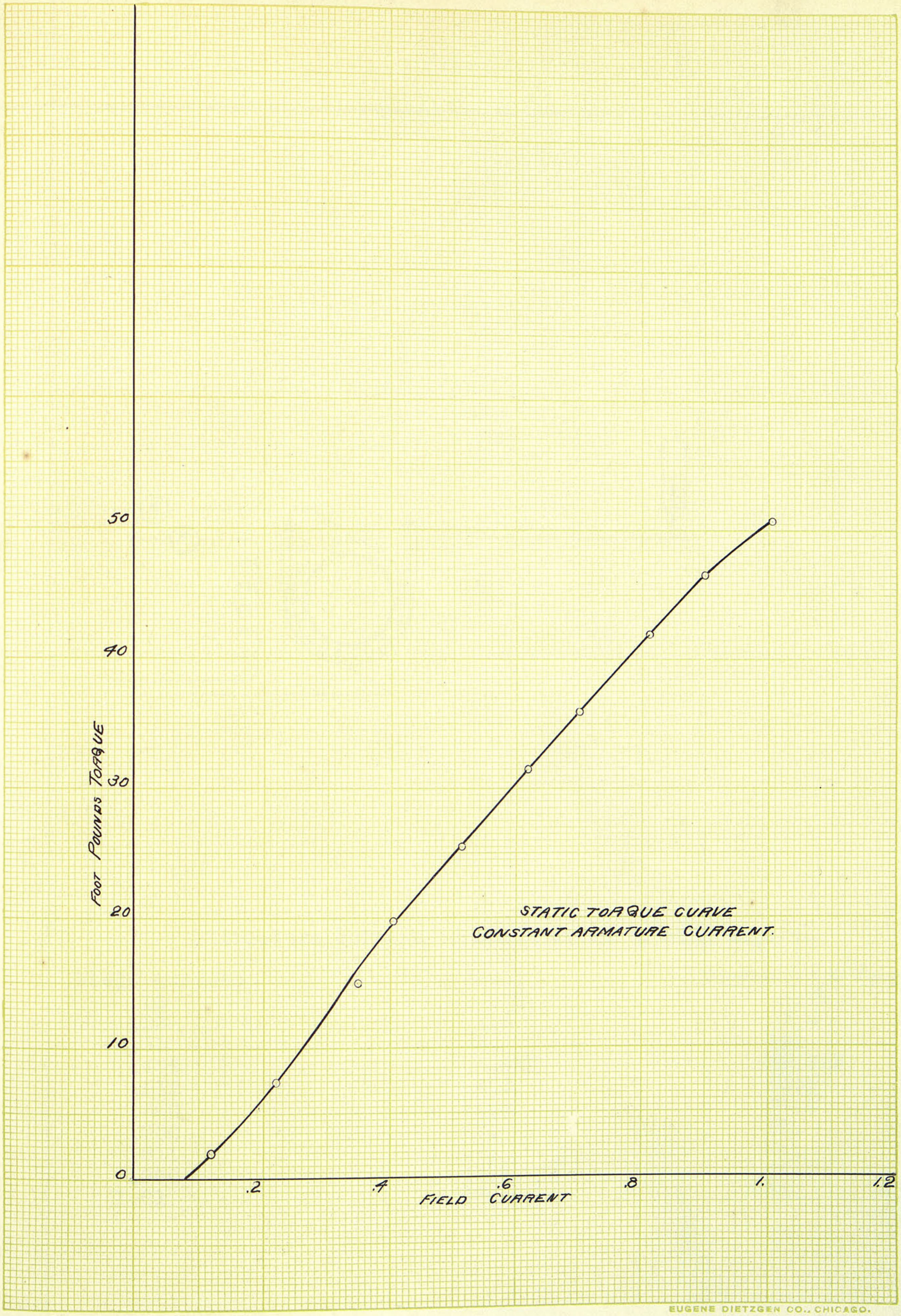
The static torque tests were made with locked armature and

1. Constant field current and varying armature current.
2. Constant armature current and varying field current.

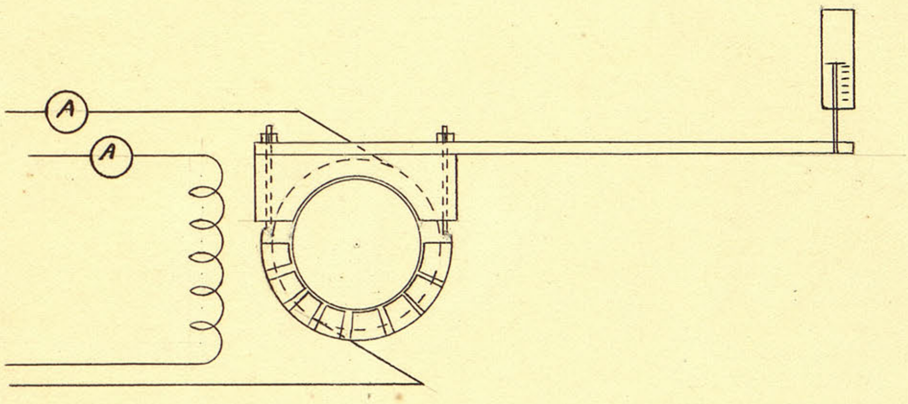
The first curve is a straight line up to nearly full load when it curves slightly. This is due to distortion of the field caused by armature reaction.

The second curve is a straight line above.4 amperes field current up to .9 amperes when it curves, due to distortion, saturation and leakage.

On the part of the curve where the machine is generally worked the torque is proportional to the armature current since the field current remains constant.

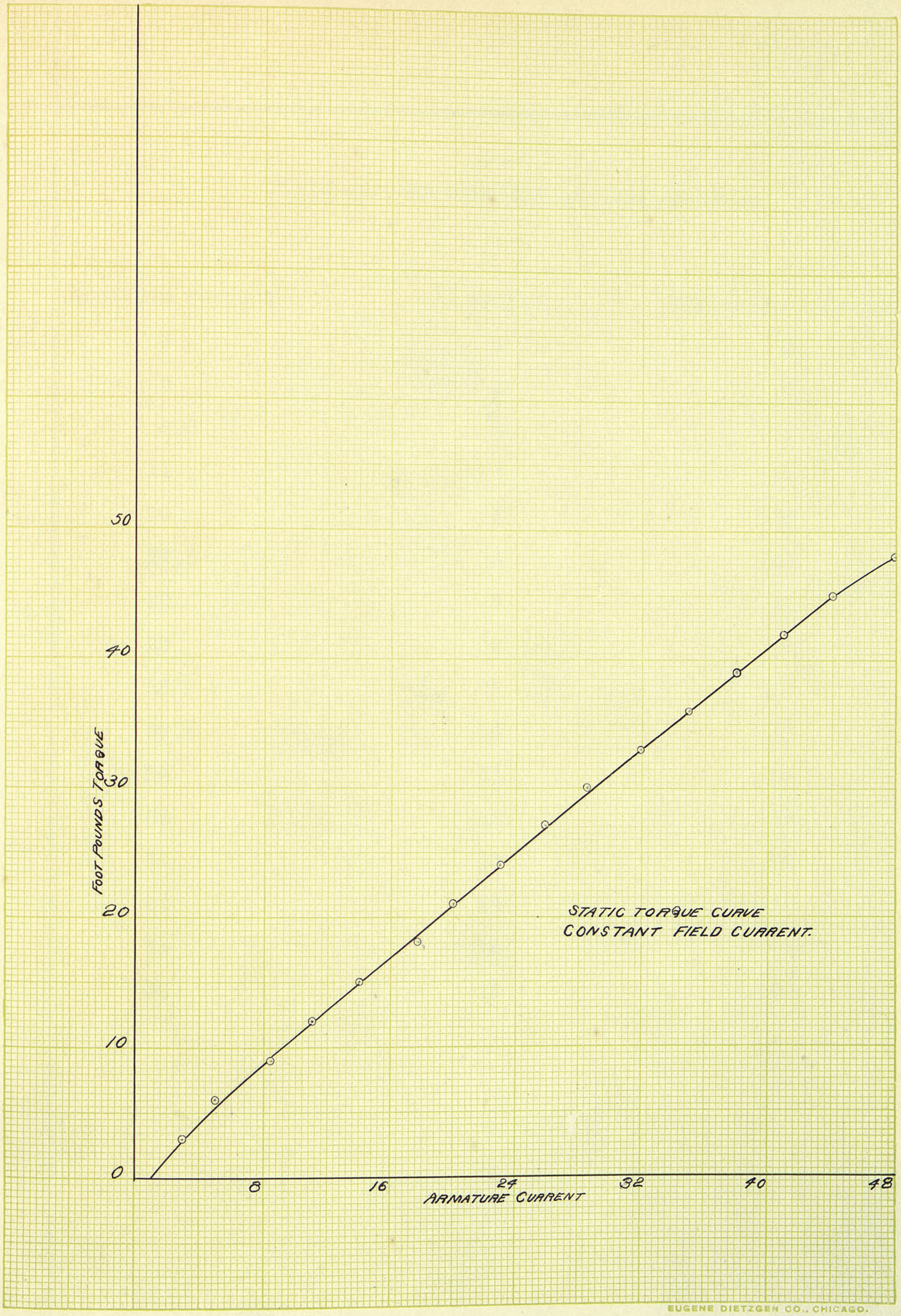


STATIC TORQUE CURVE
CONSTANT ARMATURE CURRENT.



Armature current constant at forty nine amperes.

Field current	#Pull	Torque Foot Pounds.
.12	.75	2.25
.22	2.5	7.5
.35	5.	15.
.405	6.625	19.875
.512	8.5	25.5
.620	10.5	31.5
.700	12.	36.
.811	14.	42.
.900	15.5	46.5
1.01	17.	51.



EUGENE DIETZGEN CO., CHICAGO.

Field current constant at .915 amperes.

Armature current	#Pull	Torque Foot Pounds.
3	1	3
5	2	6
8.5	3	9
11	4	12
14	5	15
17.8	6	18
20	7	21
23	8	24
26	9	27
28.5	10	30
32	11	33
35	12	36
38	13	39
41	14	42
44	15	45
48	16	48

Heat Run.

For this test the machine was run at a little above full load for about six or seven hours. No very satisfactory results were obtained. The armature showed a rise of more than the allowed 40°C. above the temperature of the room, but the rest of the machine ran within the allowable temperature rise.