

T H E S I S

TEST OF A 50 K.W. DIRECT CURRENT GENERAL ELECTRIC GENERATOR

For

The Degree of Bachelor of Science in Electrical Engineering

By

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Under

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It is the purpose of this paper to report a series of tests made on a generator manufactured by the General Electric Company and installed at the Mechanical building of the University of Tennessee in 1906. These results are to be compared with those of a similar set of tests made by Mr. Leach on a machine manufactured by the Edison Company about twenty years earlier; also with Mr. Kerr's results from tests of a generator manufactured by the Thompson-Ryan company and installed in 1898.

The generator to which this report is confined is rigidly connected to the shaft of an American Ball Compound engine. It is of the continuous current type and is rated as follows:-

Field poles	6
Output	50 K.W.
Volts	225-250
Amperes	200
Speed	290 R.P.M.
Armature windings simplex wave.	
Series field	17 1/2 turns 5.5" x .025" copper strip
Shunt field	704 turns .076" diam. wire,
Armature slots	4 conductors per slot .07"x 6.25"
Armature slots	119
Commutator bars	238

The instruments used in making the tests were: Simplex voltmeter No. 1814 reading up to 150 volts, Weston Millivoltmeter No. 7864 and Weston switch board ammeters Nos. 57856 and 57857, all of which were calibrated and correction curves plotted. The millivoltmeter was provided with three shunts so that it could be used as an ammeter to read from zero to 2 - 20 or 200 amperes.

Before the test was begun the shunt was opened and examined for loose connections and burn outs; it was found to be in good order. The millivoltmeter was calibrated by comparison with potentiometer. Since this instrument was manufactured it has been remodeled so that its readings as a millivoltmeter have to be multiplied by five to be correct. The shunt was also remodeled so that the instrument reads directly as an ammeter. As this instrument was used only as an ammeter, the potentiometer reading was divided by five thus giving what the scale reading should be. The correction curve was then plotted between the actual scale reading and its difference from $1/5$ of the potentiometer reading. The switch board ammeters were calibrated by comparison with the laboratory standard voltmeter, which in turn, was calibrated by the potentiometer.

The last pages show the correction curves for the instruments used.

The following is a list of the tests made.

1. Saturation Curve.
2. Heat run.
3. Amount of armature reaction.
4. Circular mils of wire per ampere in field.
5. Circular mils of wire per ampere in armature.
6. Leakage Coefficient.
7. Flux density in field.
8. Flux density in armature and armature teeth.
9. Weight of generator per kilowatt output.

Saturation Curve.

For any particular value of field current there is a definite amount of flux set up in the field. The saturation curve is drawn to show

how this flux varies with the field current. If Φ be the flux which enters the armature from a north pole of the field, the electromotive force E_a induced in the armature is equal to $\Phi Z'n$ where n is the rate at which the conductors are cutting the lines of force. Since the value of Z' varies only with the field current and Φ depends on Z' it is evident that if the generator be driven at a constant speed n , the value of E_a will depend only on the field current. The saturation curve for a generator is therefore plotted with the field current as abscissae and with terminal voltage, E_a , as ordinates, all readings being taken at some constant speed. In practice however it is not always possible to keep a constant speed but the value of E_a depends directly on the speed so if we have a reading of E_a at a speed n' we may find what its value would be at another speed n by multiplying E_a by $\frac{n}{n'}$. In this test the speed could not be kept constant so 280 R.P.M. was taken as a standard speed and all readings at other speeds were corrected to correspond to this standard. The measurements of voltage were taken between the middle and one outside wire as the voltmeter would not read the total drop from outside to outside. It was found however by several measurements that the voltage from one outside to the middle wire was the same as from the other outside to the middle. It is therefore evident that the total induced voltage is twice the voltage read. The following pages show the curve and the data from which it was plotted.

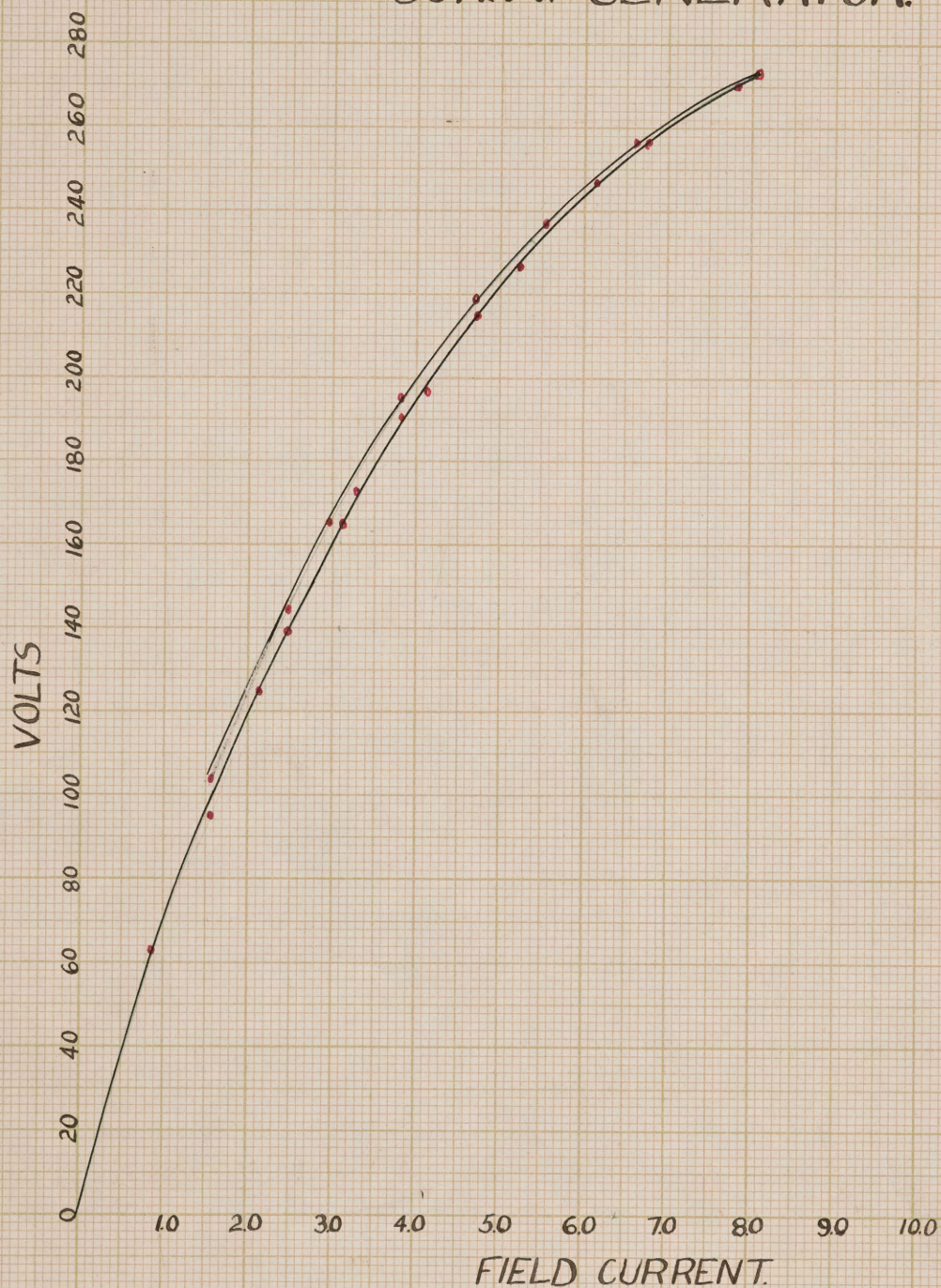
Saturation Curve for 50 K.W. Generator.

R.P.M.	Field current		Armature Volts		One side corrected for speed	Total for both sides & correct speed.
	Reading	Actual	Reading	Actual		
279	.85	..847	31.0	31.2	31.3	62.6
279	1.57	1.55	48.5	48.5	48.7	97.4
280	2.10	2.11	62.3	62.3	62.3	124.6
280	2.48	2.49	71.0	69.4	69.4	138.8
279	3.06	3.14	82.1	82.1	82.4	164.8
279	3.18	3.26	86.2	86.2	86.5	173.0
278	3.78	3.84	94.3	94.3	95.0	190.0
278	4.08	4.13	99.0	98.2	98.8	197.6
278	4.67	4.71	107.4	106.7	107.3	214.6
279	5.20	5.24	113.7	112.6	113.1	226.2
279	5.34	5.38	117.4	116.5	116.8	233.6
280	6.12	6.15	124.0	123.2	123.2	246.6
280	6.75	6.76	128.8	128.0	128.8	256.0
280	7.84	7.82	135.8	135.0	135.0	270.0
280	8.08	8.05	137.3	136.5	136.5	273.0
280	6.60	6.61	128.8	128.0	128.0	256.0
281	5.52	5.56	119.4	118.6	118.1	236.2
281	4.67	4.71	110.0	109.4	109.0	218.0
279	3.75	3.81	96.8	96.9	97.3	194.6
279	2.88	2.97	82.5	82.5	82.8	165.6
278	2.39	2.49	72.0	71.5	72.0	144.0
278	1.60	1.58	52.1	52.1	52.4	104.8

4 a

SATURATION CURVE.

FOR
50K.W. GENERATOR.



Heat Run.

The rating of a machine is based on the load it will carry without an excessive rise in temperature of its parts. The testing of a machine at full load to see if the rise in temperature is excessive is called the "Heat Run". In making this test the temperature of the field, armature, and commutator are taken before the machine is started by placing a thermometer bulb on the part and covering it with a small piece of clean dry waste. Then the thermometers are taken off the armature and commutator but left on the field to observe at intervals and to tell when the temperature ceases to rise further.

The machine was started at 2:00 P.M. and the field temperature rose quite rapidly for the first hour of run and then more gradually till about 5:00 A.M., and after an hours running the temperature showed no increase so it was evident that it had reached its maximum temperature so it was stopped and the temperatures of the field armature and commutator taken. The readings showed that during the sixteen hours of run the field had risen in temperature from 75° F or 23.9° C to 197.5° F or 90.9° C, thus giving a rise in temperature of 122.5° F or 66° C. The armature had risen from 75.7° F or 24.1° C to 146° F or 63.3° C, thus giving a rise of 70.3° F or 39.2° C while the commutator had risen 74.7° F or 23.7° C to 154° F or 67.8° C, thus giving a rise in temperature for the commutator of 79.3° F or 44.1° C.

The American Institute of Electrical Engineers recommend 50° C or 90° F as a maximum rise in temperature for the field and armature, while a rise of 55° C or 99° F is permissible on the commutator. They also state that in case the room temperature rises that 50% of this rise may be added to the values given. In this test the temperature of the room changed from 75° F to 83° F making a rise of 8° F or 4.4° C. Therefore

the total allowable rise in this case would be 94° F or 52.2° C for the field and armature while a rise of 103° F or 57.2° C is allowable for the commutator.

It is seen from the above that the field exceeded the prescribed temperature by $66 - 52.2 = 13.8^{\circ}$ C, while the armature and commutator are well within the limit.

In making this test the generator had to furnish lights and power most of the time. As this load could not be kept constant and was usually below full load it is probable that if full load could have been maintained throughout the test the maximum temperature would have been reached earlier. On the following page the data is given.

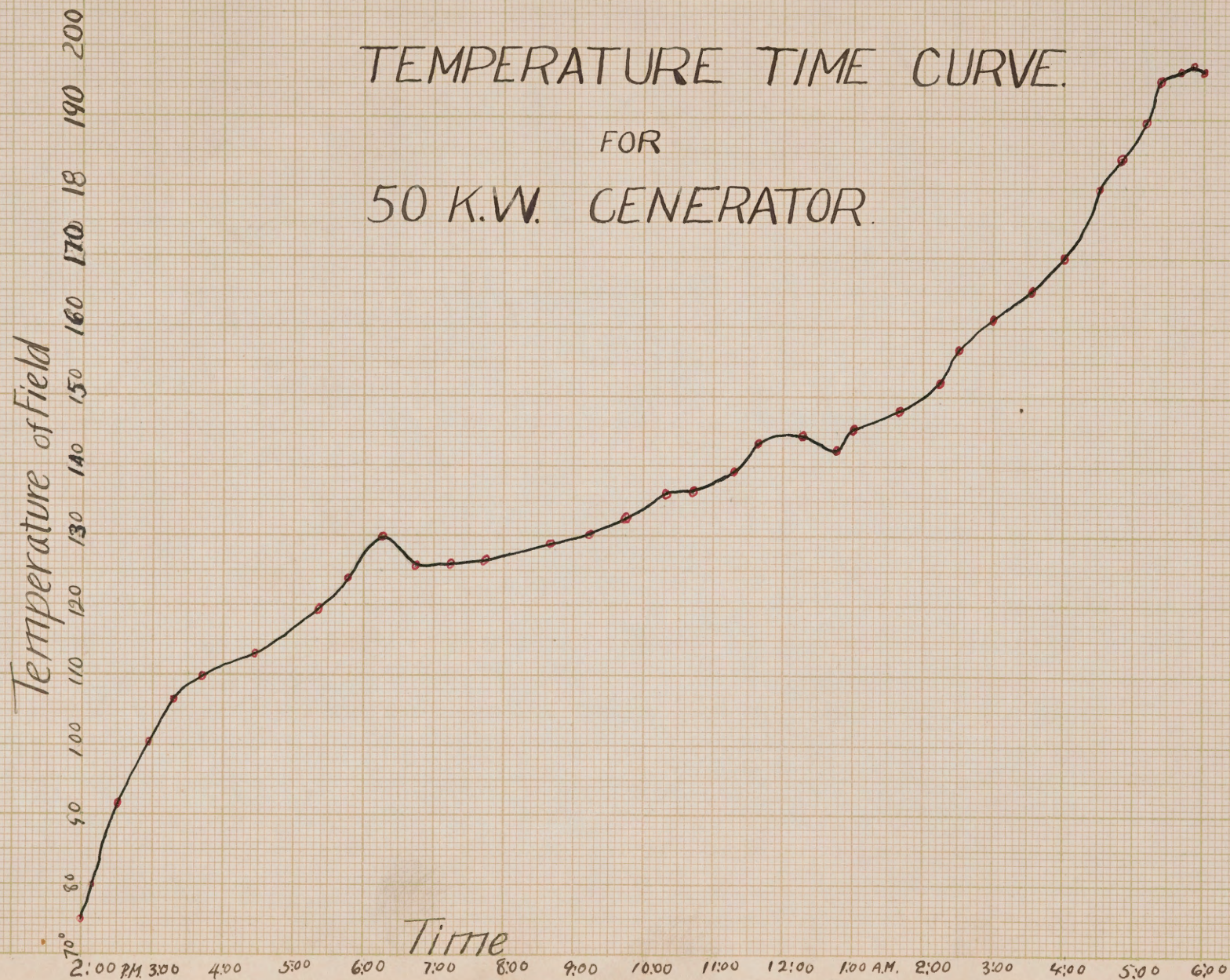
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Heat Run.

Data.

Temperatures.				Temperatures.			
Time	Field	Armature	Commutator	Time	Field	Armature	Commutator
P.M.							
2:00	75.0	75.7	72.7	1:00	145.5		
2:15	83.0			1:40	148.0		
2:30	91.5			2:15	152.0		
2:55	100.5			2:30	157.0		
3:20	106.8			3:00	161.5		
3:40	110.0			3:35	165.0		
4:25	113.0			4:00	170.0		
5:20	119.1			4:15	172.5		
5:45	124.0			4:30	179.5		
6:15	130.0			4:50	184.0		
6:45	125.5			5:10	189.5		
7:15	126.0			5:20	195.8		
7:45	126.5			5:40	197.0		
8:00	127.0			5:50	197.5		
8:40	128.8			6:00	197.0	146	154
9:15	130.0			Room 83			
9:45	132.5						
10:20	136.0						
10:40	136.0						
11:20	139.5						
11:35	143.5						
A.M.							
12:20	144.5						
12:45	142.0						

A curve is plotted on the following sheet between time and field temperature. The decreases in temperature at various places on the curve are probably due to a drop in the load.



Armature Reaction.

If a generator be run at no load and the position for the neutral axis noted, and then, if it be loaded up to full load it will be found that the neutral axis does not have the same position that it had before the load was put on. This shifting of the neutral axis is due to the distortion of the flux caused by the armature current and is called armature reaction. This is expressed in terms of the number of degrees through which the neutral axis is shifted by the effect of the armature current.

The method used in finding the armature reaction was to connect one terminal of a voltmeter permanently to one of the brushes and the other to a small piece of steel, called a pilot brush, that could be moved along the commutator until the point was found that gave the maximum voltage between the pilot brush and the brush to which the other terminal was connected. Having found this point when the generator ran on no load the pilot brush was held in place until the generator was stopped then the number of commutator bars between it and the permanent brush was found to be forty. The dynamo was then run on full load and by the same procedure the maximum voltage was given when the distance between the terminals of the voltmeter was thirty-six commutator bars. From this it is seen that the neutral axis is shifted four commutator bars between no load and full load. There are 238 bars on the commutator so the axis was shifted $4/238$ of a circle or $6^{\circ} - 3'$. The armature reaction is therefore 6 degrees and 3 minutes.

Circular Mils of Wire per Ampere in Field.

To find the number of circular mils of wire per ampere in the shunt field we find the area of the wire in the shunt field which is 0.076" in diameter to be 5776 circular mils. From the saturation curve we find that at full voltage the field current is 6.4 amperes, thus giving for the

shunt field $5776/6.4 = 902.5$ circular mils per ampere.

The series field winding is $5.5" \times .025"$ thus giving a cross section of 0.1375 sq. inches or 137500 sq. miles which is equal to 175070 circular mils. Now part of the current output does not flow around the series field but is shunted through a grid directly into the external circuit. The actual amount of current flowing in the series turns can be found by dividing the total current in the ratio of the resistances of the series turns and the grid. As the resistance of the series winding is very small and could not be accurately determined by actual measurement it was calculated from the cross-section and length of the wire. The pole pieces are $4.5" \times 11.625"$ or $31.75"$ in circumference making the length of one turn say $32"$. Then the total length of series winding is $6 \times 17.5 \times 32 = 3360"$ or 280 ft. Now allowing 5 feet for the wire leading from the grid to the series field and for that taken up in passing from one pole to the next we may call the total length 285 feet. If P be the resistance of a cubic inch of copper and A the area of the cross-section in square inches, l the length in inches and R the resistance of the conductor, then $R = Pl/A$. The resistance of a cubic inch of copper is 0.579 microhms or $P = .000001 \times .579 = .000000579$ ohms. $l = 285 \times 12 = 3220$ inches $A = 0.1375$ sq. inches.

$$\therefore R = \frac{.000000579 \times 3220}{.1375} = 0.0121 \text{ ohms.}$$

This resistance was measured by the testing set to be 0.018 ohms thus showing the resistance of the set to be $0.018 - 0.012 = 0.006$ ohms. The resistance of the grid was measured by the testing set to be 0.058 ohms but as the resistance of the set its self is 0.006 ohms the actual resistance of the grid is $0.058 - 0.006 = 0.052$ ohms. From this we find

resistance of series field	0.012	$=$	$\frac{0.012}{0.052}$	which shows that $12/52$ or 23.8%
resistance of grid	0.052			

of the current flows through the grid while 79.2 flows around the series field. At full load there will be $200 \times .792 = 158.4$ amperes flowing in the series winding. Then $\frac{175070}{158.4} = 1105.2$ circular mils per ampere in the series field.

Circular Mils of Wire per Ampere in Armature.

The armature winding is $.07" \times .625 = .04375$ sq. inches or 55704 circular mils in cross section. Since the armature is wave wound there are two paths in parallel between the brushes thus making $1/2$ the current flow in each conductor. There will therefore be $\frac{55704}{100} = 557.04$ circular mils per ampere in the armature.

Leakage Coefficient.

The leakage coefficient of a dynamo is the ratio of the total flux set up in the field to the flux that passes through the armature. In making this test the armature is kept stationary and the field is excited. A switch is put in the field circuit so that it can be made and broken. A single turn of fine wire was placed around a field pole and a galvanometer connected to it. When the exciting current was made and broken a deflection was produced on the galvanometer. A turn of the same wire was placed directly under the pole on the armature so as to surround the lines of force entering it; and the deflection of the galvanometer at make and break was again noted. The ratio of the deflections was a rough measurement of the leakage coefficient.

The following readings were taken with the field current kept constant at 5.65 amperes.

11.

Field		Armature	
Make	Break	Make	Break
2.5	2.52	2.4	2.44
2.5	2.50	2.4	2.44
2.5	2.55	2.4	2.44
Means 2.5	2.53	2.4	2.44
Ratio of makes $\frac{2.5}{2.4}$		Ratio of breaks $\frac{2.53}{2.44}$	

Now if the ratio were exactly $25/24$ and we wind 24 turns of wire around the field and 25 in the opposite direction on the armature, the two currents would exactly neutralize each other and the galvanometer would give no deflection.

The following readings were taken with different ratios.

Ratio	Make	Break
$\frac{25}{24}$	1.7 c.m. right	1.8 left
$\frac{26}{24}$	3.1 c.m. left	2.8 right

From this it is seen that the directions of deflection were reversed when the ratio was changed from $\frac{25}{24}$ to $\frac{26}{24}$. Also that a difference of one turn causes a difference in deflection at make of 4.8 c.m. to the left. But in order for there to be no deflection the reading would have to be moved 1.7 c.m. to the left when the ratio was $\frac{25}{24}$ we would add $\frac{1.7}{4.8}$ turn on the armature thus giving the ratio $\frac{25.354}{24} = 1.056$ for the leakage coefficient.

When the readings at break are used we must add $\frac{1.8}{4.6} = .391$ turn on the armature thus making the ratio $\frac{25.391}{24} = 1.058$.

Taking the mean we have for the leakage coefficient 1.057 which shows that the total flux set up in the field is 1.057 times the flux that passes into the armature.

Flux Density in Field.

If Φ = flux entering the armature.

P = number of poles.

Z = number of conductors on armature.

P' = paths in parallel between brushes.

E_a = total electromotive force induced in the armature.

N = speed in revolutions per second.

Then the fundamental equation of the dynamo is $E_a = \frac{P \Phi Z N}{P' \times 10^8}$ volts.

All of these terms are known except Φ . $E_a = 250$ $Z = 119 \times 4 = 146$

$$P = 6 \quad N = \frac{290}{60} = 4.833 \quad P' = 2$$

$$250 = \frac{6 \times \Phi \times 146 \times 4.833}{2 \times 100000000} = .000040455 \Phi$$

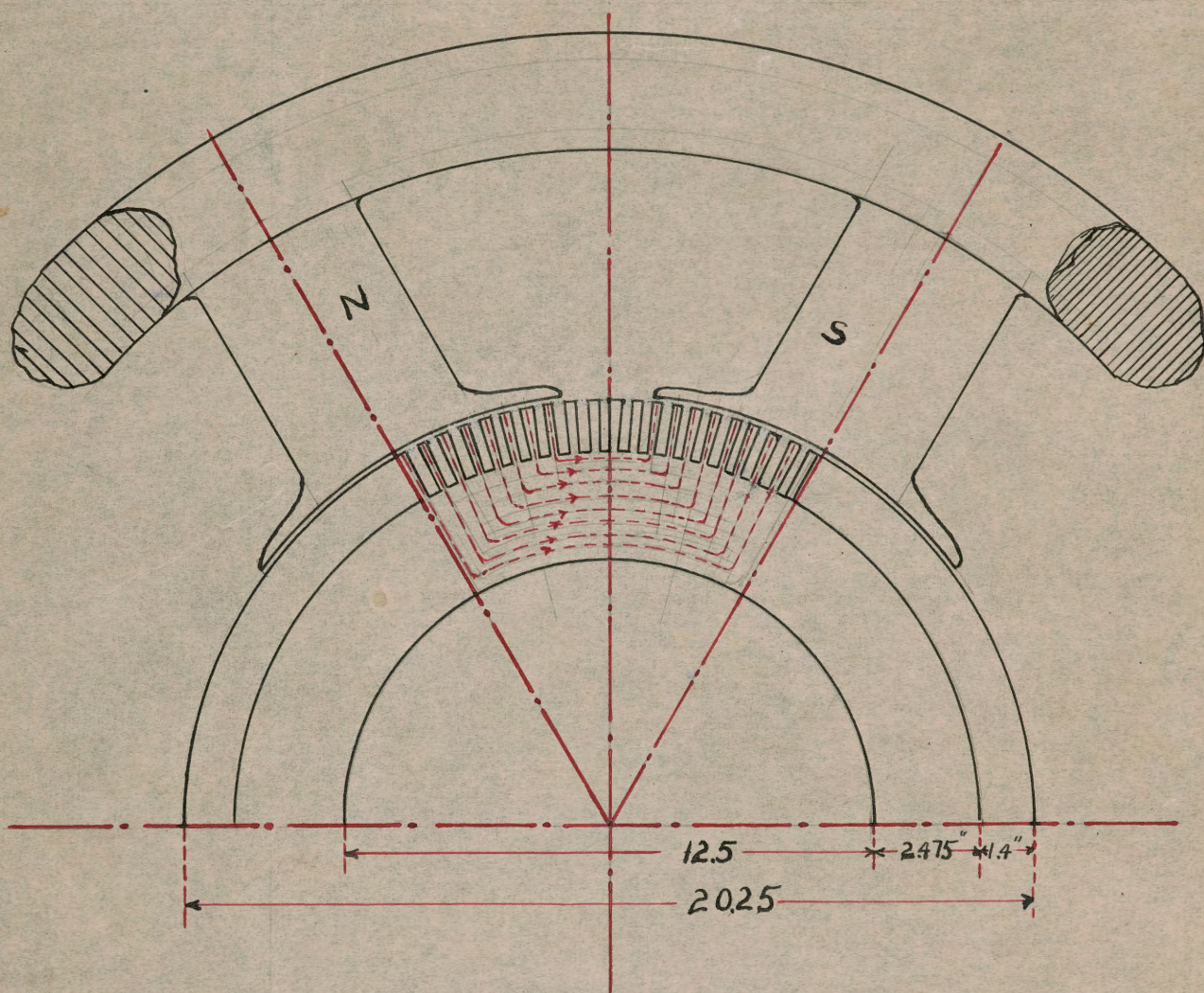
$$\Phi = \frac{250}{.000040455} = 6180000 \text{ lines entering the armature or}$$

$6180000 \times 1.057 = 6530000$ lines in the field. The area of the field is $4.5 \times 11.625 = 52.31$ sq. inches.

The flux density in the field is therefore $\frac{6530000}{52.31} = 124000$ lines per sq. inch.

Flux Density in Armature and Armature Teeth.

In the drawing on the following page the dotted lines show the approximate path of the flux in the armature. It is seen that the thickness of the iron in this portion is 2.475" while the length parallel to the shaft is 12.75", with three ventilating ducts 0.375" long



PATH OF FLUX.

Scale - $\frac{1}{4}$ size.

13.

making the net length $12.75 - 3 \times .375 = 11.625$ ". Now taking 0.9 of this length as actual iron we get $11.625 \times .9 \times 2.475 = 25.9$ sq. inches to carry the lines of force. The flux coming out from a north pole divides and only half of it flows through any cross section of the armature core and we have

$$\begin{array}{r} 6180000 \\ \hline \text{-----} = 3090000 \text{ lines passing through } 25.9 \text{ sq. inches thus giving} \\ 2 \\ 3090000 \\ \hline \text{-----} = 119000 \text{ lines per square inch in the armature.} \\ 25.9 \end{array}$$

Teeth.

The width of the top of a tooth with its slot is $0.26 + 0.274 = 0.534$ " while the width of the pole face is 8.5" thus there will be $\frac{8.5}{0.534} = 16$ teeth under each pole face. Taking 0.9 of the core length as actual iron we have for the area of each tooth at the top $11.625 \times 0.9 \times 0.274 = 2.87$ sq. inches to carry flux.

As there are 16 teeth we have for the total area of the top of the teeth per pole $2.87 \times 16 = 45.92$ sq. inches. The total flux coming from the pole into the armature is 6180000 lines which gives for the density

$$\begin{array}{r} 6180000 \\ \hline \text{-----} = 134000 \text{ lines per sq. inch. at the tops of the teeth.} \\ 45.92 \end{array}$$

Width of tooth at the root 0.238". Total cross section per tooth $11.625 \times .9 \times .238 = 2.49$ sq. inches.

Total area of 16 teeth 38.05 sq. inches.

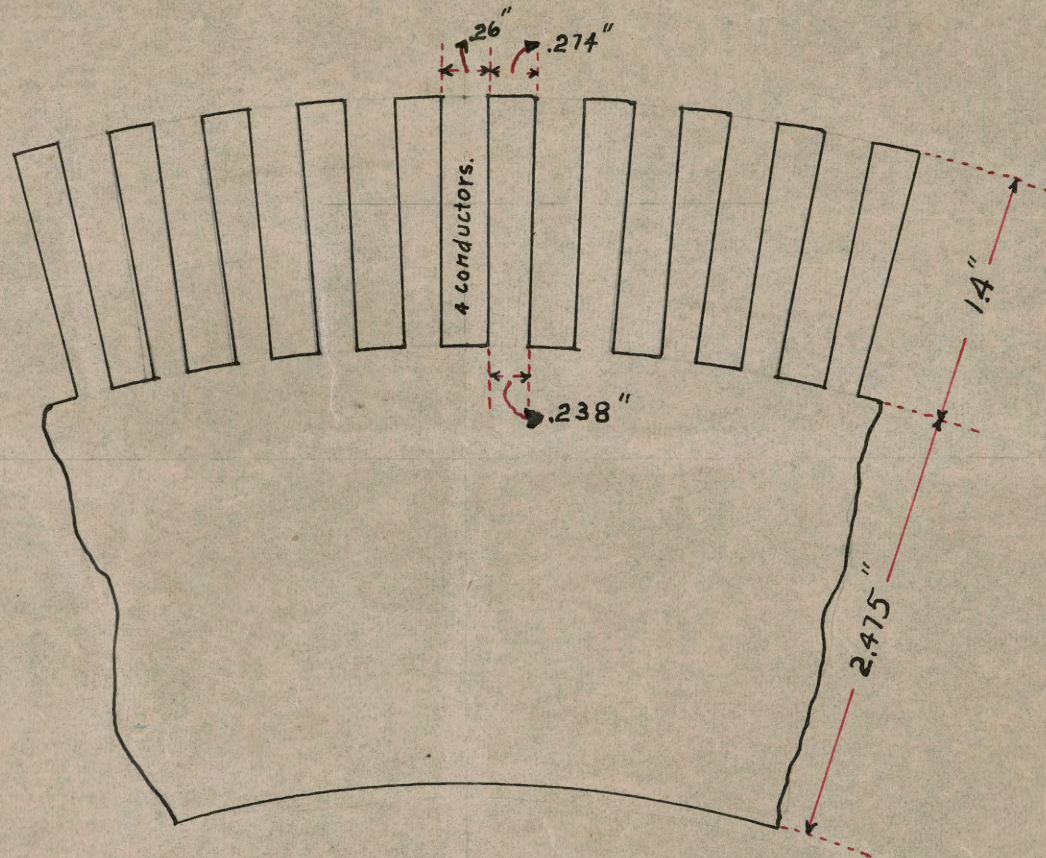
The density at the roots of the teeth is therefore $\frac{6180000}{38.05} = 162000$ lines per sq. inch.

On the following page is shown the dimensions of the teeth.

Weight Per Kilowatt.

The weight of the armature and commutator without the shaft is

SECTION OF ARMATURE TEETH.



Scale:- Full Size.

given by the manufacturer as 1400 lbs. The field without the bearings is 3800 lbs, making a total weight of 5200 lbs. which is 104 lbs. per K.W. output.

Comparison.

	Edison	Thompson-Ryan	General Electric
Output K.W.	20	25	50
Field poles	2	10	6
Voltage	125	125	225/250
Amperes	160	200	200
Speed	1500	325	290
Flux density			
field	83000		124000
armature	49000		119000
Circular mils per amp. small large			
shunt field	185.2 246.3	1088	902.5
series field		1243	1105.2
armature	5.18	1590	557.0
Armature Reaction	4°-46'- 28"		6°- 3'
Weight per K.W.	113		104
Latest patent	1882	1893	1902
Leakage coefficient	1.54		1.054

In the Edison generator there are two sizes of wire on the shunt field.

CALIBRATION CURVE
FOR
LABORATORY STANDARD VOLTMETER.

ERROR

4

2

0

2

4

6

8

10

12

10

20

30

40

50

60

70

80

90

100

110

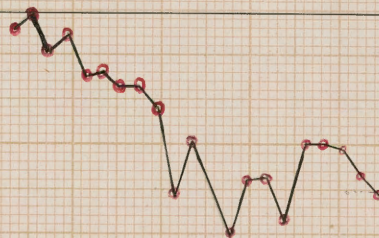
120

130

140

READINGS.

ZERO LINE OF ERROR.

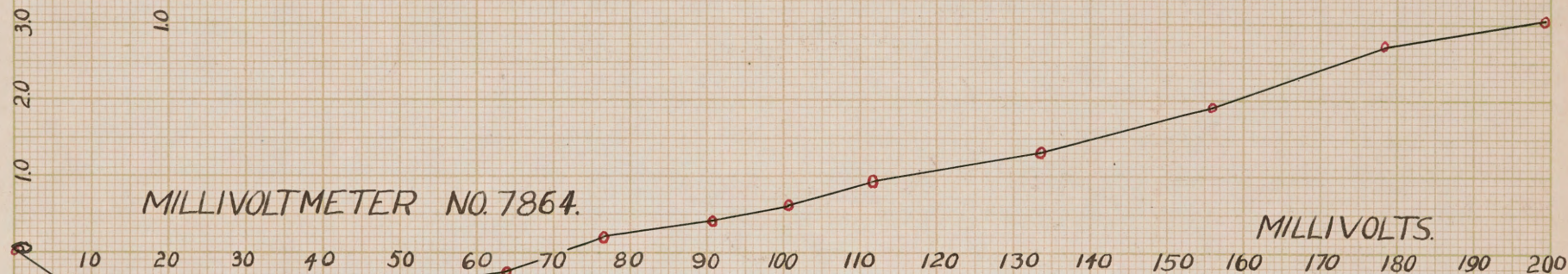


CALIBRATION CURVES FOR INSTRUMENTS.

SIMPLEX-150-VOLTMETER



MILLIVOLTMETER NO. 7864.



SWITCH-BOARD AMMETERS.

