

THE ELECTRONIC RECTIFIER AS A POWER SUPPLY

FOR

D C MOTORS

By

Thomas Leonard Phillips

A THESIS WRITTEN IN PARTIALLY FULFILLING THE REQUIREMENTS

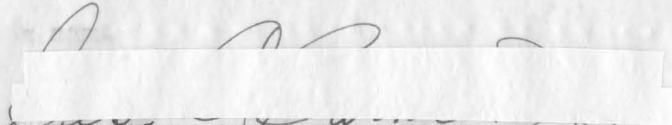
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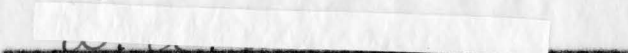
MASTER OF SCIENCE


IN


ELECTRICAL ENGINEERING

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## I. INTRODUCTION

Industrial users of direct current power, such as the Street Railway Companies, the Mining Industry, and the Electroplating Industry, have been for years faced with the problem of selecting the most economical and satisfactory way of rectifying a-c power. It has been determined long ago that direct generation of d-c power is quite useless, since the losses incurred in d-c transmission are prohibitive in magnitude. The problem therefore resolves to one of selecting the best means of a-c rectification.

Motor-generator conversion units represent one of the earliest ways of rectifying large amounts of power. Although the performance of the M-G set is quite satisfactory, the combined losses of two machines make this a rather inefficient process.

It was later discovered that a-c rectification could be accomplished by a single machine, the rotary converter. The rotary converter gives the same satisfactory performance of the M-G set; and, in addition, performs the rectifying process much more efficiently.

In recent years electronic rectifiers such as the steel-tank mercury-arc rectifier, the ignitron, and excitron, have been developed; and in many industries have replaced rotating machinery.

Manufacturers of electronic rectifiers have claimed some outstanding advantages for their product over other types of rectifiers. An example of this may be found in a pamphlet published by the Westinghouse Electric Corporation stating the advantages of the



ignitron rectifier over the motor-generator set. Among the advantages listed are higher efficiency, smaller no load losses, larger overload capacity, better voltage regulation and less noise. In view of all these advantages it is small wonder that many industries have replaced their M-G sets and converters by electronic rectifiers.

However, despite all the advantages claimed by rectifier manufacturers, the real merit of the rectifier should be judged on its ability to satisfactorily fulfill the various industrial needs. With the exception of the electroplating industry, the principal need of rectified power is for the operation of d-c motors. The question therefore resolves to one of whether or not satisfactory operation of d-c motors can be achieved with a rectifier power supply. To help answer this question, the author has conducted tests with both a rectifier and a converter output, and has noted especially the heating, efficiency, and commutation effect on several motors.

## II. THE PLAN

The principles governing the operation of d-c motors are well known to all electrical engineers. The shunt motor is ideally suited for industrial uses requiring almost constant speed under varying load. The series motor finds wide usage in hoists, cranes, and locomotives where high starting torque is the primary requirement. Any desired combination of speed regulation and starting torque is attainable in compound motors by proper design of the series and shunt fields.

Various other considerations are introduced, however, if the d-c power to operate these motors is obtained by electronic rectification of a-c power. For example, a motor under the same load will heat faster when operating from an electronic rectifier than when operating from the conventional rotary converter.

In an effort to obtain definite results, a series of tests have been conducted on several motors, first using the rotary converter as a source of power, then the electronic rectifier.

In the explanation of experimental results, a standard procedure will be followed in this entire report. First, a brief consideration of the normal operating characteristics of d-c motors will be made to refresh the reader's memory. Then all changes in conventional characteristics due to electronic rectification will be considered.

### III. THE TESTS AND RESULTS

The two different sources of power used for conducting the various tests are listed with their name-plate data as follows:

Direct Current Generator

General Electric Co.

35-KW Compound Wound

125-Volts 200-Amps 1750 RPM

and

The Ignitron

Westinghouse Electric Corporation

3-Phase Half-Wave

250-Volts 75-Amps

The generator was used instead of a rotary converter merely because it was more convenient to do so. There is no error introduced by doing this, since the outputs of the two machines are identical.

It is realized that the three-phase half-wave rectifier available in the VPI power laboratory is not representative of electronic rectifiers used in industry. However, the problems that would arise in larger rectifiers with a greater number of phases are similar in nature to the ones arising here. The basic difference is only in the magnitude of current distortion that rectifiers with different design features give.

The motors tested are all located in the Virginia Polytechnic Institute power laboratory and are listed with their name-plate data as follows:

Direct Current Motor

General Electric Company

10-HP Shunt Wound

115 Volts 76.5 Amperes 900/1800 RPM

Direct Current Motor

General Electric Company

Compound Wound

125-Volts 56 Amperes 1500 RPM

Direct Current Motor

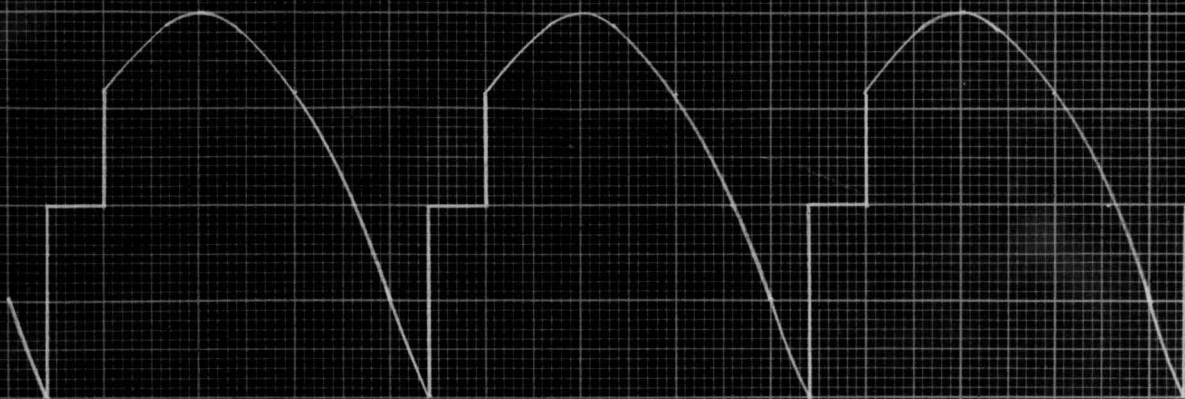
General Electric Company

10-HP Shunt Wound

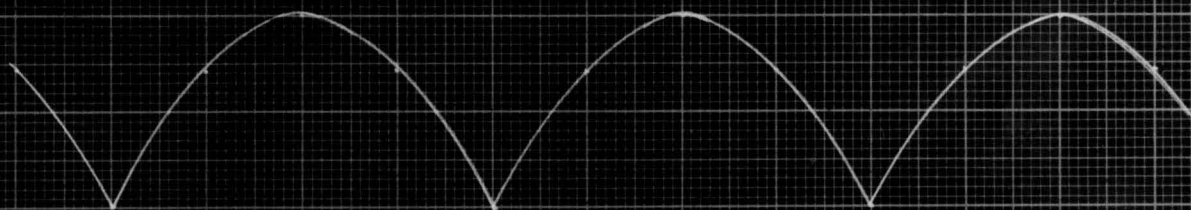
220-Volts 38 Amperes 3600 RPM

Due to the fact that the rated output of the Westinghouse Ignitron is 250 volts, and all the generators available have outputs of 125 volts, it became necessary to make certain arrangements in the operation of the various motors tested. The 250-volt motor was operated directly from the ignitron in one test, and from two generators connected in series in a comparison test. The 125-volt motors were operated directly from the generator in one series of tests and from the ignitron with a voltage-reducing resistor in series in the corresponding comparison tests. This arrangement slightly altered the input wave form to the armature, but not enough to cause an appreciable error.





(a) VOLTAGE WAVE FORM



(b) CURRENT WAVE FORM

FIG. 1  
TYPICAL WAVE FORMS  
OF WESTINGHOUSE RECTIFIER  
THE THREE PHASE IGNITRON

The output voltage wave form of the Westinghouse Ignitron as observed in the cathode ray oscilloscope is pictured in Fig. 1 (a). A typical current wave form is pictured in Fig. 1 (b). The cut-off point in the voltage wave form is controlled by a saturable reactor type of firing circuit in the rectifier unit. The cut-off point may be varied, thereby varying the output voltage. The current wave form will always have approximately the shape shown in Fig. 1 (b). The percentage ripple will vary inversely with the inductance of the load.

Although the tests conducted were very simple in nature, the results obtained were quite conclusive. Three distinctly different types of tests were made; namely, temperature tests, pronybrake full load efficiency tests, and stray power tests.

#### The Temperature Tests

Full-load temperature tests were conducted on two different motors. The motors were purposely chosen with widely different operating characteristics. One motor was rated at 220 volts, 38 amps, 3600 RPM and contained interpoles. The other was rated at 115 volts, 56 amps, 1500 RPM and did not contain interpoles. Both were shunt wound. Direct temperature measurements were made by means of thermometers in direct contact with the yoke. In addition, resistance measurements of armature and field windings were made before and after the temperature runs as a check against the thermometers. Temperature measurements were taken every half hour and the tests were continued until three consecutive thermometer readings indicated no further change in temperature.



Fig 2

COMPARISON OF TEMPERATURE VS TIME CURVES  
 ON A 110-VOLT 56 AMP 1500 RPM GE MOTOR  
 WHEN OPERATED FROM CONVERTER AND RECTIFIER  
 MOTOR LOADED TO 100% OF RATED LOAD.  
 THERMOMETER LOCATED ON YOKE OF MOTOR.

TEMPERATURE °C

TIME : HOURS



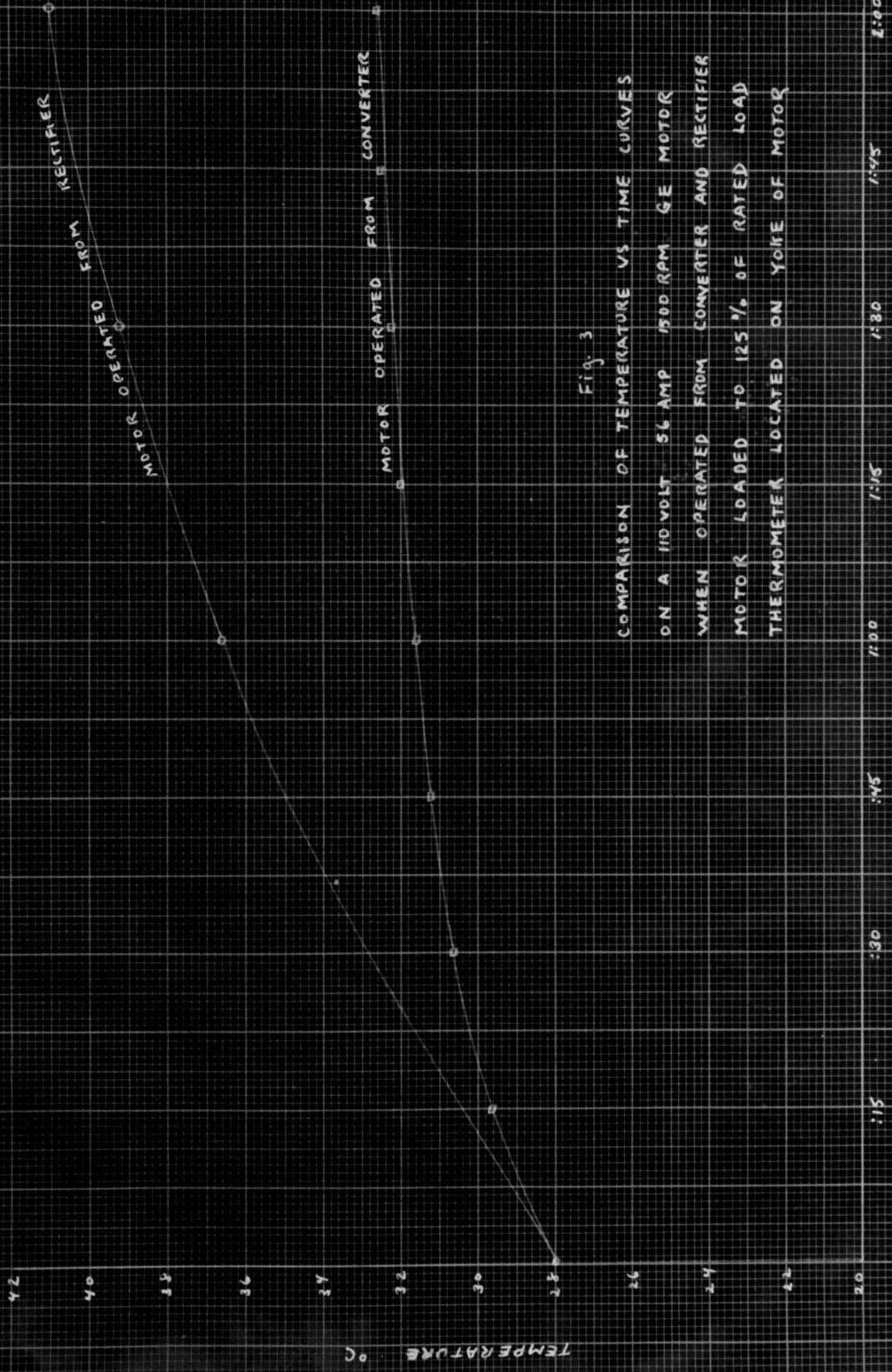


Fig. 3

COMPARISON OF TEMPERATURE VS TIME CURVES  
 ON A 110VOLT 56 AMP 1500 RPM GE MOTOR  
 WHEN OPERATED FROM CONVERTER AND RECTIFIER  
 MOTOR LOADED TO 125 % OF RATED LOAD  
 THERMOMETER LOCATED ON YOKE OF MOTOR

TIME : HOURS AND MINUTES



In addition to the full load temperature tests, temperature runs of two-hour duration were made with the motors loaded at 125% of rated load.

#### Results of Temperature Tests

Consider first the curves of Fig. 2. Here the 110-volt motor has been loaded to its rated full-load value and operated alternately from the converter and the rectifier. In operating from the converter, the motor heated from a room temperature of  $28.6^{\circ}\text{C}$  to an equilibrium temperature of  $34.2^{\circ}\text{C}$ , a net rise of  $5.6^{\circ}\text{C}$ . In operating from the rectifier, the motor heated from a room temperature of  $28.6^{\circ}\text{C}$  to an equilibrium temperature of  $40.5^{\circ}\text{C}$ , a net rise of  $11.9^{\circ}\text{C}$ . When the motor under both operating conditions has reached a temperature equilibrium, it is seen that rectifier operation is  $11.9^{\circ}\text{C}$  hotter than converter operation. Resistance measurements of field and armature, and temperature-resistance calculations verify the thermometer readings.

Next consider the curves of Fig. 3, where the same tests are conducted on the same motor under conditions of 125% rated load. Since these tests were conducted for a duration of only two hours, a temperature equilibrium was not reached in either converter or rectifier operation. Converter operation shows a temperature rise of from  $28^{\circ}\text{C}$  to  $32.6^{\circ}\text{C}$ ; rectifier operation shows a temperature rise of from  $28^{\circ}\text{C}$  to  $41^{\circ}\text{C}$ . At the end of two hours, rectifier operation has made the motor  $8.4^{\circ}\text{C}$  hotter than converter operation. It is worthy to note from Fig. 3 that at the end of two hours the rectifier curve is still rising faster than the converter curve.

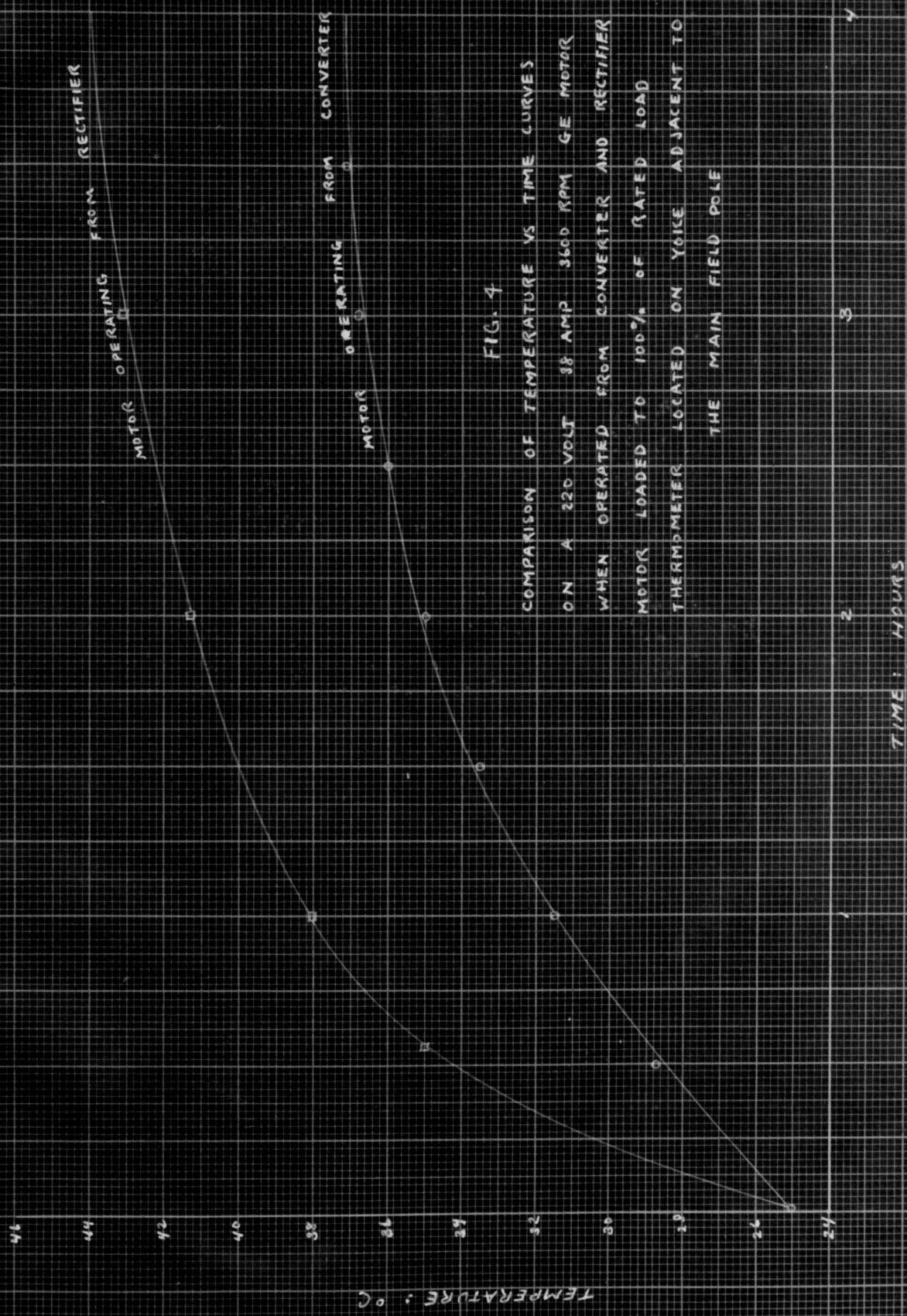


FIG. 4  
 COMPARISON OF TEMPERATURE VS TIME CURVES  
 ON A 220 VOLT 38 AMP 3600 RPM GE MOTOR  
 WHEN OPERATED FROM CONVERTER AND RECTIFIER  
 MOTOR LOADED TO 100% OF RATED LOAD  
 THERMOMETER LOCATED ON YOKE ADJACENT TO  
 THE MAIN FIELD POLE





FIG 5

COMPARISON OF TEMPERATURE VS TIME CURVES  
 ON A 220 VOLT 38 AMP 3600 RPM 6.5 MOTOR  
 WHEN OPERATED FROM CONVERTER AND RECTIFIER.  
 MOTOR LOADED TO 125% OF RATED LOAD.  
 THERMOMETER LOCATED ON YOKE ADJACENT TO  
 THE MAIN FIELD POLE.

TIME : HOURS AND MINUTES

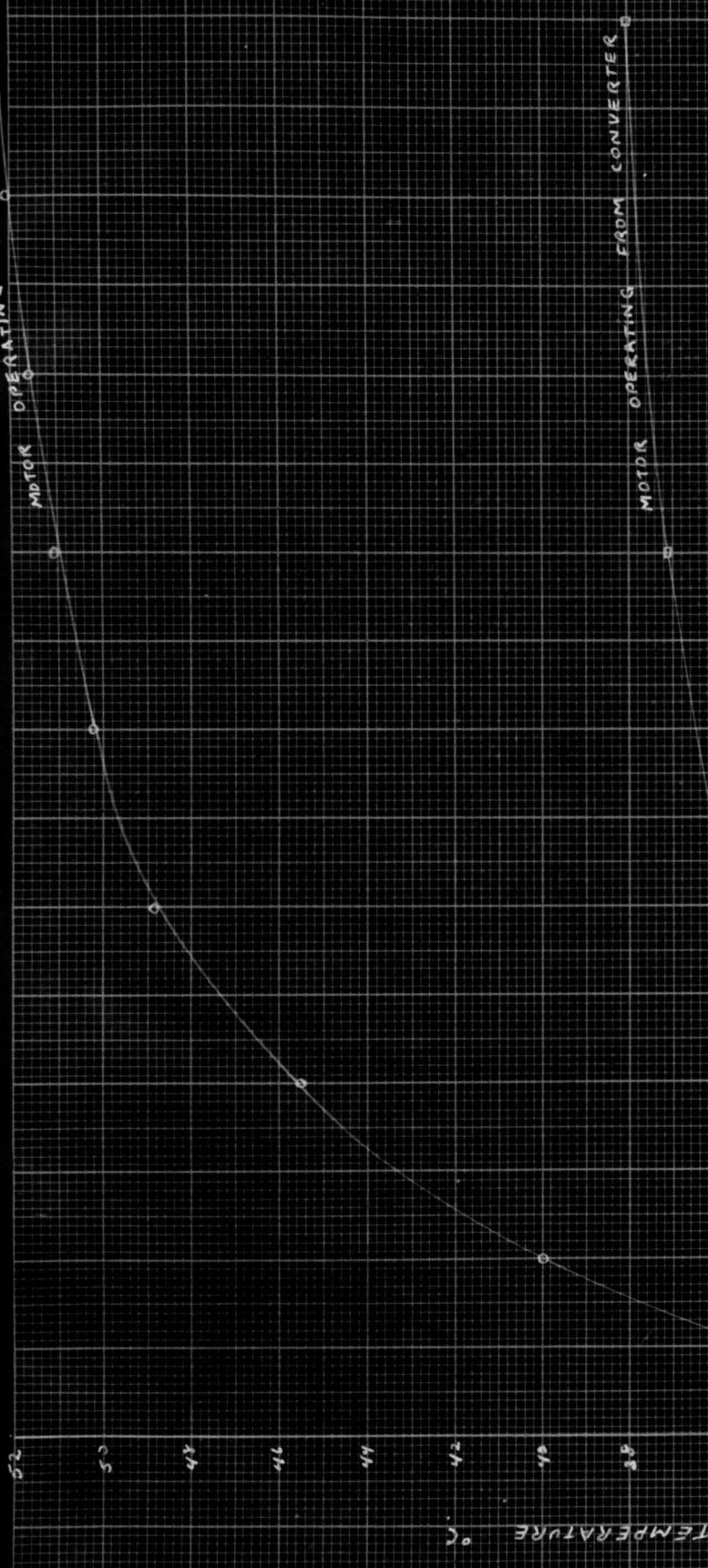
Fig. 4 shows 100% full load temperature versus time curves on the 220-volt motor tested. At the end of four hours both converter and rectifier operation show that the motor is approaching a temperature equilibrium. Under converter operation, the motor heated from a room temperature of  $25^{\circ}\text{C}$  to an equilibrium temperature of  $37.1^{\circ}\text{C}$ , a net rise of  $12.1^{\circ}\text{C}$ . Under rectifier operation, the motor heated from a room temperature of  $25^{\circ}\text{C}$ , to an equilibrium temperature of  $44^{\circ}\text{C}$ , a net rise of  $19^{\circ}\text{C}$ . The equilibrium temperature from rectifier operation is  $6.9^{\circ}\text{C}$  higher than the equilibrium temperature from converter operation. The 220-volt motor tested is a 4-pole motor with two interpoles. The data for the curves of Fig. 4 was read from a thermometer fastened to that part of the yoke adjacent to a main field pole.

As in the case of the 110-volt motor, 125% rated load temperature tests were also taken on the 220-volt motor, and were again conducted for a period of two hours. The results of these tests are shown in Fig. 5. Again the motor proved to heat faster under rectifier operation than under converter operation. At the end of two hours the rectifier-operated motor became  $3.7^{\circ}\text{C}$  hotter than the converter-operated motor.

During the conduction of a temperature test on the motor when operated from the rectifier supply, it was noticed that certain parts of the yoke were much hotter to the touch than others. Closer examination revealed that the part of the yoke adjacent to the interpoles was from 10 to  $12^{\circ}\text{C}$  hotter than all other portions of the yoke. It was this rather startling discovery which led to the curves of Fig. 6. The curves of



MOTOR OPERATING FROM RECTIFIER



MOTOR OPERATING FROM CONVERTER

Fig 6

COMPARISON OF TEMPERATURE VS TIME CURVES  
 ON A 220 VOLT 38 AMP 3600 RPM GE MOTOR  
 WHEN OPERATED FROM CONVERTER AND RECTIFIER.  
 MOTOR LOADED TO 125% OF RATED LOAD.  
 THERMOMETER LOCATED ON YOKE ADJACENT  
 TO THE INTERPOLE.

TIME : HOURS AND MINUTES

Fig. 6 are identically the same as the curves of Fig. 5; the only difference being that on the curves of Fig. 6, the thermometer was strategically located on that part of the yoke nearest an interpole. The temperature variation between rectifier and converter operation is the largest observed in any of the temperature tests. At the end of two hours, the motor when operated from the rectifier becomes  $14.3^{\circ}$  C hotter than when operated from the converter. An explanation of this phenomenon will be given in a later section of this report.

#### The Prony Brake Full Load Efficiency Tests

Since the temperature tests showed conclusively that a motor does operate hotter when operating from a rectifier than when operating from a converter, it was reasoned that hotter operation must also be less efficient operation. For this reason, full-load efficiency runs were made on the same 10-hp, 115-volt, 76.5-ampere motor first using the converter as the source of power, then the rectifier. The motor was loaded down by means of a prony brake. Direct readings of torque and speed substituted in the equation  $hp = \frac{2\pi NT}{33,000}$  gave a fairly accurate indication of the output power. The input was calculated directly from electric meter readings. The problem involved in metering pulsating direct current will be discussed in a section under "The Stray Power Test". A total of four efficiency runs were made; two each from the converter and rectifier and two each at 900 RPM and 1200 RPM.

Efficiency in Percent

Output in Horsepower

100  
90  
80  
70  
60  
50  
40  
30  
20  
10  
0

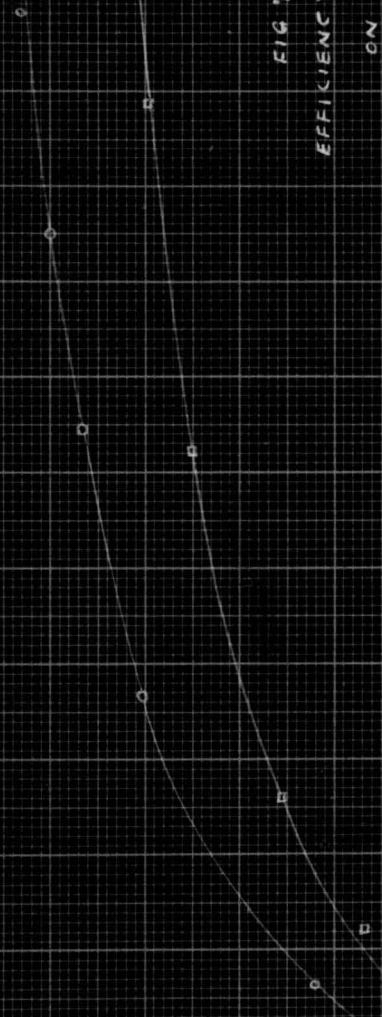
0 1 2 3 4 5 6 7 8 9

MOTOR OPERATED FROM CONVERTER  
MOTOR OPERATED FROM RECTIFIER

FIG 7  
EFFICIENCY TESTS

ON

GENERAL ELECTRIC DIRECT CURRENT MOTOR  
10-HP 115-VOLT 76.5-AMPS SHUNT-WOUND  
OPERATING SPEED: 1200 RPM





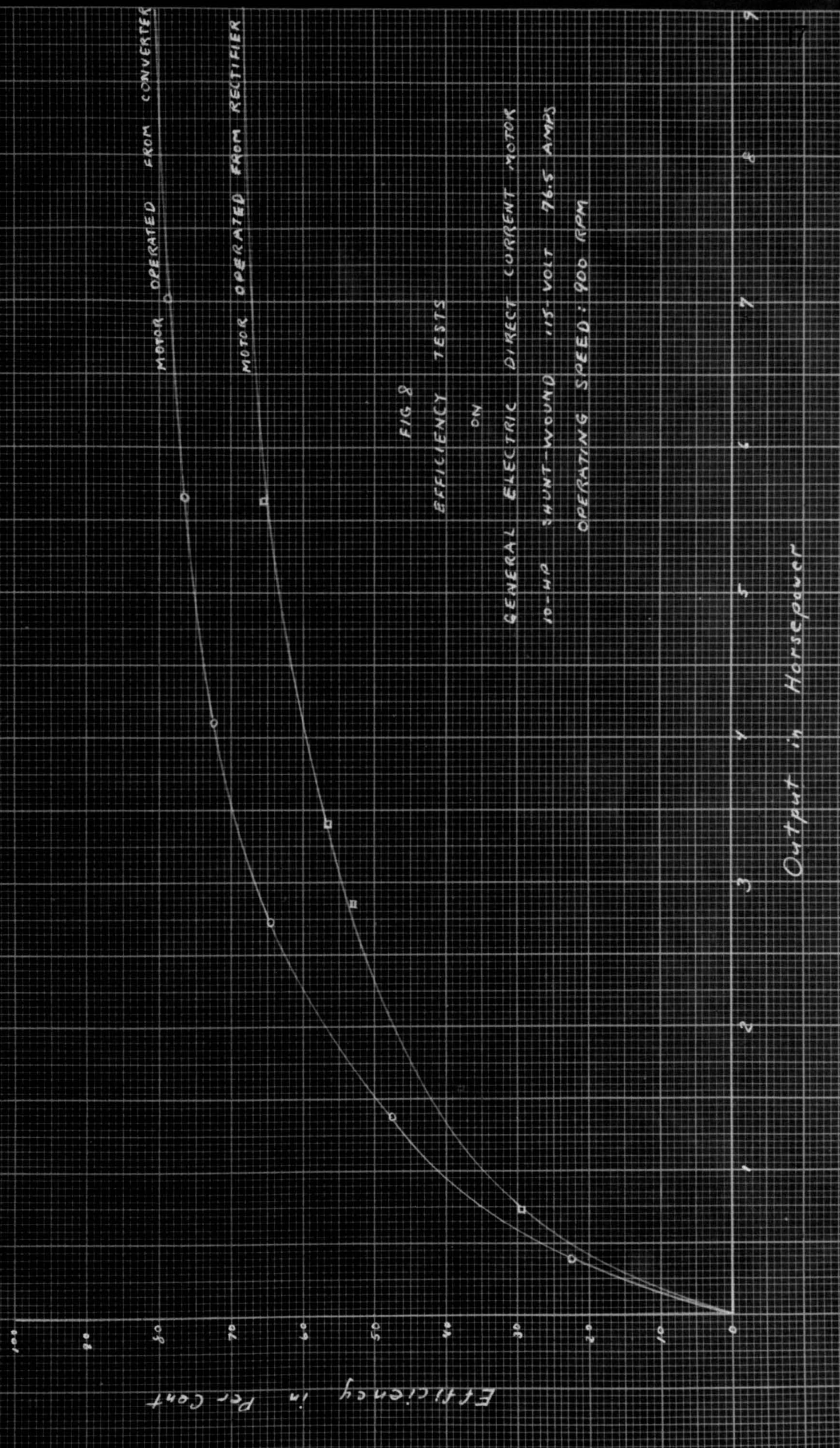


FIG. 8

EFFICIENCY TESTS

ON

GENERAL ELECTRIC DIRECT CURRENT MOTOR  
 10-HP SHUNT-WOUND 115 VOLT 76.5 AMPS  
 OPERATING SPEED: 900 RPM

Efficiency in Per Cent

Output in Horsepower

MOTOR OPERATED FROM CONVERTER

MOTOR OPERATED FROM RECTIFIER



### Results of the Efficiency Tests

The results of the efficiency tests are shown clearly in the curves of Figures 7 and 8. The curves of Fig. 7 were both calculated from data taken with the motor running at 1200 RPM; those of Fig. 8 were calculated from data taken with the motor running at 900 RPM. At all loads and speeds recorded, the motor tested operates more efficiently from the converter than it does from the rectifier. Over the most common operating range of a motor (from 50% load to 100% load), the motor tested operates from 10 to 12% more efficiently from the converter than it does from the rectifier.

Since in the case of every energy converting device the output equals the input minus the losses, it is quite easily believed that the losses incurred in rectifier operation greatly exceed those incurred in converter operation. The problem now is to locate the various losses in a motor and to determine why the losses increase when a rectifier supply is used.

### The Stray Power Test

In an attempt to compare the component losses, stray power runs were made on the same 115-volt motor, first supplying the power from a rotary converter, then from a three-phase electronic rectifier. To facilitate separation of the mechanical and core losses, the runs were made holding the speed constant and varying the field current over the operating range of the motor. In this manner it is possible to extend the curves to zero field current and find the power used at zero field current and a given

speed. Since core losses vary with speed and flux, while mechanical losses vary only with speed, the power measured at zero field current would constitute the mechanical losses at that speed.

The results of stray power tests on the motor operating from the synchronous converter are seen in Fig. 9. The results of stray power tests on the motor operating from the electronic rectifier are seen in Fig. 10. The combined results are seen in Fig. 11.

It must be admitted here that the accuracy of the results in Figures 9, 10, and 11 is rather questionable because of the inadequate means of taking measurements. At first an attempt was made to measure current and voltage with ordinary d-c meters. This was in error because d-c meters read average current and average voltage, while for power calculations a knowledge of RMS current and RMS voltage is required. When the rectifier is used, the ratio of RMS to average current is found to be about 1.25 in this particular motor. Therefore, the error involved in taking measurements with ordinary d-c instruments is substantial.

Next an attempt was made to measure stray power using an a-c wattmeter and a current transformer in conjunction with the d-c instruments. It was reasoned that only the a-c component of current would appear in the secondary of the current transformer. The wattmeter, with its current coil connected to the secondary of the current transformer and its potential coil connected across the armature would then only measure the a-c or "ripple power". This added to the product of the readings of the d-c voltmeter and d-c ammeter, was to give a fairly accurate measurement of stray power.

The difficulty found in this arrangement, was that the wattmeter available failed to give accurate readings. The a-c component of current from a 3-phase rectifier has a frequency of 360 cycles. The wattmeter used is guaranteed by the manufacturer to give accurate readings at frequencies below 133 cycles. Therefore this method too proved inadequate.

It was finally decided to use RMS a-c or d-c meters, and to take the product of RMS current and RMS voltage as an indication of the stray power used. This undoubtedly gives an accurate measurement of volt-amperes, but does it also give an accurate measurement of power? It must be remembered that the applied e.m.f. pulsates with a frequency of 360 cycles and that there is a considerable amount of inductance in the armature. The inductive reactance that results may be enough to cause the current to lag the voltage by a definite angle. If this angle of lag is considerable, then the power calculations made may well be in excess of the actual stray power.

This method of measurement was used for both the converter and the rectifier. It is undoubtedly the most accurate method with the instruments available in the Virginia Polytechnic Institute power laboratory. Therefore, for purposes of further discussion, it will be assumed that the graphs in Figures 9, 10, and 11 are correct.

#### Results of Stray Power Test

It was stated previously that the mechanical losses, brush friction, bearing friction, and windage, vary only with speed. Therefore, it would be expected that the mechanical losses in a motor will remain constant



FIG. 9

STRAY POWER VS FIELD CURRENT CURVES

FOR THE G.E. SHUNT WOUND D-C MOTOR

10 HP 115 VOLTS 76.5 AMPS 900/1800 RPM

OPERATING FROM SYNCHRONOUS CONVERTER

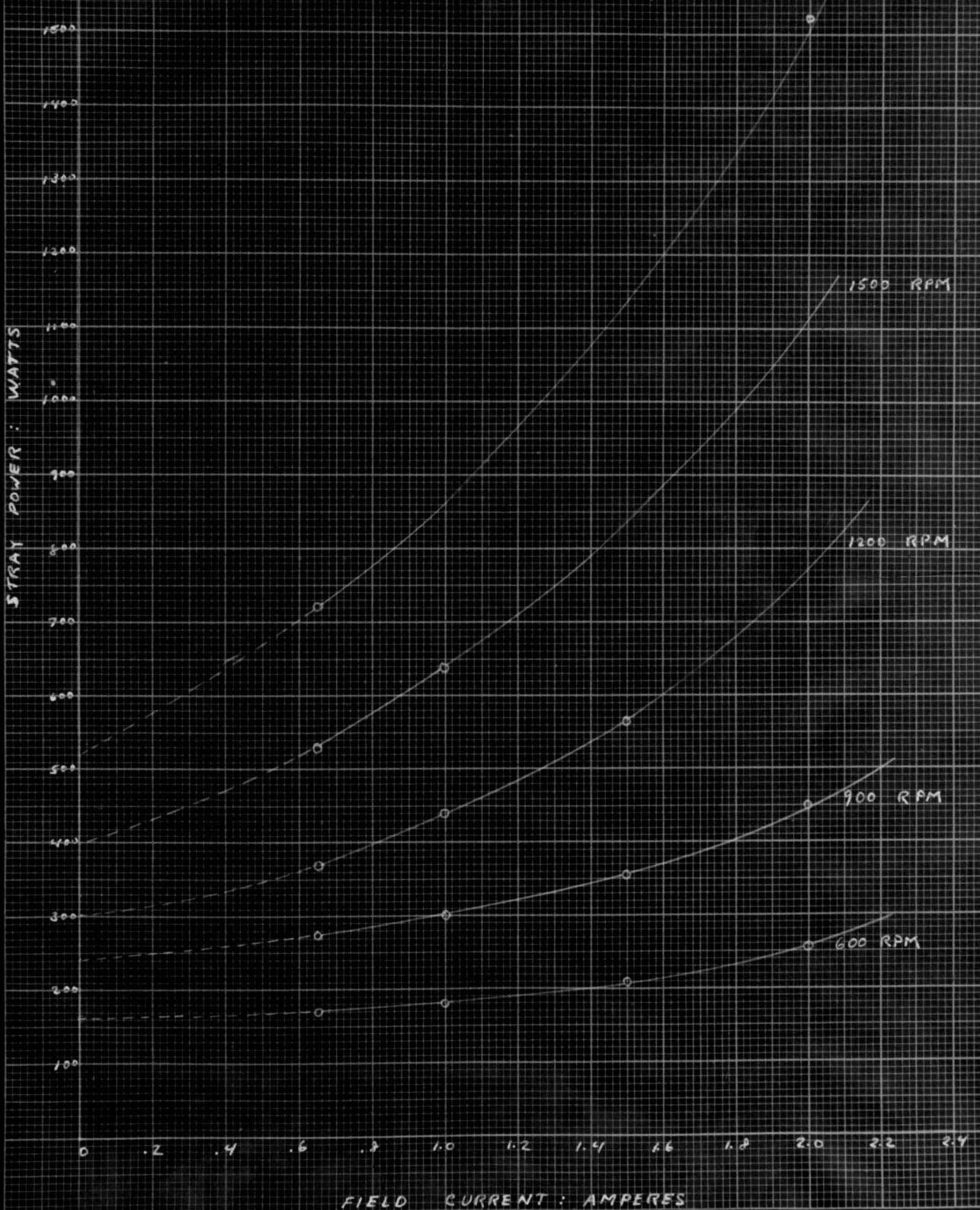


FIG. 10

STRAY POWER VS FIELD CURRENT CURVES  
 FOR THE G.E. SHUNT WOUND D-C MOTOR  
 10 HP 115 VOLTS 76.5 AMPS 900/1800 RPM  
 OPERATING FROM IGNITRON RECTIFIER

STRAY POWER : WATTS

1800  
1700  
1600  
1500  
1400  
1300  
1200  
1100  
1000  
900  
800  
700  
600  
500  
400  
300  
200  
100

.2 .4 .6 .8 1.0 1.2 1.4 1.6 1.8 2.0 2.2 2.4

FIELD CURRENT : AMPERES

1800 RPM

1500 RPM

1200 RPM

900 RPM

600 RPM

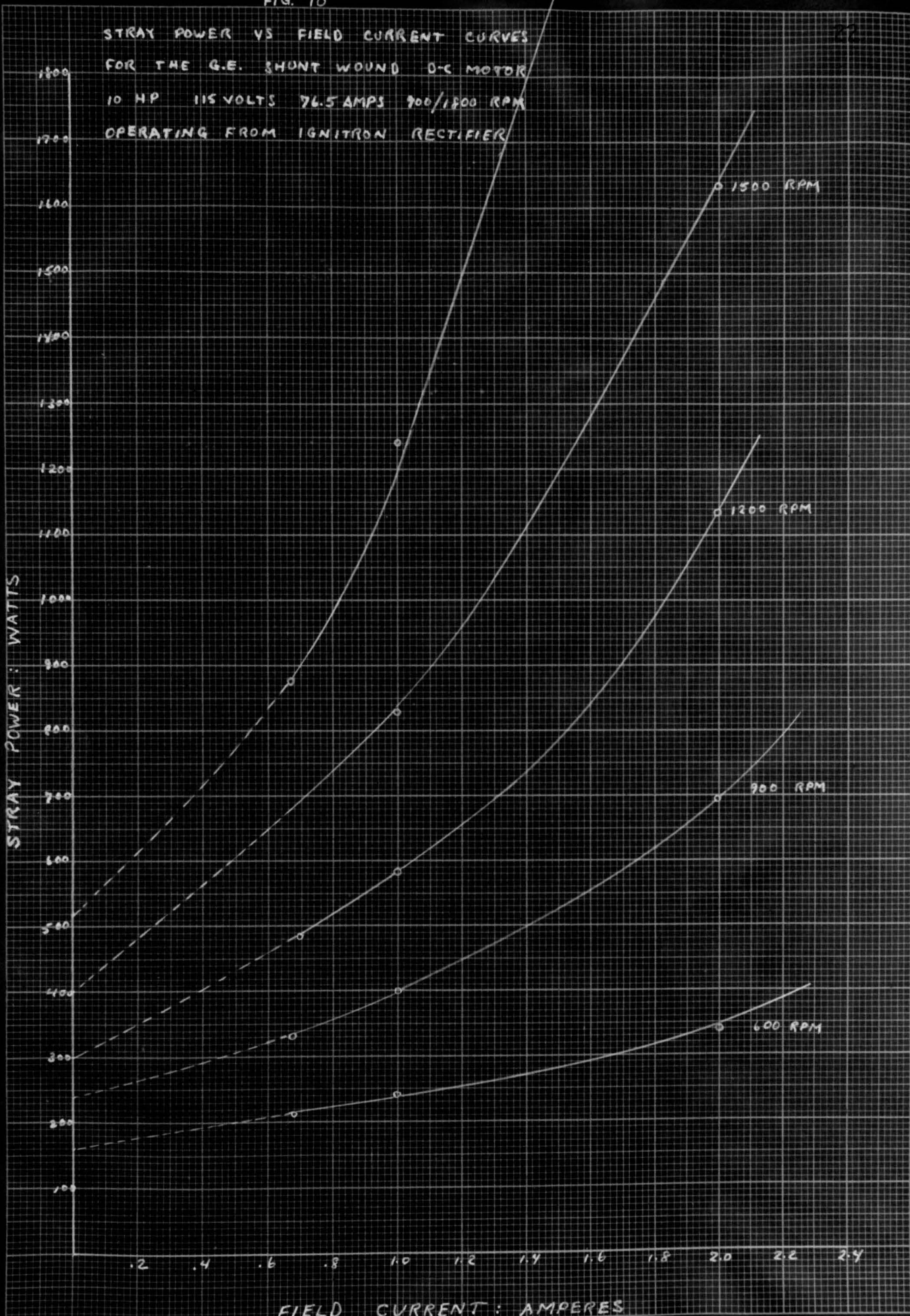
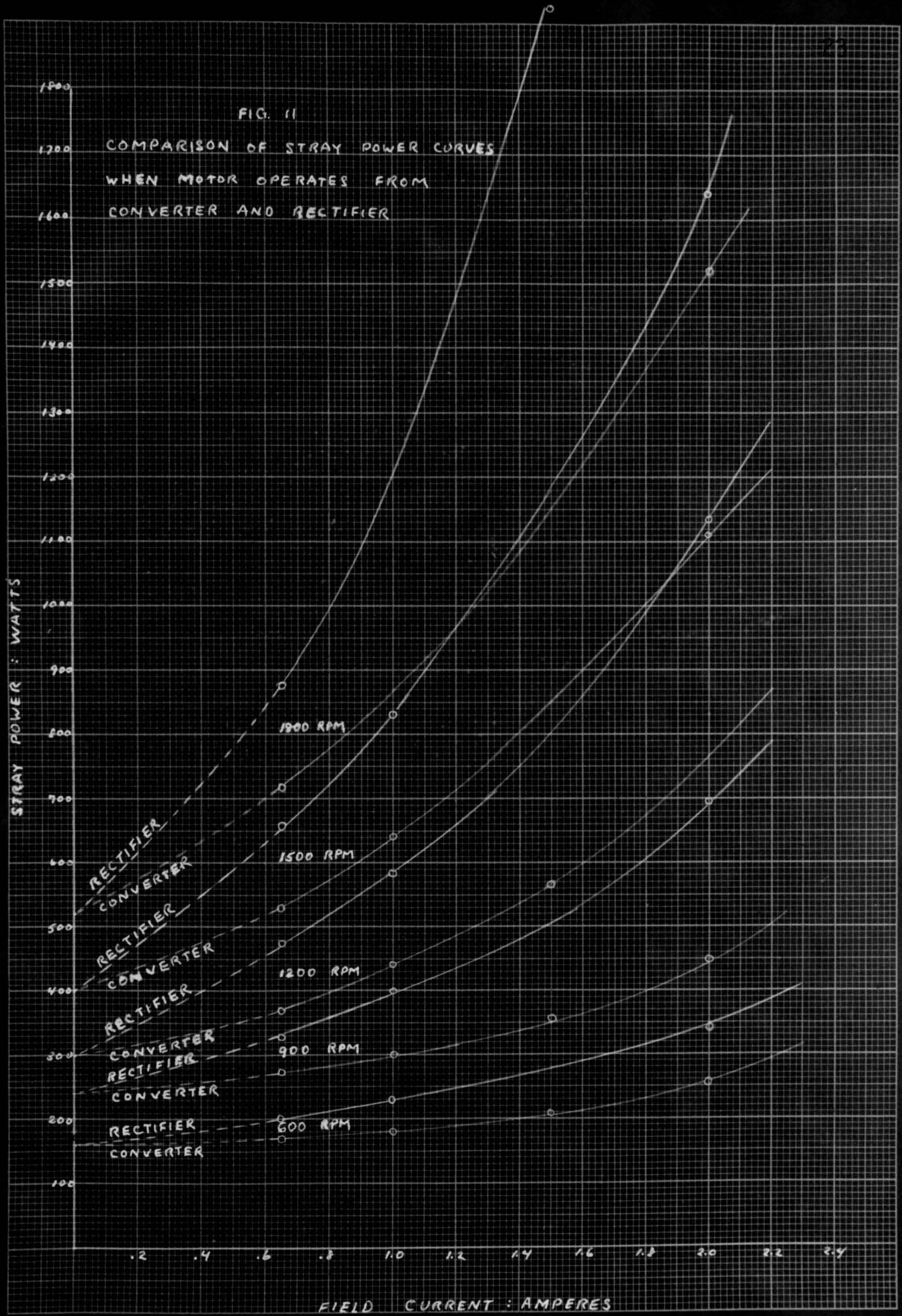




FIG. 11  
COMPARISON OF STRAY POWER CURVES  
WHEN MOTOR OPERATES FROM  
CONVERTER AND RECTIFIER





for a constant speed, regardless of whether the motor is operated from a converter or a rectifier. Although no actual readings are possible at a zero field current, it is seen from Fig. 11 that for each recorded speed, the "rectifier curve" approaches the same Y-intercept as the "converter curve". Therefore the assumption that mechanical losses will not vary with the amount of pulsation of the supply is fairly well established by experimental results.

It can be seen from the Stray Power Curves of Figures 9, 10, and 11 that the friction and windage losses for either source of power are as follows: 160 watts for 600 RPM, 240 watts for 900 RPM, 300 watts for 1200 RPM, 400 watts for 1500 RPM, and 520 watts for 1800 RPM. Consider, specifically, on Fig. 9 the Stray Power versus  $I_f$  curve for a constant speed of 1500 RPM. At any given field current the stray power reading on that curve is the sum of the friction and windage losses, the core losses, and an armature copper loss which is small enough to be neglected. Subtracting the constant friction and windage losses of 400 watts from the reading on the curve will give the core losses for that particular value of field current and for the particular speed of 1500 RPM. In like manner, the core losses for any field current and any speed in the operating range of the motor can be found. The curves of Figures 9, 10, and 11 reveal the fact that core losses increase with increased field current and also increase with increased speed. The fact that the curves are concave upwards shows that core losses increase as some power of field current which is at least greater than one. The fact

that the curves are not parallel to one another but diverge as the speed increases shows that core losses increase as some power of speed which is at least greater than one. This is merely pointed out to show that the curves obtained are in harmony with the empirical equations for hysteresis and eddy currents developed by Steinmetz\*.

$$*Hysteresis = k_1 f B^{1.6}$$

$$Eddy currents = k_2 f^2 B^2$$

#### IV. EXPLANATION OF RESULTS

##### Heating

The factor of greatest interest in the stray power curves may be found by observation of Fig. 11. Here it is seen that the core losses of the motor when operated from a rectifier are greater than the core losses of the motor when operated from a converter. This is true for any given value of field current and speed within the operating range of the machine. To better understand the reason for this, it is best to separate the core losses into hysteresis losses and eddy current losses and to consider each individually.

Consider, first, the hysteresis loss in the armature. Under normal operating conditions, the relative motion between the armature and the magnetic field will cause periodic reversals of magnetism in the armature core. This results in a loss of power due to molecular friction in the mass of the core, usually known as a hysteresis loss.

In general, any changing magnetic field will be accompanied by a hysteresis loss, the magnitude of which depends on the magnitude of the magnetic field, the rate at which the field is changing, and the quality of the magnetic material.

When a motor is operated from a rectifier supply, the field will pulsate in space at a rate depending on the number of phases in the rectifier. The magnitude of the pulsations will depend on the percentage ripple of the rectifier and the amount of inductance in the field circuit. The pulsating field now gives rise to a hysteresis loss in the armature



core that would exist even if the armature were not rotating. The resultant hysteresis loop due to the rotation of the armature in a pulsating field would be irregular in shape and of larger area than the customary hysteresis loop of a non-pulsating field.

Consider the specific problem of a 4-pole 900-RPM motor supplied by a three-phase electronic rectifier. The magnetism in the armature core will reverse completely 60 times a second due to the rotation of the armature. The magnetism in the armature core will increase and decrease 360 times a second due to the pulsations of the field. The hysteresis loops due to rotation will vary as the 1.6 power of the magnitude of the field flux. The hysteresis loops due to pulsations in the field will vary as the 1.6 power of the magnitude of the pulsations. Thus for every large hysteresis loop due to rotation there will be six small hysteresis loops due to pulsations. Because the two occur simultaneously, the pulsating effect will not actually give closed hysteresis loops. The net resultant configuration will be a large hysteresis loop with three pulsations on one side and three on the other. In any event, it can easily be seen that the hysteresis loss in the armature will be greater, when the main field is pulsating.

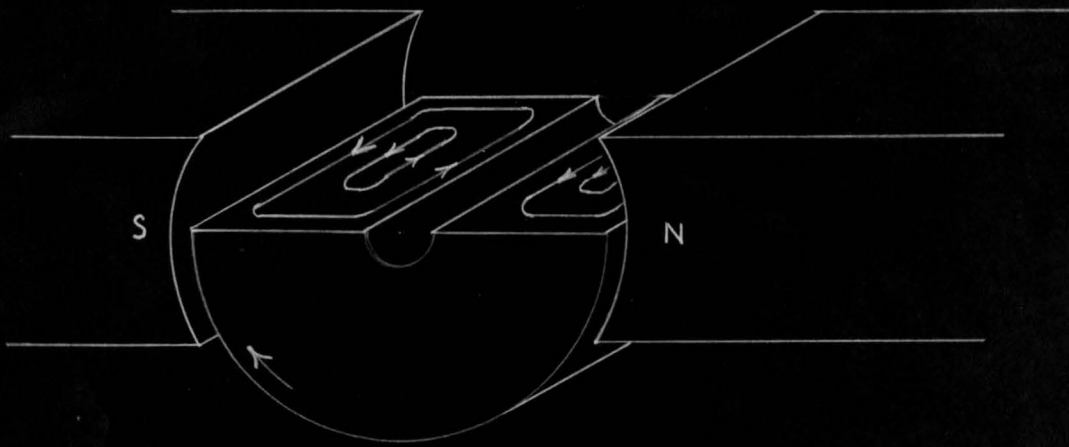
In the ordinary operation of a d-c motor, hysteresis losses do not occur in the yoke, and pole pieces because of the steady condition of the flux existing in that part of the magnetic circuit. When a rectifier supply is used, however, the flux in the yoke and pole pieces will pulsate, although it will never actually reverse in direction. The result is hysteresis losses in the yoke and pole pieces of a magnitude

proportional to the frequency of the rectifier and the 1.6 power of the pulsations of the field.

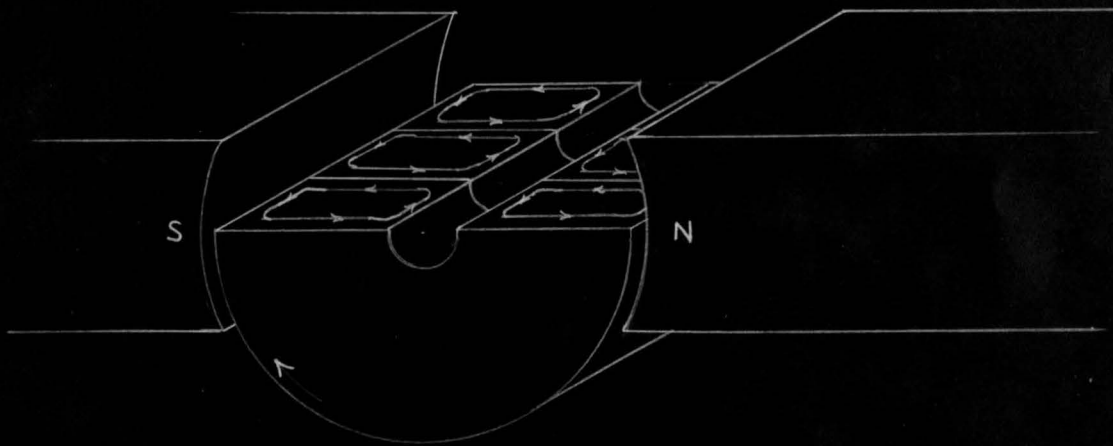
Good design in d-c motors usually calls for careful selection of armature core steel to keep hysteresis losses down. A rugged but less expensive type of steel is used for the yoke and pole pieces because under ordinary conditions hysteresis losses are not expected to occur there. But, when a rectifier source is used, hysteresis losses do occur in the yoke and pole pieces. The magnitude of these losses will be greater because of the poorer quality magnetic material of which the yoke and pole pieces of ordinary d-c machines are made.

No special attention will be given here to armature teeth and pole shoes because even under ordinary operating conditions the varying reluctance of the armature teeth causes a shifting magnetic field in these members. A pulsating main field will still result in a shifting field in the pole shoes and armature teeth, even though the magnitude and direction of the field may be slightly altered due to the pulsations.

Next, consider the effect of eddy currents in the armature core. Under normal operating conditions, as the armature core rotates in a magnetic field, emfs will be induced in the armature core as well as in the armature conductors. Since the armature iron is a good conductor of electricity, and since the current paths are short and of large cross section, large circulating currents, known as eddy currents, result in the core as shown in Fig. 12 (a). The power lost due to eddy currents is more than can usually be tolerated in a commercial machine. To reduce



(a) without laminations



(b) with laminations

Fig. 12 Eddy Currents in armature iron



eddy currents the core is laminated as shown in Fig. 12 (b). Naturally, eddy currents vary as speed and flux and the eddy current loss varies as the square of both speed and flux.

When the motor is operated from a rectifier supply, the magnetic field will pulsate causing the armature core to behave as the short-circuited secondary of a transformer. Now the armature core will contain, in addition to the emfs induced by rotation, a series of emfs due to transformer action, which will be  $90^\circ$  out of phase with the emfs due to rotation. The resultant emfs around the armature core will be somewhat greater than the emfs induced by rotation alone. The result will be larger eddy currents in the armature core and a larger amount of power lost.

Under normal operation of d-c motors, there will be a shifting flux between the armature teeth and the pole face caused by the varying reluctance of the air gap. The flux pulsation at any given point in the pole face passes through a complete cycle in the time it takes a point on the armature to move over a distance equal to the tooth pitch. This will induce emfs in the pole face and cause eddy currents to circulate there. For this reason, the pole faces of most large machines are laminated. In smaller machines the power loss here is tolerable and the pole faces are made of solid metal.

When a motor is operated from a rectifier supply, the flux in the pole face will pulsate not only because of the variable reluctance of the air gap but also because of the pulsations in the main field itself.

The resultant pulsations of flux will be greater than those normally existing in the pole face, and consequently, the resultant eddy currents will also be greater.

Now consider the yoke and pole cores. Under normal operation of a d-c motor the flux in the yoke and pole cores remains stationary and non-pulsating unless a voltage or rheostat adjustment is made. For this reason, no eddy currents will circulate in either the yoke or pole cores, and consequently ordinary design of d-c motors does not call for laminations in either of these two elements.

When an electronic rectifier is used as the source of power, the flux in the yoke and pole cores will not remain constant but will pulsate at the output frequency of the rectifier. This will induce emfs in both the yoke and pole cores. The eddy currents that result will now be of large magnitude because neither the yoke nor pole cores are laminated to protect against them. Consequently, the yoke does get much hotter under rectifier operation than it does under converter operation. This is borne out in the heat tests illustrated graphically in Figures 2 through 6.

The magnitude of the eddy currents circulating in the yoke will be a direct function of the magnitude of the pulsations in the field flux. In an interpole machine, the pulsations of the interpole field flux will be much greater than those of the main field flux, because the inductance of the interpole field and armature circuit is relatively small when compared with the inductance of the shunt field. Therefore, the eddy currents that circulate in the interpole cores will be of greater magnitude than

those circulating in either the yoke or the main field pole cores. This perhaps explains why in the heat tests conducted a thermometer adjacent to the interpole consistently read  $10^{\circ}$  C higher than a similar thermometer adjacent to the main field pole.

It was noted during the series of tests, that the operation of every d-c motor from a rectifier supply is accompanied by a distinct a-c hum, not common to the normal operation of d-c machinery. It is reasoned that additional power is required to create this sound; and since the d-c motor is hardly an efficient acoustical device, the power used may well be appreciable.

It has therefore been conclusively shown by experiment and explained in detail that the core losses of a d-c motor operated from an electronic rectifier exceed the core losses normally encountered in a d-c motor operated from a converter. In general the core losses will become greater or less as the magnitude of the pulsations in the field current increase or decrease. Machines with low-inductance series fields will experience a wider difference of core losses with the two different sources of supply than will shunt-wound machines. Remedies for this situation include special design of d-c motors to reduce the various core losses discussed.

Additional core losses are not the only reason for the added heating and poorer efficiency evidenced in rectifier operation of d-c motors. Consider for example the torque equation for a motor:  $T = K\phi I_A$ . The torque produced is seen to be proportional to flux and the average armature current. Now consider the equation for power lost in the armature circuit:  $P = I_A^2 R_A$ . The loss is proportional to the second power of the root-mean-square armature current. This distinction is not usually pointed



out in texts on D-C Machinery, because in the converter or normal operation of a motor the ratio of RMS current to average current is usually one. Not so when the motor is operated from an electronic rectifier. In this case, the ratio will always exceed one, and will depend directly on the number of phases of the rectifier and the inductance of the armature circuit. To show what happens in a typical case, consider an  $I_{RMS} / I_{AVE}$  of 1.2. In order for the motor to produce rated torque, the average armature current must reach its rated value, and the root-mean-square current must be 120% of rated value. The armature loss will be 144% of its normal full-load value. Thus an armature current pulsating enough so that  $I_{RMS} / I_{AVE} = 1.2$ , increases the armature copper loss by 44%. An armature current pulsating so that  $I_{RMS} / I_{AVE} = 1.41$  will increase to exactly double the normal armature copper loss.

For exactly the same reasoning, rectifier operation will also increase the series and shunt field losses. In the case of the shunt field, however, the ratio of RMS to average field current will be kept fairly low by the inductance of the field so the loss will not increase quite so appreciably.

Then too the armature and copper losses will also increase somewhat due to skin effect caused by the high frequency pulsations. The concentration of current in the outer surfaces of the conductor due to skin effect effectively reduces the area of the conductor and thus increases its effective resistance. Therefore it is reasonable to expect that the effective resistance of the armature and field is larger when these elements

are carrying pulsating current than when they are carrying non-pulsating current.

To review briefly, the results of heat tests shown in Figures 2 through 6, and efficiency tests shown in Figures 7 and 8 are explainable by the increased losses experienced by a motor when operating from a rectifier supply. The component losses are broken down as follows: Friction and windage losses remain materially unchanged when a rectifier supply is used. Those core losses normally existing in a motor are increased and some new core losses are introduced by the pulsations of the field. The copper and field losses are increased due to the increase in the ratio of RMS to average current and also due to the skin effect caused by the a-c component in all motor currents.

Remedies for the reduction of these losses will be discussed after a brief consideration of commutation problems.

#### Commutation

During several full load temperature tests, it was observed that the commutation of a d-c motor becomes much worse when the motor is operated from an electronic rectifier than when operated from a synchronous converter. An attempt will be made in this report to explain the reason for such an observation.

In a d-c motor operated from a non-pulsating source such as the converter, the armature rotates in a stationary, non-fluctuating field. The direction of the emfs generated in each conductor due to the rotation of

the motor are shown in Figure 13. For purposes of illustration, a ring-wound armature is shown.

When the d-c motor is operated from an electronic rectifier source, the field axis will continue to remain stationary in space; but now it will fluctuate in accordance with the wave shape of the rectifier. Consequently, the emfs generated in each armature winding and the current which must be commutated at the brushes is unidirectional, but highly pulsating.

Consider now the commutation of an interpole machine operated from a pulsating source of emf such as the ignitron rectifier. In an interpole machine, theoretically the interpoles will set up a field directly proportional to armature current. This will allow each coil undergoing commutation to generate a voltage equal and opposite to the voltage of self-induction. The net voltage between brushes and commutator segments is thus reduced to zero, and the circulating currents which cause sparking are thereby eliminated.

If the current is pulsating at a frequency of 360 cycles per second, as is the case when supplied by a half-wave, three-phase rectifier, the commutating poles should still set up a field which is instantaneously proportional to the current being commutated at all times. Thus, when an instantaneous current of maximum value is being commutated, the field set up by the interpoles should be one corresponding to a maximum value of armature current; and correspondingly, when a minimum value of current is being commutated, the field set up by the interpoles should be one corresponding to a minimum value of armature current. This would undoubtedly



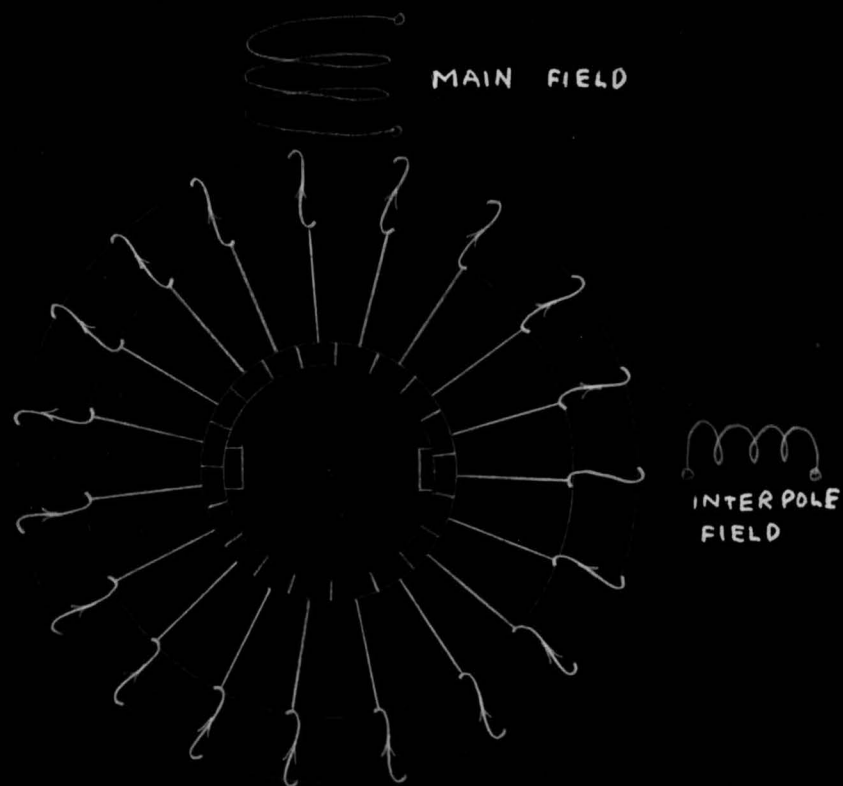


Fig 13

Rotational emfs due to pulsating flux of main field winding

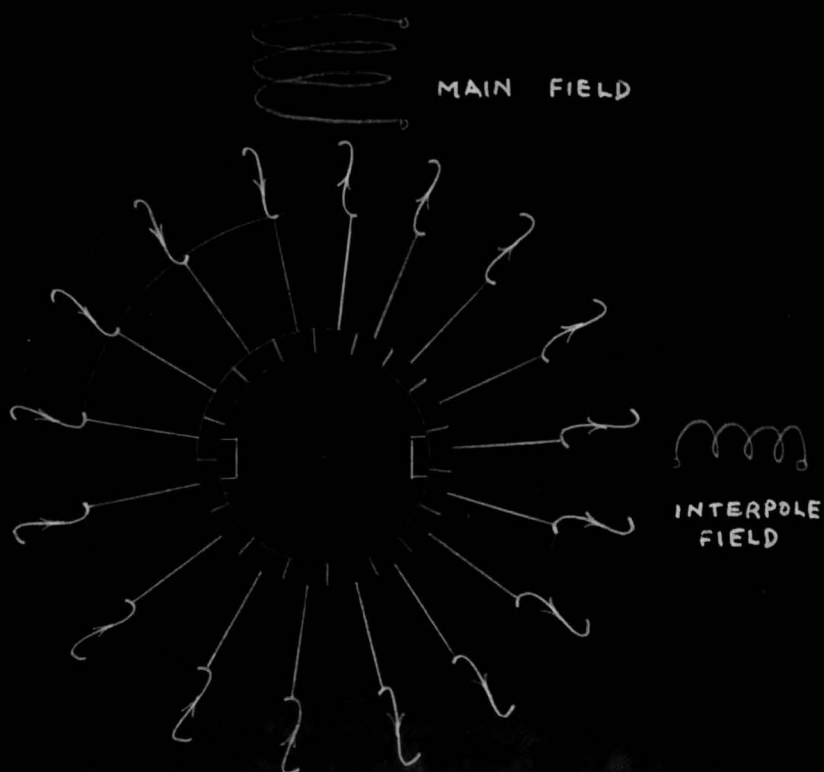


Fig. 14

Transformer emfs due to pulsating flux of main field winding

be true if there were no inductance in the interpole circuit. However, since inductance does exist in the interpole windings, the field set up by the interpoles will always lag the current undergoing commutation. It is quite possible that the angle of lag is such that when a maximum value of current is being commutated a field is set up by the interpoles corresponding to a minimum value of current. In this case, the interpole emf would not completely counterbalance the emf of self-induction. The resultant emf would cause current to circulate between brushes and commutator segments. The difficulty involved here would increase as the difference between maximum and minimum values of current, or the percentage of ripple in the current increased.

If this were the only difficulty in the commutating process, a source of pulsating d-c could well be tolerated.

However, when the motor is operating from a rectifier, there will exist in the armature an emf due to transformer action caused by the pulsating d-c field. This is in addition to the rotational emf. The direction of the emfs in each conductor due to transformer action are shown in Fig. 14. It can easily be seen from the figure that if the brushes are exactly  $90^\circ$  displaced from the main field axis, the transformer emfs will effectively cancel one another at the brushes, and therefore produce no current and torque. It is worthy to note from Figures 13 and 14 that the rotational emf is in phase with the flux producing it, while the transformer emf lags the flux producing it by  $90^\circ$  as in every transformer. The rotational emf is directly proportional to the speed of rotation of the armature, while the transformer emf is

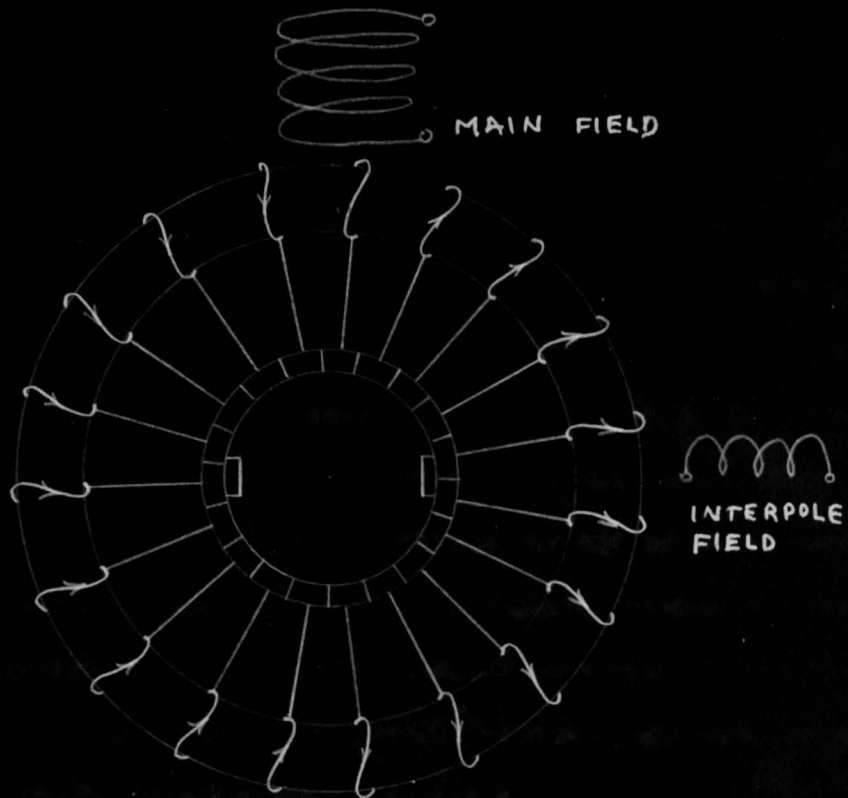


Fig. 15

Rotational emfs due to pulsating flux of interpole field

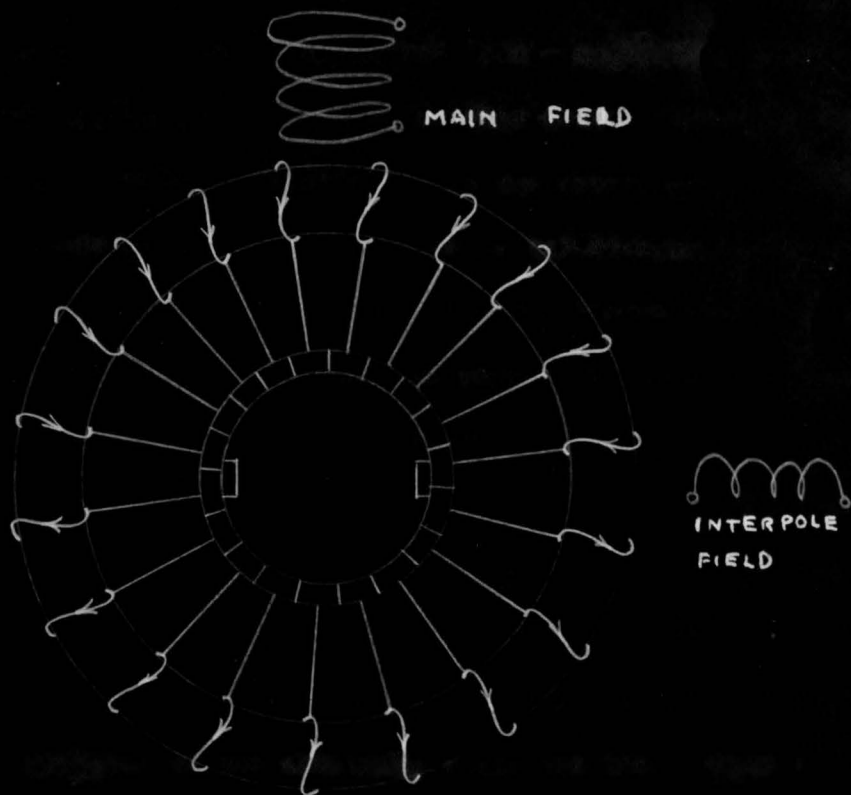


Fig 16

Transformer emfs due to pulsating flux of interpole field



independent of the speed of the armature but directly dependent on the amount of ripple of the d-c source.

In addition to the rotational and transformer emfs due to the main field, there will also exist in every coil a rotational and transformer emf due to the interpole field. Everything said about rotational and transformer emfs due to the main field will also apply to rotational and transformer emfs due to the interpole field. The directions of rotational and transformer emfs due to the interpole field in the various conductors are shown in Figures 15 and 16 respectively. The vector relationship of the various emfs existing in a coil is shown in Figure 17. For purposes of simplicity, armature reaction will be neglected here and will be considered in a later vector diagram.

In Figure 17  $\Phi_f$  represents the direction of flux in the main field and  $\Phi_i$  represents the direction of flux in the interpole field.  $e_{rf}$  represents the rotational emf due to the main field,  $e_{tf}$  represents the transformer emf due to the main field,  $e_{ri}$  represents the rotational emf due to the interpole field,  $e_{ti}$  represents the transformer emf due to the interpole field, and  $e_s$  represents the self induced emf existing when a coil is short circuited at the brushes. If a coil were located in the ZZ axis, it would contain components of all the emfs mentioned except the emf of self induction. This entire picture is represented in Figure 17.

Consider now the components of emf which will exist in a coil undergoing commutation. At the time a coil is undergoing commutation, it is located in the brush and interpole axis, and 90 electrical degrees away from the main field axis. Therefore, in that position  $e_{rf}$  and  $e_{ti}$  will

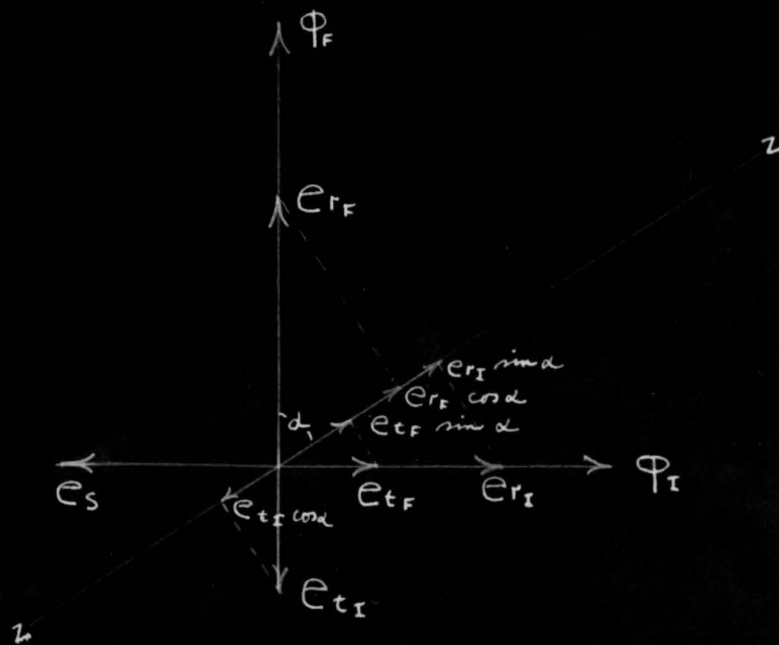


Fig 17 Vector diagram showing main field flux, interpole field flux, and the various components of emf that exist in a coil instantaneously on the  $z-z$  axis and under the influence of pulsating fields. (armature reaction neglected)

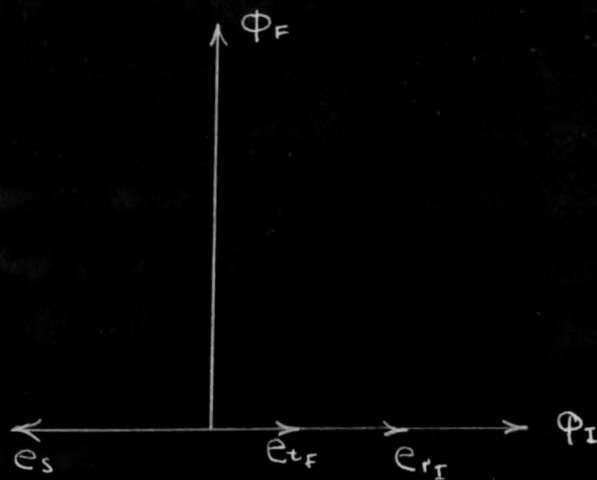


Fig 18 Vector diagram showing main field flux, interpole field flux, and the various components of emf that exist in a coil instantaneously on the brush or commutating axis. (armature reaction neglected)

be zero. A coil undergoing commutation will have the following components of emf: an emf of self induction, a rotational emf due to the interpole field, and a transformer emf due to the main field. This situation is represented by the vector diagram of Fig. 18. As has been stated previously, the magnitude of  $e_s$  and  $e_{r1}$  will vary with the fluctuations in armature current, and because of the inductance of the interpole circuit, it is quite likely that these two emfs will not be equal at all times. If this factor were of negligible importance, there would still be a component of emf which does not appear in the normal operation of a d-c motor; namely, the transformer emf due to the main field. This aids the rotational emf due to the interpole field and causes a resultant emf of considerable magnitude to exist in a coil undergoing commutation.

Since the transformer emf due to the main field appears to be the greatest source of difficulty, it is wise to consider here the magnitude of this emf. As was stated previously, the magnitude of the transformer emf is independent of the speed of the armature, but directly dependent on the amount of fluctuation of the main field, which in turn is dependent upon the ripple component of the field current. In the case of a shunt machine, it was expected that the high inductance of the shunt field would practically eliminate any ripple in the field current. Oscilloscope tests showed differently, however. In one shunt motor tested, it was seen that the amount of ripple in the field current was 40% of the ripple existing in the line current. In another, the field current ripple was found to be 12% of the line current ripple. To reduce the magnitude of the transformer emf, the ripple of the ignitron supply must be reduced, or the



shunt field must be especially designed with a very high inductance.

When a series or compound motor is operated from a rectifier, commutation difficulties become still more pronounced. In this case the series field is not very highly inductive and must carry armature current with its relatively high component of ripple. Now the main field will fluctuate considerably more and will result in a transformer emf of greater magnitude, and consequently, a larger resultant emf in the coil undergoing commutation.

Since the emf of self induction and the transformer emf are inherent in a machine operating from a fixed pulsating source, any attempt to reduce the resultant voltage to zero must center around adjustment of the rotational emf due to the interpoles. Thus with reference to Fig. 18 the following remedies are suggested:

- (a) If  $e_s$  exceeds  $e_{tF}$ , reduce the number of interpole turns until

$$e_{tF} + e_{rI} = e_s$$

- (b) If  $e_s$  equals  $e_{tF}$ , remove the interpoles.

- (c) If  $e_s$  is smaller than  $e_{tF}$ , then reverse the direction of the interpoles and adjust the number of turns until  $e_s + e_{rI} = e_{tF}$

It might be mentioned here that in an attempt to improve commutation in a 230 volt, 3600 RPM motor, the interpoles were removed and commutation immediately became worse. It appears that in this case  $e_{tF}$  was small in comparison to  $e_s$  and  $e_{rI}$  and removal of the interpoles not only reversed the direction of the resultant emf, but also increased its magnitude.

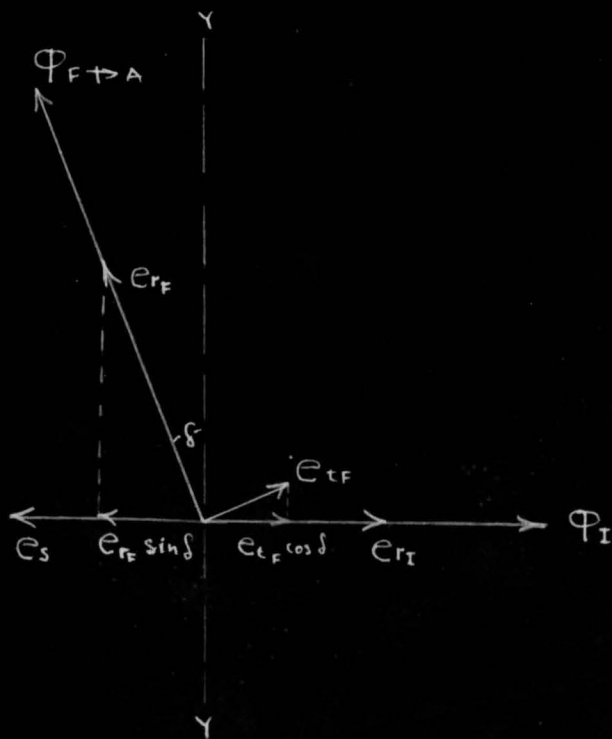


Fig. 19

Vector diagram showing resultant field when armature reaction is considered, interpole field, and the various components of emf that exist in a coil instantaneously on the brush or commutating axis.

The vector diagram of Fig. 19 takes into account the effect of armature reaction. Note that the resultant flux due to the main field and armature has been shifted an angle " $\delta$ " counter-clockwise from its original position. It should be remembered that the armature reaction component of flux will vary with fluctuations in armature current, so that the angle " $\delta$ " will not remain constant. Now the coil undergoing commutation will contain a component of rotational emf due to the main field, its magnitude being  $E_{rf} \sin \delta$ . Also the entire transformer emf due to the mainfield will not be present in the commutated coil, but only a component of it,  $E_{tf} \cos \delta$ . As long as the brush axis is not shifted, all other emf vectors will remain unchanged.

Close examination of Fig. 19 shows that the shifting of the resultant field axis due to armature reaction tends to improve commutation. However, even now it is unlikely that the resultant emf in the commutated coil will be zero. The remedy is still to adjust the direction and number of turns in the interpole field until satisfactory commutation is achieved.

In conclusion, it has been shown by vector diagrams and proven by experiment that a motor designed to operate on a non-pulsating direct current, will not commute satisfactorily when operated on a pulsating direct current. Especially is this true if the motor has a strong series winding or if the ripple of the supply is large as is the case in a three-phase half-wave rectifier. If an electronic rectifier such as the ignitron should be used as a source of d-c, motors with special design features must be used to give satisfactory commutation.



V. CONCLUSIONS

The two greatest difficulties encountered in rectifier operation of d-c motors are added heating and a reduced commutating capacity. Both come as a direct result of the pulsations in the rectifier supply. Theoretically, if a non-pulsating rectifier could be built, it would prove fully as satisfactory in d-c motor operation as the synchronous converter.

To achieve satisfactory motor operation from a rectifier supply, either the rectifier must be designed to have almost negligible ripple, or the motor must be especially designed to operate off one given rectifier supply.

The General Electric Company is currently engaged in building entire drive systems, where rectifier and motor are especially designed for one another. Motor design features must necessarily include highly inductive windings for both armature and fields.

It is not recommended that a replacement of synchronous converters be made by electronic rectifiers, unless the d-c motors which are to operate from the rectifiers be replaced also, or unless the replacement rectifiers have at least 12 phases. Especially is this true in industries which employ a large percentage of series motors.

It is quite true that in rectifiers with a large number of phases, the percentage of ripple becomes very small; but it is equally true that such rectifiers are not as feasible economically. For example, a 12-phase electronic rectifier must be supplied by a transformer whose KVA rating must be over 2-1/2 times as great as the power to be rectified.

There is a utilization factor defined in connection with rectifiers which states that  $u$ , the utilization factor, is the ratio of the d-c kilowatts supplied by the rectifier to the KVA rating of the transformer required to supply the rectifier. Obviously, from the definition, the ideal utilization factor is one, the poorest is zero. To show how the utilization factor varies with the number of phases the following approximate relationship is given without proof:  $u = \frac{\sqrt{2p}}{\pi} \sin \frac{\pi}{p}$ ,\* where  $p$  is the number of phases. Calculation of utilization factor can be made by substituting the proper number of phases for  $p$ . The following table shows utilization factors for most common rectifiers employed.

Phases	1	3	6	12	18	$\infty$
Utilization Factor	.636	.675	.636	.399	.332	0

In view of this consideration it would seem that 12 and 18-phase rectifiers are not very feasible economically. On the other hand 3 and 6-phase rectifiers make the difficulties discussed in d-c motor operation more pronounced.

The question arises again: Is the rectifier always a completely satisfactory replacement for the rotary converter? Certainly there is more to be considered than the advantages advertised by rectifier manufacturers.

\*See "Applied Electronics" MIT Staff

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