DRY DISK RECTIFIER-MOTOR DRIVES

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PREFACE

The percentage of D-C motors being used in industry is greater than ever before. One reason for this is that in the last twenty years the development of the electronic tube rectifier has facilitated the economical conversion of A-C power to D-C power. The recent improvement of dry disk rectifiers, particularly selenium rectifiers, suggests that they may soon seriously compete with tube rectifiers in many applications.

The writer has attempted in this thesis to do two things. Firstly: to outline the theory of rectification, dwelling particularly upon the advantages and disadvantages of the commonly used rectifier circuits. This material has been augmented with numerous oscillograms which are so often lacking in texts and technical literature. Secondly: to point out the advantages and disadvantages of dry disk rectifiers as applied to rectifier-motor drives. This work is not original, but rather a compilation of information found scattered throughout the literature.

The use of a multi-rectifier-motor drive is suggested; this type of drive has not, to the writer's knowledge, been discussed elsewhere in the literature. Time limitations have made a study of this drive impossible.

CHAPTER ONE

MOTOR SPEED CONTROL

1-0 Introduction.

If necessity is the 'mother of invention', then the rectifier drive has been born of the need for an economical, convenient and reliable method of motor speed control.

In industry, accurate speed control systems tend to increase efficiencies and speeds of processes, and often these two factors are accompanied by the production of a higher quality product. A simple example will bear out this statement. In the production of copper wire it is frequently necessary, during such operations as drawing, annealing, tinning and insulating, to rewind the material being processed from one reel to another. In general, such operations require the material to travel at constant speed. If however a constant speed motor were used to drive the take-up reel, as the layers built up on the reel the linear velocity of the material would increase. As a result of this variable linear speed a non-uniform product would result; further, since the process may run at maximum speed for only the last layer on the reel production is below maximum. Thus it becomes apparent that optimum operating conditions may be obtained only by the introduction of an adjustable speed drive on the reel take-up.

1-1 Choosing a speed control system.

Several methods of speed control are available. In some cases mechanical means are used, such as slipping clutch or conical gear arrangements. Multi-speed A-C motors are available. Also in many cases, special systems, such as the Kramer and Scherbius speed control systems, are used to control A-C motors. In other applications various methods are used to make use of the D-C motor adjustable speed characteristics. The adaptability of each particular method of speed control to any given drive can only be arrived at by comparing the characteristics of each method with the requirements of the drive in question. Some of these drive requirements necessary of consideration are listed below:

1. Accuracy of speed control. What is the allowable deviation of speed from the theoretically required speed?

2. Smoothness of speed control. Are there any limits pertaining to the acceleration or deceleration of the drive?

3. Speed range. What are the probable maximum and minimum speeds required?

4. Applicability of control. From a purely economical view point, it is desirable to control the speed of a

D-C motor by armature voltage for constant torque loads, and by field for constant horsepower loads.

5. Response characteristics. What time lag is permissible between the instant of sensing a need for a speed adjustment and the instant the speed once again is at the required value?

6. Power to be developed by the drive. Practical upper and lower power limits exist for most types of speed control systems.

7. Automatic or manual speed control. In many cases the increased expense of an automatic control is not warranted.

8. If automatic speed control:

(a) To what reference value must the speed be adjusted? Is the speed to vary at a fixed rate or is it to be dependent upon some other variable such as the number of layers of wire on a reel?

(b) How may the speed of the drive be adjusted according to variations in the reference value? In many cases the lack of a suitable regulator requires that an otherwise excellent speed control system be ignored.

9. Reliability of the drive. In some cases an interruption in service may be exceedingly costly, hence reliability of control may be more important than quality of control.

10. Location of drive. Such factors as extreme temperature

or excessive vibration may rule out the use of drives using electronic tubes.

11. Space available. Due to the relatively high volume and weight to horsepower ratios of a Ward Leonard speed control system, the use of this system in light aircraft, for example, may not be pratical.

12. Initial cost. An increase in cost must be accompanied by equivalent benefits before the extra expenditure is warranted.

CHAPTER TWO

CONVERSION OF A-C POWER TO D-C POWER

2-0 Need for conversion.

It is the purpose of this thesis to consider only those methods of speed control which use directly coupled D-C motors, and in particular to consider the practicability of using dry disk rectifiers to supply the required D-C power from A-C power lines.

It is well-known that A-C motors are inherently constant speed motors, whereas shunt excited D-C motors may be readily controlled by the proper variation of armature or field voltages. However about 90% of industrial establishments are provided with A-C power only. Further, even if D-C power were available the voltage would be fixed (since transformers cannot be used to give the desired voltages as may be done with A-C power), hence only speed control above the D-C motor base speed could be economically used. Speed control below base speed is obtainable, by use of series resistance in the armature circuit, but this is not generally acceptable in industry due to the prohibitive losses in the rheostat, cost and size of the series resistance, and the excessively drooping speed-torque characteristics of a drive controlled in this manner.

It then becomes apparent that to satisfactorily apply the D-C motor to industrial speed control problems requires, in many cases, the conversion of available A-C line voltages to adjustable D-C voltages.

2-1 Methods of conversion.

At present there appear to be four chief methods by which D-C power may be obtained from the A-C power lines. These methods entail the use of:

1. Motor generator sets.
2. Rotary converters.
3. Contact rectifiers (mechanical rectification).
4. Electronic rectifiers:
    (a) Tube rectifiers.
    (b) Dry disk or metallic rectifiers.

The first three methods listed above will be discussed briefly, whereas the last one will be discussed in some detail.

2-1-1 Motor generator sets.

For many years the motor generator set was the only means available for converting A-C power to D-C power. Even now an A-C motor driving a D-C generator is widely used in industry as a source of D-C power.

If the D-C voltage of the generator is applied directly to the D-C motor whose speed is to be controlled, a variation of the field resistance of the generator will result in a change in output voltage and hence a change in speed of the D-C motor. Such a drive will readily be recognized as the Ward-Leonard system of speed control. It will suffice to say here that even though this system makes available an excellent reversible speed control drive for many processes, the excessive requirements on space and capital expenditure, and the low overall efficiency all tend to outweigh the advantages of this system in many possible industrial applications.

2-1-2 Rotary converters.

A rotary converter is essentially a synchronous motor and a D-C generator combined into one machine having only one armature, one main field winding, one set of slip rings to bring in the A-C power, and one commutator to take out the D-C power. The rotary converter was developed after the motor generator set and, because it was cheaper and more efficient than the latter, it gradually replaced the motor generator set. However, in applications requiring a wide variation of D-C voltage the Ward-Leonard system is used rather than the rotary converter. This follows since the ratio of A-C voltage to D-C voltage of a rotary converter is fixed for any given flux distribution, and hence the D-C voltage cannot be varied as simply as in the D-C generator. There are however three practical methods of varying the rotary converter D-C output voltage. They are:

(a) Variation of the applied A-C voltage by use of:

1. Variable tap transformers.
2. Induction regulators.
3. Series reactance in supply lines.
4. Synchronous boosters.

(b) Variation of the D-C voltage output by use of a D-C booster.

(c) Variation of the flux distribution as in split pole converters.

With the advent of the large capacity mercury-arc rectifier the rotary converter has been used less and less in industry. The industrial fields in which rotary converters have persisted, and are only now gradually being replaced by more highly developed electronic rectifiers, are those requiring low voltage and high current capacity such as electrolytic processes. This is due to the fact that rotary converters have an efficiency which is practically independent of voltage, whereas mercury-arc rectifiers because of their constant arc drop regardless of voltage output, have an efficiency which decreases with a decrease in operating voltage.

2-1-3 Contact rectifiers (mechanical rectification).

A rectifier is a device which converts alternating current into unidirectional current by virtue of a characteristic permitting the flow of current effectively in one direction only. This definition is based upon A.I.E.E. standards.

With the above definition in mind, it may be seen why many attempts have been made to develop a contact rectifier. Basically all that would be required to change the direction of the alternating current are contacts that open and close at the proper moment and in the correct sequence. These contacts could be operated by a revolving cam driven by a synchronous motor operating on the same A-C power that is being rectified.

However until very recently the efficient use of contact or mechanical rectifiers had been frustrated by commutation difficulties. Commutation must take place at the current zero, but, for an ordinary alternating current wave, the rate of change of current with time at the current zero is a maximum. This results in injurious sparking.

In Germany, Siemens-Schuckertwerke obtained satisfactory commutation by using saturable core reactors in series with the alternating current leads (ref. 1 and 2).

This produced a step in the alternating current wave, as shown in Fig. 2-1, and hence reduced the time rate of change of current at the current zero, to practically zero. Silver tipped contacts were used. The resulting rectifier has been used successfully in industry on a small scale since 1943.

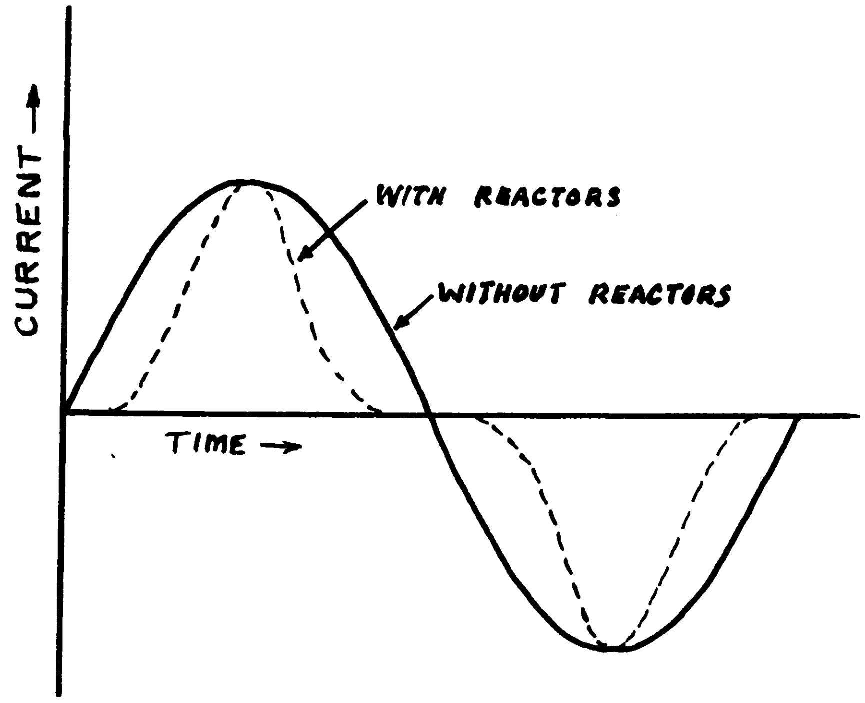


Fig. 2-1 Current wave form modified by series saturable core reactors.

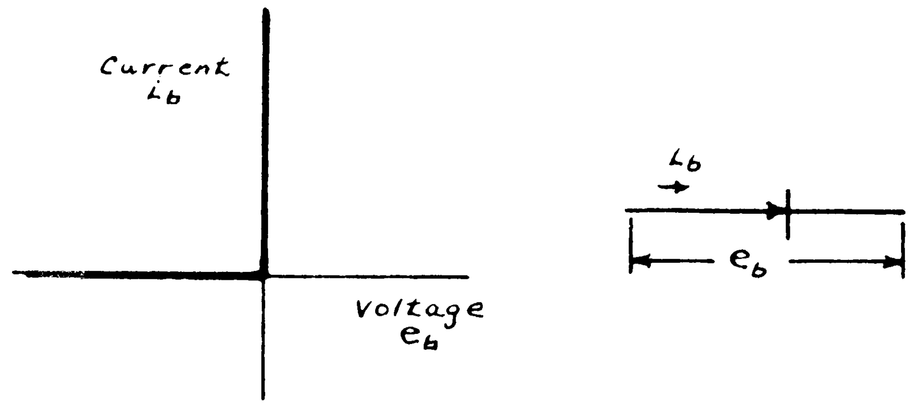
The advocated commercial advantages of this contact rectifier are:

1. Higher electrical efficiency than motor generator sets, rotary converters, and mercury-arc rectifiers.
2. These rectifiers will operate at 30 volts or lower, where mercury-arc rectifiers cannot operate due to their relatively large arc drop.
3. These units are considerably lighter than other rectifiers with equivalent capacities and voltage ratings.

2-1-4 Electronic rectifiers.

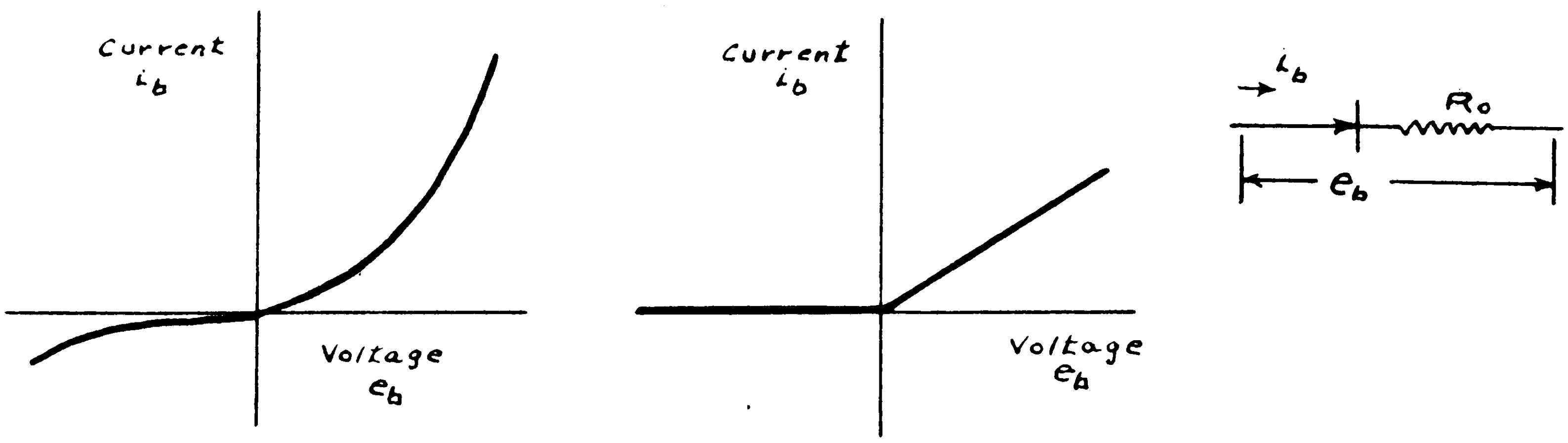
From the definition of a rectifier, stated on page 8, it follows that if a non-linear element, having the current-voltage characteristic indicated in Fig. 2-2(a), were inserted in a circuit having an A-C voltage applied across it then the original alternating current would become unidirectional. The current-voltage characteristic indicated in Fig. 2-2(a) is that of an ideal rectifier and Fig. 2-2(b) shows the circuit representation of such a rectifier. In practice, however, such ideal characteristics can only be approached, the actual shape of the characteristic depending upon the type of rectifier it represents.

Fig. 2-3(a) shows the current-voltage characteristic typical of such non-linear elements (called rectifiers) as thermionic high vacuum diodes (kenotrons) and dry disk rectifiers. Because of the inherent difficulty in analyzing circuits having non-linear elements, simplifying assumptions are made to facilitate the solving of rectifier circuit problems. Fig. 2-3(b) indicates the assumed current-voltage characteristic of this type of rectifier. Fig. 2-3(c) then shows the circuit representation of such a rectifier, where R_o is the constant resistance to forward flow of current. (The forward direction of a rectifier is the direction of lesser resistance to current flow through the rectifier.) In most practical cases the assumption that the rectifier resistance is independent of current introduces only a very small error, since the forward voltage drop of a rectifier must be small compared to the output voltage in order to obtain economical rectification.



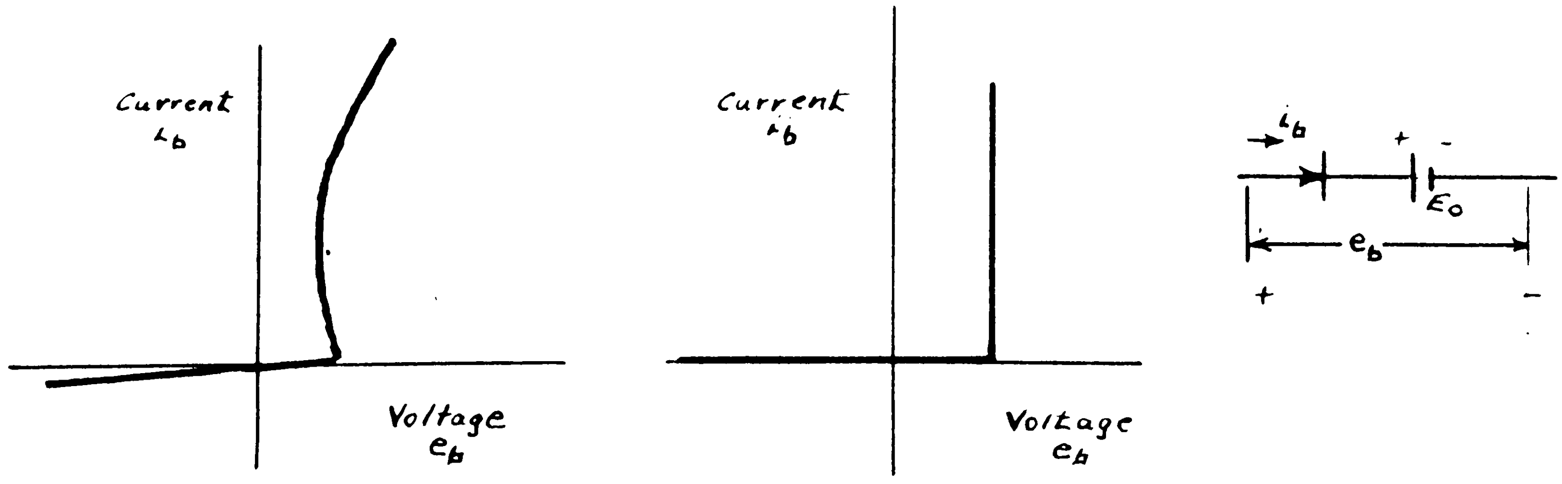
(a) IDEAL CHARACTERISTIC (b) CIRCUIT REPRESENTATION

Fig.2-2 Ideal rectifier



(a) ACTUAL CHARACTERISTIC (b) ASSUMED CHARACTERISTIC (c) CIRCUIT REPRESENTATION

Fig.2-3 Group 1 rectifiers--kenotrons and dry disks.



(a) ACTUAL CHARACTERISTIC (b) ASSUMED CHARACTERISTIC (c) CIRCUIT REPRESENTATION

Fig.2-3 Group 2 rectifiers--thyratrons, mercury arc rectifiers, and phanotrons.

Fig.2-4 corresponds to Fig.2-3 but shows characteristics for such rectifiers as mercury arc rectifiers, thyratrons, and phanotrons. For this type of rectifier a different simplifying assumption is necessary, for it is well known that gas tubes, such as thyratrons, have an arc drop which only slightly increases with an increase in current. Since this arc drop is generally considered of constant magnitude a more reasonable simplification would be to incorporate a back emf (electromotive force) with an ideal rectifier (see Fig.2-4(c)) when representing such rectifiers.

Before discussing the two classifications of electronic rectifiers individually it is of interest to note that the so-called electronic rectifier differs from the contact rectifier in two chief ways. Firstly, the electronic rectifier has no moving parts whereas the contact rectifier relies upon mechanically operated contacts to provide the unidirectional conduction typical of rectifiers. Secondly, whereas the electronic rectifier uses a non-linear element of the type shown in Fig.2-3(a), in which the instantaneous current is a function of the instantaneous voltage across the rectifier; the contact rectifier uses a time-varying element thus making the instantaneous current dependent upon both the instantaneous voltage and the time-varying position of the contacts.

CHAPTER THREE

OPERATION OF ELECTRONIC TUBE RECTIFIERS

3-1 Types of tubes used.

Tube rectifiers may be subdivided into two general groups:

Group 1. Rectifiers having non-electronic control of the output power.

Group 2. Rectifiers having electronic control of the output power.

The electronic tubes commonly used in the above mentioned rectifiers may be grouped as follows:

(a) Mercury vapor or inert gas filled, grid controlled, hot cathode rectifiers, commonly known as thyratrons. These are widely used as power supplies for D-C motor drives where electronic control is used.

(b) Mercury pool type rectifiers with ignitor controlled firing, known as ignitrons. These tubes generally replace the thyratrons as power supplies for D-C motors of ratings above 25 horsepower.

(c) Mercury vapor or inert gas filled, hot cathode rectifiers, called phanotrons. These are used when non-electronic control is used, or when no control is necessary as for the fields of armature controlled D-C shunt motors.

(d) High vacuum, low power control tubes such as diodes, triodes, and pentodes. These tubes are employed to provide the controlled firing of tubes noted in groups (a) and (b).

3-2 Tube rectifier operation.

Let us first discuss the operation of a group 1 rectifier, that is, one having no means of electronically controlling the output voltage. Since no control is required the tube will have two elements, and may be either gas filled or high vacuum.

If a phanotron is supplying rectified A-C power to a pure resistance load of R ohms, then, by simplifying the non-linear characteristic of the rectifier as indicated in Fig.2-4(b), Fig.3-1(a) will be the circuit to be analyzed in order to obtain the current and voltage wave forms. The tube will begin conducting at the instant the positive anode voltage exceeds the arc drop, E_0, of the tube and continue to conduct until the positive anode voltage drops to E_0. Thus the voltage across the rectifier, e_b, will be as shown in Fig.3-1(b), and the voltage across the load, e_r, and the current, i,

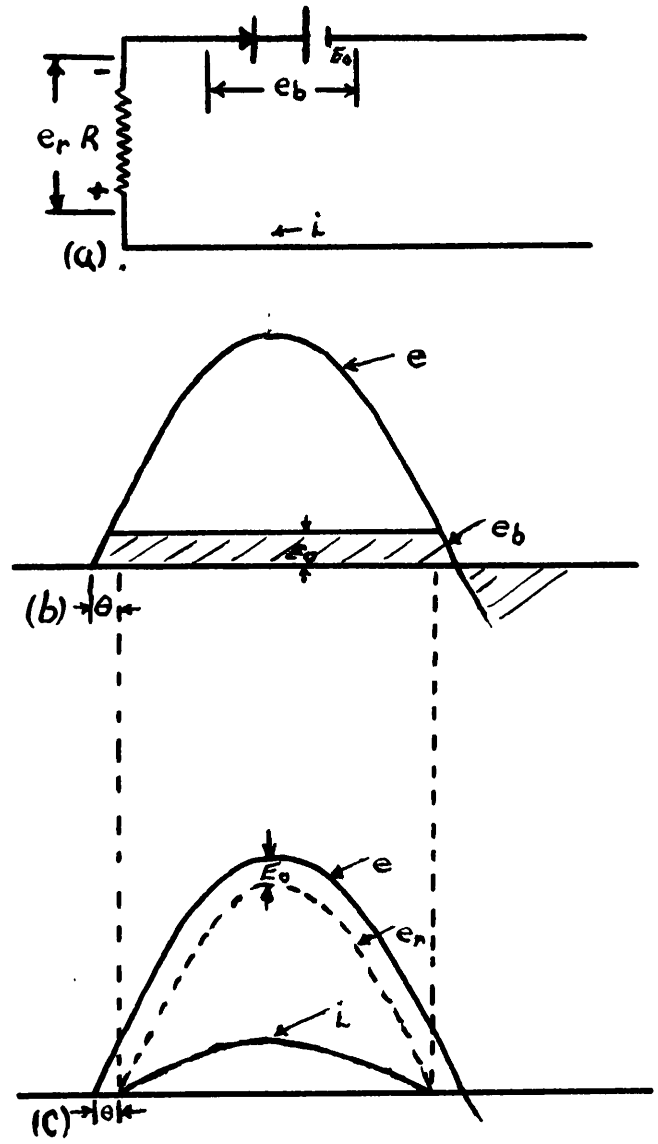


Fig.3-1 Phanotron rectifier circuit and wave forms.
(a) Simplified circuit.
(b) Voltage across rectifier.
(c) Load voltage and current.

as in Fig.3-1(c). It must be remembered that this analysis is based upon the assumption that the arc drop is independent of current and not as indicated in Fig.2-4(a); also, in most cases, the arc drop is very small compared to the peak value of the A-C applied voltage, hence little error is introduced if the tube is considered to conduct for the whole half cycle instead of 180° less $2\theta^{x}$.

If the rectifier in Fig.3-1 were a kenotron (high vacuum diode) the back emf would have to be replaced by a resistance R_o, see Fig.2-3(c), and different wave forms would be obtained.

If the circuit shown in Fig.3-1(a) is now considered to have a Group 2 rectifying element, such as a thyratron, then it is well known that the instant of firing may be controlled by varying the grid voltage of the tube. Fig.3-2 shows the various wave forms obtained if the grid is used to hold off the firing equivalent to an angle θ. It is evident from Fig.3-2 that by varying θ the D-C output power can be

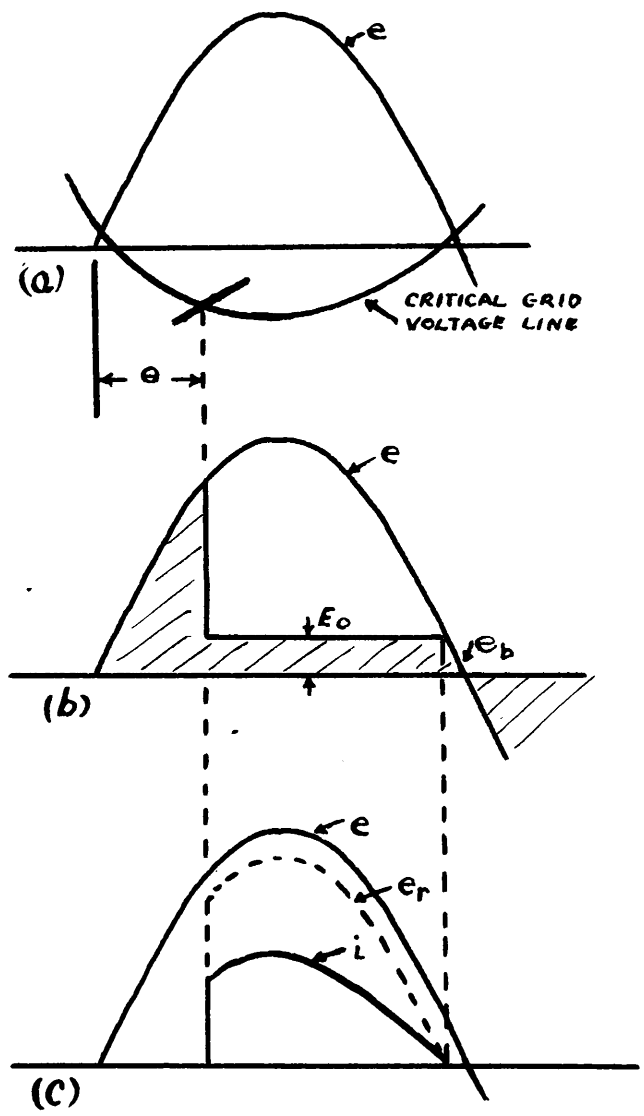


Fig.3-2 Controlled grid rectifier wave forms on resistance load.

x For list of symbols refer to appendix.

varied. Fig.3-3 shows the variation of average current, as a percent of maximum average current, due to delaying the instant of firing. This curve ignores the delay in firing caused by the arc drop of the rectifier.

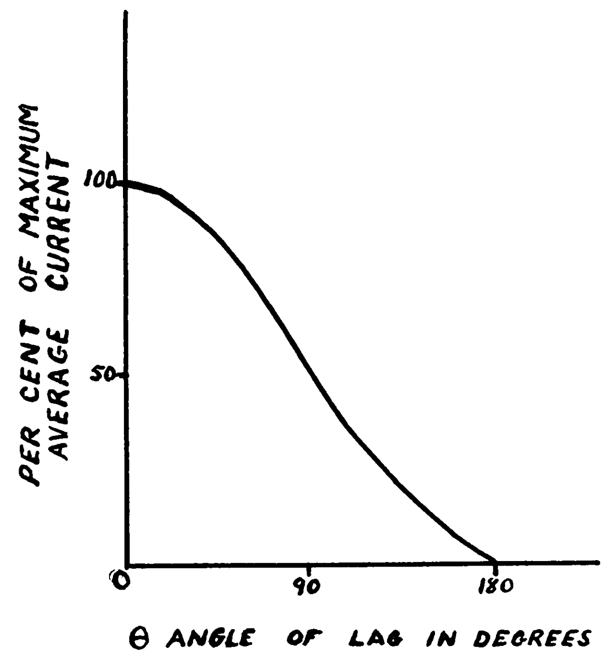


Fig.3-3 Variation of current with firing angle.

It is also apparent from Fig.3-2 that the ratio of the root mean square (rms) current to the average current (i.e. current form factor) decreases as the angle of lag decreases. The form factor is a minimum when no delay in firing occurs, which is always the condition obtained with Group 1 rectifiers. The higher form factor characteristic of Group 2 rectifiers is a disadvantage in applications where average, not rms, current is required as is the case in rectifier-motor drives.

3-3 Methods of controlling firing angle.

The fact that the D-C voltage and current may be controlled when a Group 2 rectifier is used immediately suggests that such a source of D-C power would be ideal for many D-C motor speed control drives, providing a suitable method of varying the grid voltage, and hence the firing angle, is available. Two chief methods of grid control are in industrial use. They are:

1. 'Vertical' control- The grid voltage is comprised of a variable D-C grid bias and an A-C voltage of constant magnitude, and constant phase relation with respect to the anode voltage.

2. 'Horizontal' control- The grid voltage has no D-C component, but the phase relation with respect to the anode voltage is variable.

Fig.3-3(a) shows the elementary circuit of a single phase, half-wave, rectifier using 'vertical' control. The

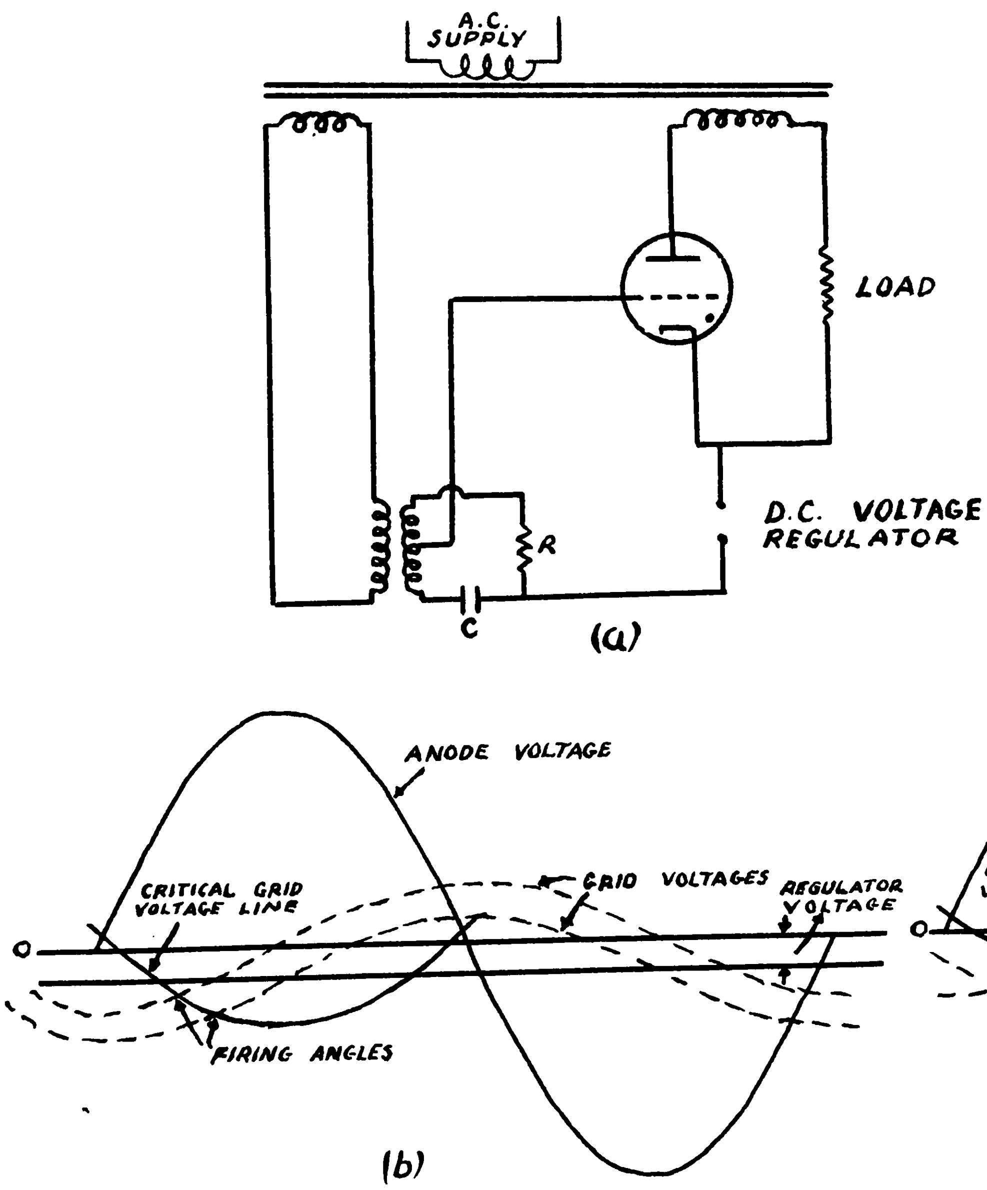


Fig.3-3 Elementary circuit and principle of 'vertical' control.

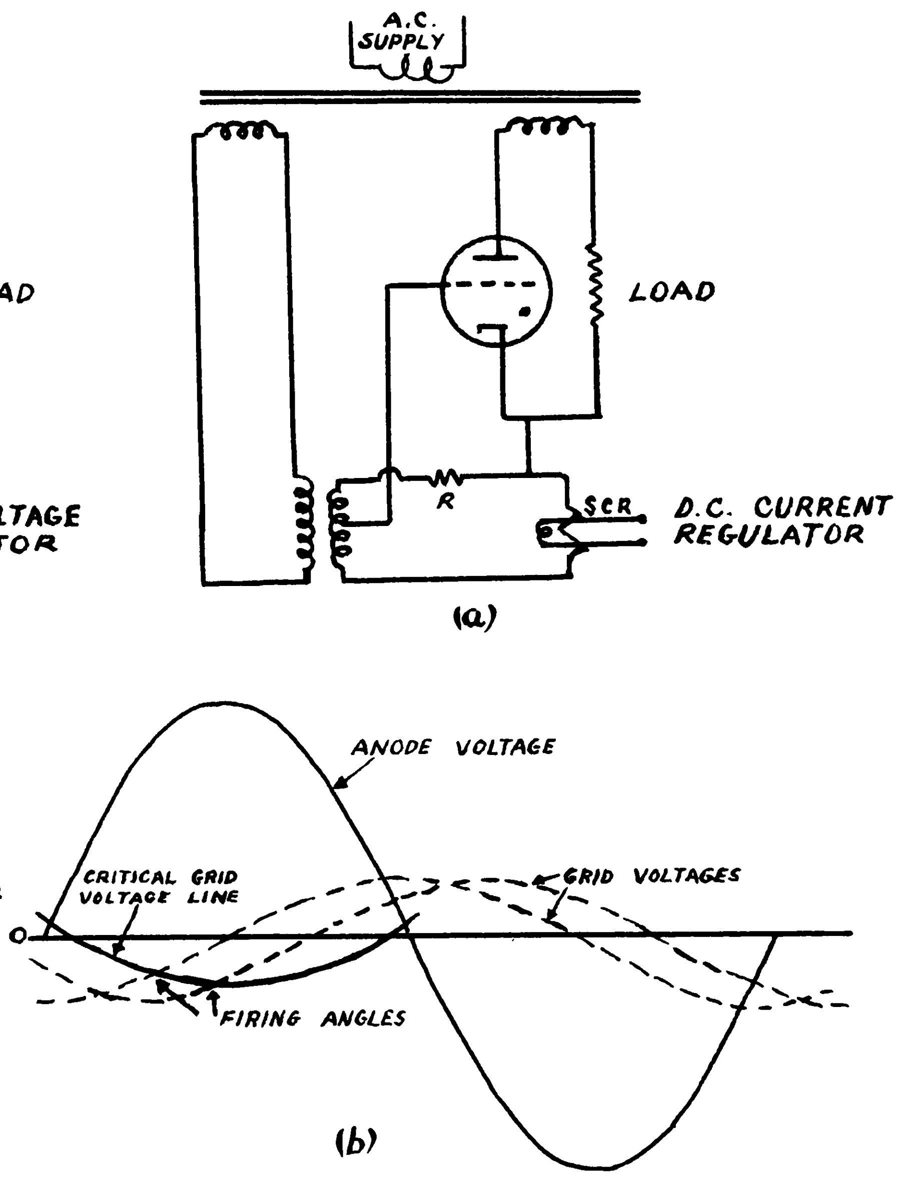


Fig.3-4 Elementary circuit and principle of 'horizontal' control.

A-C component of grid voltage is shifted, by means of a centre tapped transformer, condenser and resistance, to lag the anode voltage by about 90°. If the grid voltage were not shifted control in only one direction would be available, that is, control to decrease, but not increase, the rectified output current; or vice versa if the grid transformer polarity were reversed. Referring to Fig.3-3(b) it is readily seen that a variation of the D-C voltage from the regulator shifts the grid voltage curve vertically, and hence varies the firing angle. This type of control theoretically may be used to vary the firing angle from 0° to 180° lagging. In actual practice this is never achieved because, as the firing angle approaches 180°, the critical grid voltage line and the grid voltage curve tend to become parallel and hence the firing point, at any given setting of the regulator, is indefinite. 'Vertical' control is used by the Westinghouse Company in their 'Mototrol' speed control drives.

Fig.3-4(a) shows an elementary circuit for the same rectifier discussed above, but using 'horizontal' control. As with 'vertical' control, a phase shift is imparted to the grid voltage, but in this aontrol a resistor and a variable reactor are used to give a variable phase shift. The variable reactor is a saturable core reactor, whose reactance may be varied by controlling the current through its D-C winding. Thus the current output of a regulator controls the phase shift of the grid voltage, and from Fig.3-4(b) it is seen that this varies the firing angle. 'Horizontal' control is used in the General Electric Company's 'Thy-mot-rol' speed control drives.

CHAPTER FOUR

OPERATION OF DRY DISK RECTIFIERS

4-1 Theory of Rectification.

A dry disk rectifier is one which utilizes the asymmetrical conductivity of the junction between dissimilar solid conducting materials to obtain flow of current effectively in one direction only. This definition is based upon A.I.E.E. standards.

There are a number of different types of dry disk rectifiers, however the fundamental principle underlying the operation of all these types is the same. The selenium rectifier will be described here because it is the type the writer used to study the speed control characteristics of dry disk rectifier-motor drives.

A quotation from Richards (ref. 3) will serve to show that the theory of dry disk rectification is not clearly understood. 'Prof. Fortescue is quite correct in stating that the dry-contact rectifier is still in the transition stage in which the laws of its action are only imperfectly understood.' No attempt here will be made to outline all the theories that have been put forward to explain the rectifying properties of dry disks, however a modern view of the electronic mechanism on which their operation depends will be set forth. This theory, even though it may not be absolutely correct, at least aids in the predicting of operating characteristics of dry disk rectifiers.

According to this theory the selenium rectifier consists essentially of a semi-conductor separated from a good conductor by a barrier layer which is itself an insulator but through which electrons may pass. The selenium layer, which plays the role of semi-conductor, is sprayed onto a supporting disk of some nickel-plated material (generally iron or aluminium); then this selenium surface is sprayed with a low melting point alloy which is also a good electrical conductor. An electrical 'forming' process, which consists of applying a potential across the rectifier in the reverse direction, is then used to build up the barrier layer between the selenium and alloy surfaces.

In the alloy layer there is an abundance of free electrons; whereas in the selenium layer, since it is a poor conductor, there are relatively few free electrons. If a potential is applied across the very thin barrier layer a high potential gradient will be set-up across the barrier layer. Consider first the selenium layer to be at

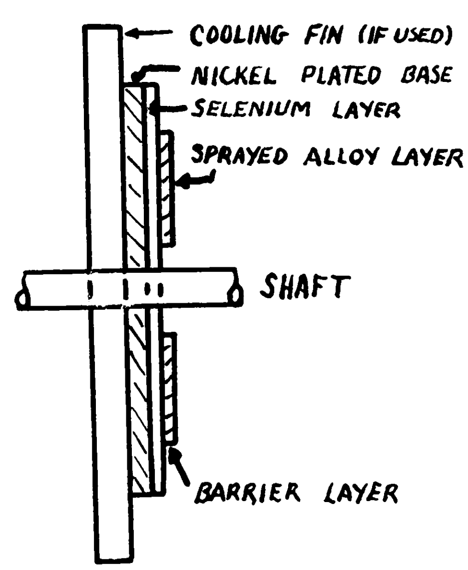


Fig.4-1 Cross-section of selenium rectifier disk.

a higher potential than the alloy layer; electrons will flow from the alloy layer through the barrier layer to the selenium layer and supporting disk. Since the alloy layer is a good electrical conductor there is an abundance of free electrons present to be accelerated to the selenium layer. This large flow of electrons is equivalent to a conventional current flow from selenium to alloy layer through the barrier layer. Now let us consider the polarity of the applied voltage to be reversed. Since the selenium layer has fewer free electrons compared to the alloy layer, the same potential applied will now produce a much smaller electron and current flow. Further, this electron and current flow will be in the reverse direction. Hence it is now clear that the selenium rectifier conducts conventional current easily from selenium to alloy layers, but difficultly in the reverse direction. It then follows that the alloy layer is the positive terminal of such a rectifier.

Fig.2-3(a) shows the typical current-voltage characteristic of a dry disk rectifier. For a selenium rectifier the ratio of forward current to reverse current is about 100 to 1, over the normal operating range. Hence it can be seen that little error will be introduced in most practical calculations if the characteristic is assumed to be as shown in Fig.2-3(b), and therefore the circuit representation assumed to be as in Fig.2-3(c).

It is worthy of note that, for a selenium rectifier, the ratio of forward current to reverse current would be of the order of 1500 to 1, instead of 100 to 1, if it were not for the fact that an undesirable barrier layer is formed between the selenium layer and the nickel-plated supporting disk, see Fig. 4-1. Counter-rectification takes place at this junction, thus reducing the forward current and hence the above mentioned ratio is also reduced. This suggest that the reason for nickel-plating the supporting disk is to obtain a junction with the selenium which produces the least possible counter-rectificiation, and therefore the highest possible ratio of forward current to reverse current.

4-2 Comparison of selenium and copper-oxide rectifiers.

It is true that the fundamental principle of operation of copper-oxide and selenium rectifiers is the same, nevertheless dissimilarities in their operating characteristics do exist. These dissimilarities must be weighed when chosing the type of dry disk rectifier for a particular application. A comparison of the characteristics of copper-oxide and selenium rectifiers follows.

1. Current-voltage characteristics. These are substantially the same shape for both types of disks, however the rated current densities and voltages are radically different. (Current density, rather than current, is plotted against voltage, see Fig. 4-2, because current density is independent of rectifying area.) Fig.4-2 shows these characteristics for both types over the complete operating range. From these curves it is apparent that the forward resistance of copper-oxide cells is less that that of the selenium cells.

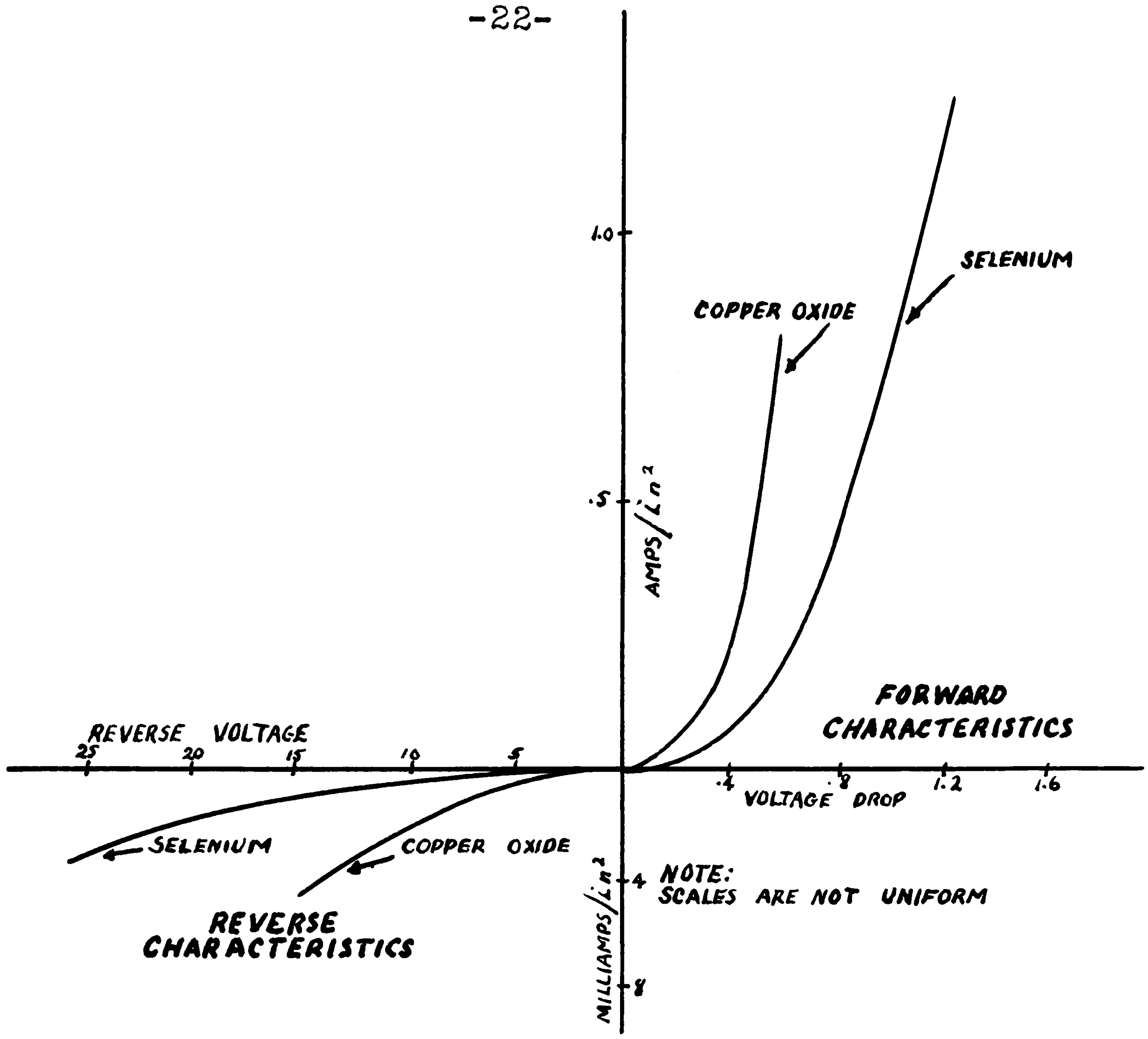


Fig.4-2 Current-voltage characteristics of dry disk rectifier cells. Operating temperature 25° C.

However, because the copper-oxide cells must operate at lower reverse voltages, in many applications two of these cells must be used in the place of one selenium cell. In this light then, the forward resistance of a copper-oxide rectifier is normally considered to be equal to, or slightly greater than, that of a selenium rectifier having an equivalent rating. The reverse or leakage characteristic of these types of rectifiers is also substantially the same when the rectifiers have equal ratings.

2. Reverse voltage ratings. Selenium cells have a maximum rated reverse voltage of about 18 volts rms or higher, whereas the copper-oxide reverse voltage may not exceed 8 volts rms. The decision as to whether or not this variation favors the selenium rectifier will depend upon the rectifier's rated output voltage. If the A-C voltage required for this output voltage is very low, then the higher reverse voltage rating of a selenium cell is in itself of little advantage because regardless of the type of disks used one disk must be used in each arm of the rectifier.

3. Weight to power ratio. The weight per unit of output power is much less for the selenium rectifier cell using an aluminium supporting disk than for the ordinary copper-oxide rectifier cell. However if the copper oxide cells have an oxide coating on both sides of a common copper base, then the weight to power ratio becomes only slightly greater than that of selenium cells using iron supporting disks. It should be remembered that cells having a coating on each side of a common base are not applicable to single phase half-wave rectifiers, nor are they as easily stacked for high voltage outputs as cells having only one rectifying surface. Generally where weight to power ratios are important selenium rectifiers are preferred to copper-oxide rectifiers.

4. Life and aging. Copper-oxide rectifiers have an almost unlimited life if operated within their rated limits. Selenium rectifiers, having come into the industrial field

about 1924, have not as yet been established as having as long a life as their competitors.

The D-C output voltage of both types of rectifiers, for a given A-C voltage input, will decrease about 10 percent with aging equivalent to about 15,000 hours service.

5. Efficiency. Both types have nearly constant efficiency from 25 percent full load to full load. Thus at moderate loads these rectifiers have efficiencies which exceed those of motor generator sets having the same full load ratings.

6. Output voltage regulation. When copper-oxide and selenium rectifiers are operated at equivalent ratings their regulations are almost the same. However for low voltage applications, where one copper-oxide disk per rectifier arm is sufficient, it is readily seen from Fig.4-2 that the voltage drop across a copper-oxide rectifier would be much less than that across a selenium rectifier, and hence the former would definitely have a lower voltage regulation.

7. Maximum permissible temperature rise. Copper-oxide rectifiers have a much smaller permissilble temperature rise than selenium rectifiers. The former type are usually allowed a 12° Centigrade temperature rise above an ambient temperature of 35° C; whereas the limiting factor concerning the temperature rise of selenium rectifiers is the melting point of the alloy layer which, after applying a safety factor, is about 75° C. This variation in permissible temperature rise directly concerns the relative abilities of each type

of rectifier to handle intermittent overloads and will be discussed shortly.

8. <u>Derating of rectifiers.</u> Rectifier ratings are generally based upon a 35° C ambient temperature. For higher ambient temperatures it is necessary to reduce the rating of both types of rectifiers. An important difference between the two types exists in the method of derating applied to each. For copper-oxide rectifiers, see Fig.4-3(a), the rated current does not have to be decreased, but the rated D-C output voltage of the rectifier must be decreased rapidly until at about 70° C ambient temperature it is only 25 percent of its normal rated value. Beyond 72° C ambient temperature the copper-oxide rectifier is not to be used as its rectifying property becomes unstable.

For selenium rectifiers, see Fig.4-3(b), the derating

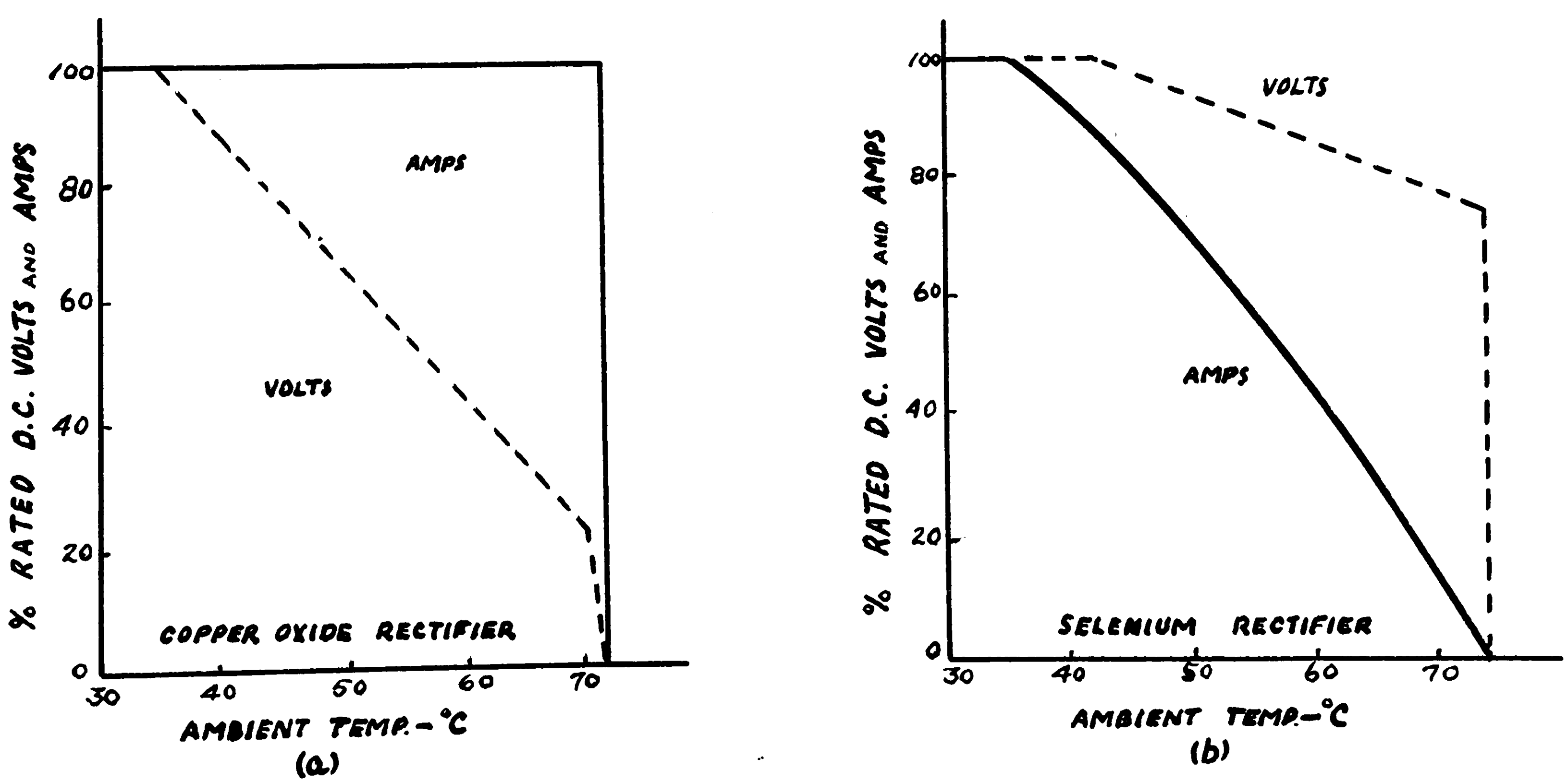


Fig.4-3 Derating curves for copper-oxide and selenium rectifiers operating at ambient temperatures above 35° C.

of output voltage is small, but the current output is derated rapidly such that at an ambient temperature of 75° C and above the rectifier may not be operated within the limits set by the manufacturers' safety factor.

Summarizing, it may be said that neither type of rectifier is to be used at an ambient temperature above about 70° C; and that the more suitable type of dry disk rectifier at ambient temperatures above 35° C depends upon the particular application. For a high voltage, low current D-C output the selenium rectifier will be better; for a low voltage, high current D-C output the copper-oxide rectifier will be more suitable.

9. <u>Intermittent overload duty.</u> Both types of rectifiers may be operated intermittently at higher than rated current. The product of I^2R and duration of overload determines the amount of heat generated in the rectifier, where R is approximately equal to the rectifier's forward resistance, and I is the rms rectifier output current. The two types have, as noted previously, substantially the same resistances; and under overload conditions of short duration it may be assumed that both types have the same thermal capacities. It then follows that the rectifier with the higher permissible temperature rise will withstand the more severe overload, since all the other factors concerning the temperature rise are approximately equal. Since selenium rectifiers normally have a considerably greater permissible temperature

rise than have copper-oxide rectifiers the former will withstand the more severe overloads. Fig.4-4 shows the intermittent overload characteristics of the two types of rectifiers being considered.

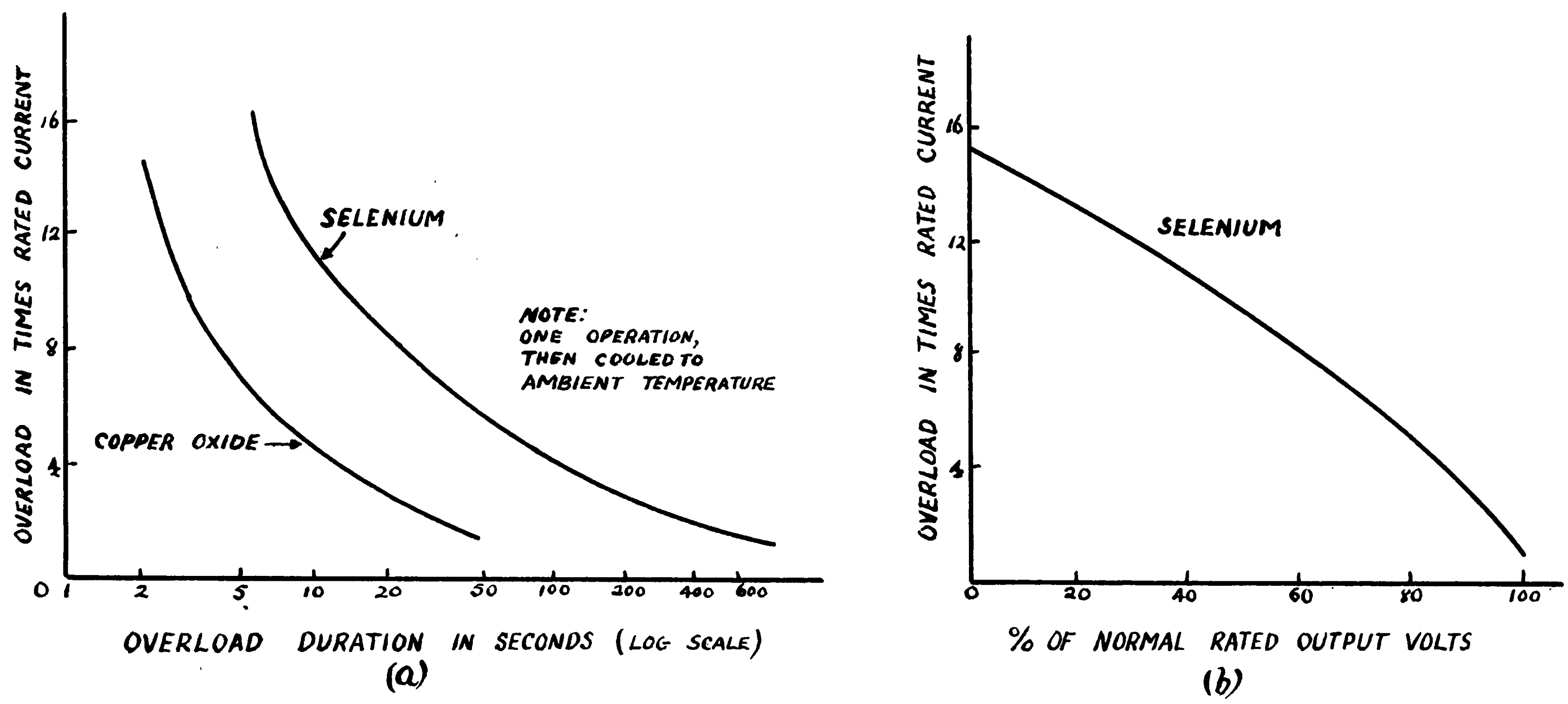


Fig.4-4 Intermittent overload characteristics of rectifiers.

Since the IR drop of rectifiers increases on overload, the D-C output voltage must drop. Fig.4-4(b) shows the resultant decrease in output voltage plotted against the magnitude of overload current for a selenium rectifier. This characteristic of rectifiers is desireable in such applications as starting D-C motors directly across the line because the higher the current drawn, the lower the output voltage, and hence the starting current may be limited by the regulation of the rectifier. In such applications the selenium rectifier is superior to copper-oxide or tube rectifiers, because of its greater overload capacity.

Copper-oxide rectifiers will withstand intermittent overvoltages. An application of this characteristic is in overvoltage protection. The A-C line voltage applied to the rectifier may exceed the rectifier's rated value and thus force an overload current through the D-C trip coil of a circuit breaker. Since the time required for the circuit breaker to trip is very short, no damage is done to the copper-oxide rectifier, whereas a selenium or tube rectifier would probably be ruined by even this short duration overvoltage.

A factor limiting the duration and magnitude of overloads a rectifier will withstand is the frequency of occurrence of these overloads. Fig.4-5 shows that the longer the period between successive overloads the greater is the permissible duration of overload. This follows from the fact that to achieve maximum overload capacity the rectifier must be at ambient temperature when each overload begins.

10. Standby service. Copper-oxide rectifier current-voltage characteristics do not change during long periods of idleness, whereas selenium rectifiers undergo an unforming process during long periods of idleness which reduces the reverse resistance and hence the rectifying property of the disk. The selenium rectifier will recover its normal

characteristic upon applying a small A-C voltage across it; however since such a procedure is unnecessary with copper-oxide rectifiers the latter are obviously superior in applications requiring full output power immediately after long periods of idleness, such as in circuit breaker operation.

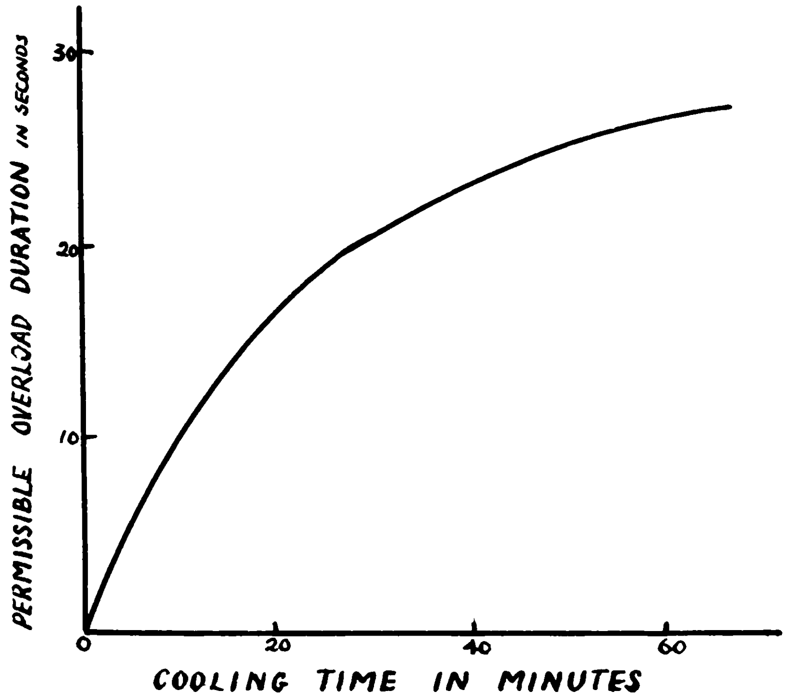


Fig.4-5 Permissible duration of 1000% overload against cooling time between overloads.

CHAPTER FIVE

RECTIFIER CIRCUIT CHARACTERISTICS

5-1 Common rectifier circuits.

There are numerous ways of arranging rectifier elements in a rectifier; no one particular circuit is best suited to all applications. The following, using the proposed A.I.E.E. terminology, are the more commonly used rectifier circuits.

1. Half-wave	5. Three phase zigzag
2. Full-wave	6. Three phase bridge
3. Single phase bridge	7. Six phase diametric
4. Three phase wye	8. Double wye

No attempt will be made to discuss fully the operation of these circuits. Such material is available in text books dealing with rectifier operation, ref. 4, 5 and 6. However an attempt will be made to summarize the characteristics of of some of these circuits , and to augment this theory with oscillograms of current and voltage obtained from actual rectifier operation. Such oscillograms are sadly lacking in many references. The inherent advantages and disadvantages of each rectifier circuit will be indicated, particular attention being paid to these as they affect dry disk rectifier applications.

5-2 Definitions.

Before continuing it is essential that certain factors, which are universally used to compare rectifier characteristics, be defined and their significance noted.

1. Inverse peak voltage. It is the maximum reverse voltage applied across the rectifying elements. These elements have a maximum permissible reverse voltage which, if exceeded, usually results in destruction of the rectifying property of the element. The higher the inverse peak voltage of a circuit the greater the number of rectifier elements, in the case of dry disk rectifiers, required in series in each arm of the rectifier. If a tube rectifier is concerned, higher inverse peak voltage means tubes of higher ratings must be used, otherwise arc backs may occur.

2. Ripple factor. (symbol p) It is defined as the ratio of the root mean square value of the alternating components of the current or voltage wave to the average or mean value of the same wave. Hence the ripple factor is a measure of the smoothness of the output current or voltage wave. The smaller the ripple factor the smoother the wave form; a

ripple factor of zero indicating the output is pure D-C. Generally a rectifier is used to supply D-C power, therefore any A-C component is undesirable; hence as the ripple factor decreases to zero the rectifier approaches conditions of optimum operation.

3. Form factor. (symbol F) It is defined as the ratio of the root mean square value of the current or voltage wave to the average value of the same wave. As the wave shape approaches that of pure D-C the form factor approaches unity. It is readily seen that form factor and ripple factor are dependent upon the same variables and describe the same characteristics of a wave form, in fact they are mathematically related by the formula $p = \sqrt{F^2 - 1}$.

4. Maximum theoretical efficiency. The theoretical efficiency of a rectifier is defined as the conventional efficiency referred to the conversion of A-C power to D-C power, assuming no losses in this conversion. If the form factor were unity, no A-C component would exist, and since all the A-C power is converted to D-C power the maximum theoretical efficiency would be 100 percent. However there is always an A-C component in the output and hence the maximum theoretical efficiency is always less than 100 percent, the actual value depending upon the number of phases in the rectifier and the type of load the rectifier is feeding.

5. Power factor. It is defined as the ratio of the power output from the rectifier to the input line volt-amperes. For dry disk rectifiers the power factor is high

on resistance load because the A-C components of voltage and current are in phase, there being only a small inductive effect due to the transformer. However with controlled grid tube rectifiers the delay in the firing angle is equivalent to forcing the A-C components of voltage and current out of phase. This is then equivalent, in so far as the line is concerned, to connecting an inductive load across the line and thus lowering the line power factor. This decrease in line power factor resulting from delayed firing is one of the chief objections to large installations of tube rectifier-motor drives.

6. <u>Utilization factor.</u> It is defined as the ratio of the rectifier rating to the required transformer rating. This factor is not unity as is the case with power transformers. It is dependent upon two things-

(a) In most rectifier circuits the transformer secondary carries current for only a portion of each cycle, the percentage conducting time depending upon the number of phases.

(b) The more phases there are in the rectifier circuit the lower the peak anode current for a given D-C current output, and hence the lower the required rating of the transformer secondary.

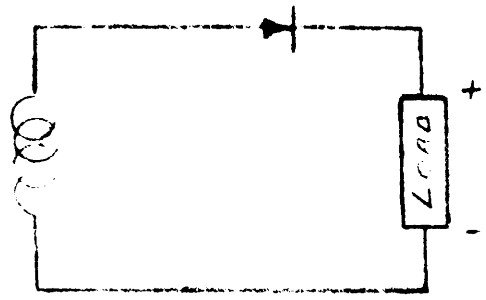
It will be readily seen that the first factor will increase the utilization factor as the number of phases decreases, whereas the second factor decreases the utilization factor as the number of phases decreases. It then follows, since these factors oppose each other, that an optimum number of phases must exist, and in fact three phases give the highest possible secondary utilization factor, which is 0.675. (Mathematically the optimum number of phases is 2.69, however it is obvious that the number of phases must be an integer.)

Note that the foregoing reasoning only holds for circuits having the transformer secondaries connected in star. For circuits such as the bridge type the utilization factor is much higher. Also the primary and secondary transformer utilization factors are not necessarily equal, and in fact are only equal for bridge circuits since no D-C current flows in the secondary windings.

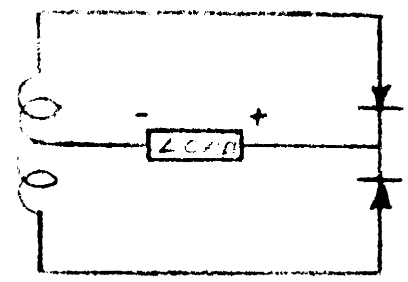
5-3 Characteristics of various rectifier circuits.

5-3-1 Half-wave rectifier see Fig.5-1(a)

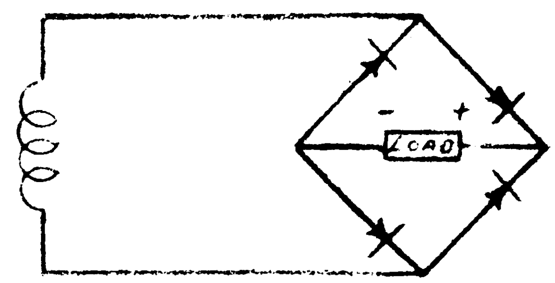
Such rectifiers have very high ripple factor, low maximum theoretical efficiency and secondary utilization factor. Current through the transformer secondary is unidirectional, as is the case for all star connected rectifiers, and transformer saturation may occur unless the transformer is specially designed. These factors all tend to suggest that the half-wave rectifier is not to be used except for very low power outputs where efficiency and ripple factor are not important. In such applications the simplicity of the circuit and low cost are the main advantages.



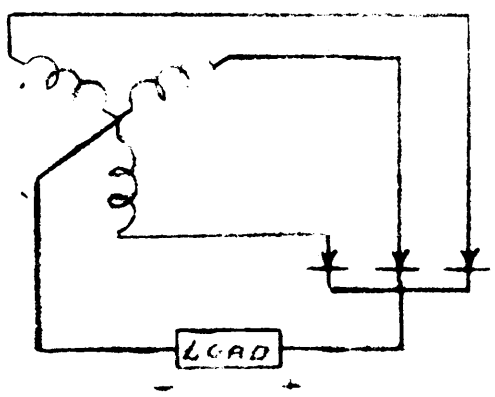
(a) Half-wave



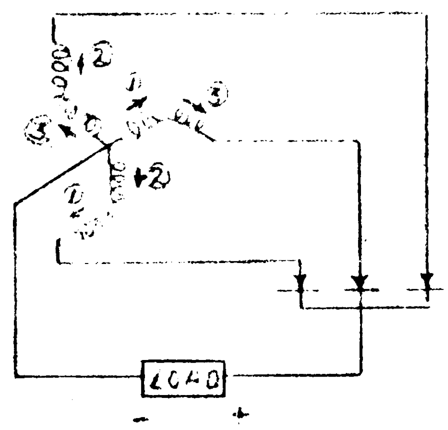
(b) Full-wave



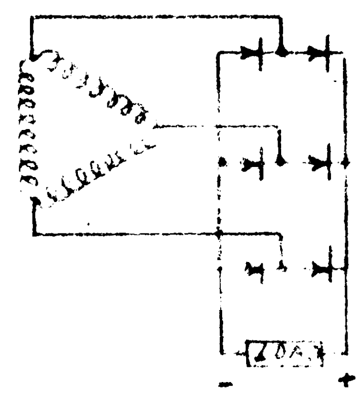
(c) Single phase bridge



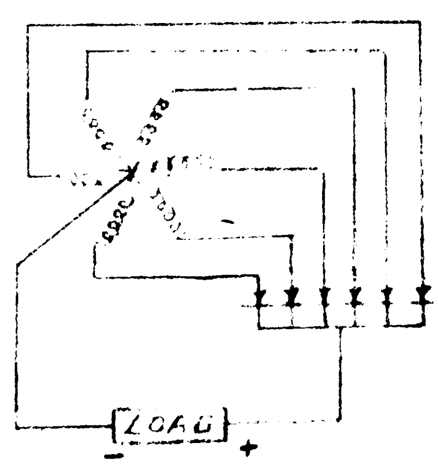
(d) Three phase wye



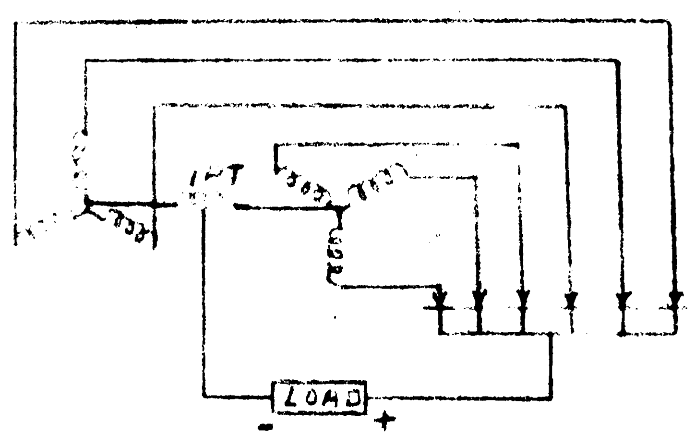
(e) Three phase zigzag



(f) Three phase bridge



(g) Six phase diametric



(h) Double wye

Fig.5-1 Circuit diagrams for various rectifiers.

5-3-2 Full-wave rectifier see Fig.5-1(b)

The ripple factor and maximum theoretical efficiency are by no means optimum, but are considerably improved over the half-wave rectifier. No transformer saturation exists since current flows in opposite directions through each half of the secondary, but the necessity of a centre tapped secondary increases the transformer cost. The secondary utilization factor is nearly the optimum for star connected secondaries, but is much lower than for the single phase bridge rectifier. The inverse peak voltage across the rectifying elements is high, being equal to the full secondary peak voltage. This is a distinct disadvantage as far as dry disk rectifiers are concerned since the number of disks required per arm is consequently high, however this is offset by the fact that there are only two arms as compared with four for the single phase bridge rectifier.

5-3-3 Single phase bridge rectifier see Fig.5-1(c)

Fig.5-2 is an oscillogram[x] of the open circuit voltage of such a rectifier. The secondary transformer voltage is also shown for comparison. The wave form is identical with that of a full-wave rectifier; however because two arms are always conducting in series the inverse peak voltage is low, thus making this circuit ideal for dry disk rectifiers. The utilization factors are almost optimum, and no saturation of the transformer occurs. The chief disadvantage of such a

[x] The non-uniformity of successive pulses in these oscillograms was caused by the non-linearity of the oscilloscope sweep circuit. For description of method employed in obtaining oscillograms see appendix.

circuit is that the cathodes of the rectifying tubes may not be connected together and, in fact, the individual windings of the heater transformer must be insulated from

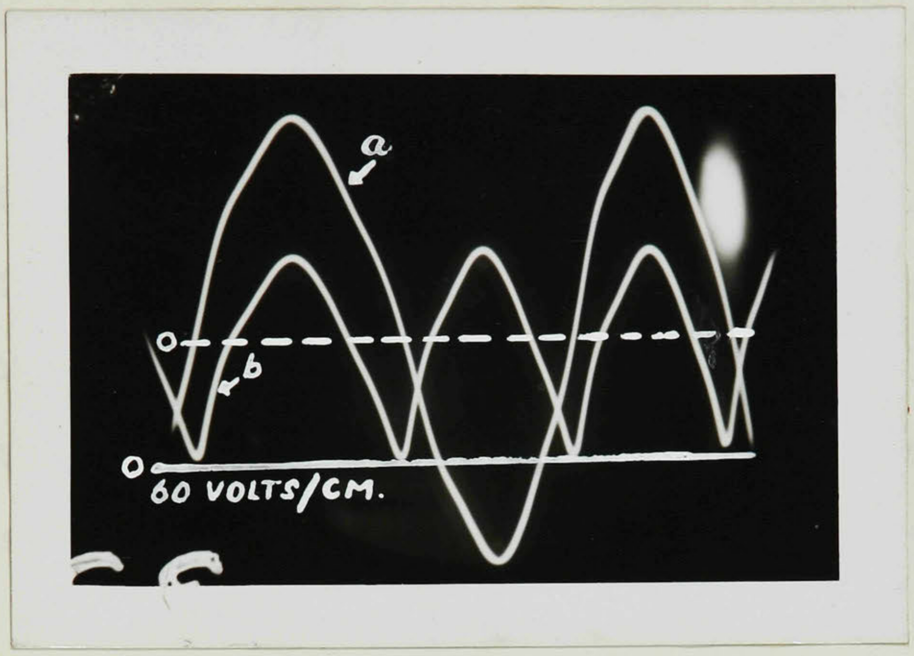


Fig.5-2 Single phase bridge selenium rectifier voltages- (a) transformer secondary (b) open circuit

each other for the maximum potential of the circuit. However this disadvantage does not apply to dry disk rectifiers.

5-3-4 <u>Three phase wye rectifier</u> see Fig.5-1(d)

It is readily seen from the oscillogram in Fig.5-3

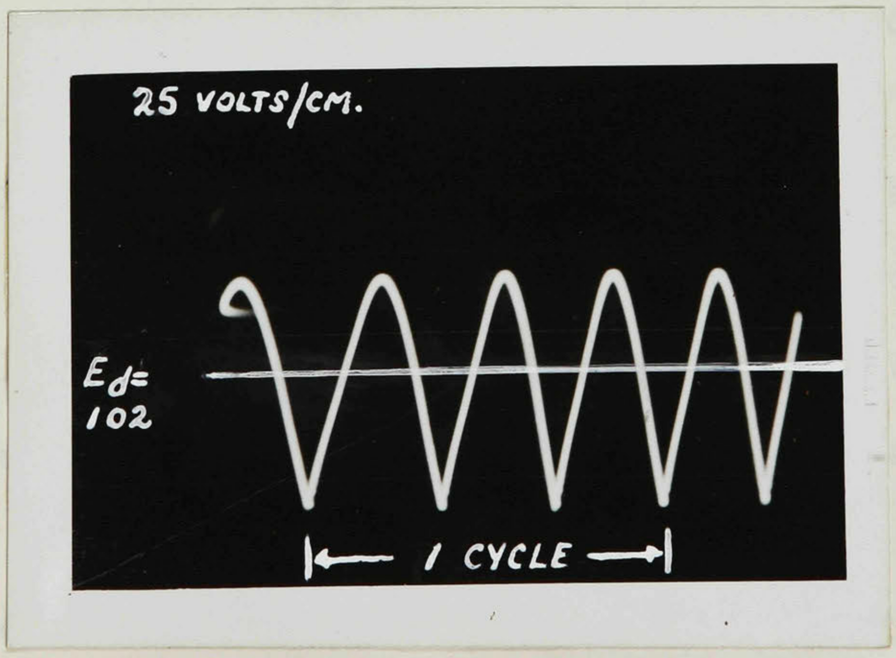


Fig.5-3 Three phase wye selenium rectifier open circuit voltage.

that the output voltage from this rectifier circuit never goes to zero and as a result the ripple factor is much lower than for the previously discussed circuits. Also the chief ripple frequency is now three times the fundamental frequency thus making the filtering of the output still easier than for the other circuits. As mentioned previously, the secondary utilization factor is high; however, as with all star connected rectifier circuits, transformer saturation occurs. Because of these disadvantages this circuit is seldom used in large installations. However for small installations the advantages of requiring only three rectifying elements, and in the case of tube rectifiers, of being able to connect the cathodes together makes the circuit widely used. This circuit is often used to supply armature power to commercial rectifier-motor drives.

5-3-5 <u>Three phase zigzag rectifier</u> see Fig.5-1(e)

This connection overcomes the inherent disadvantage of star connected secondaries by using two secondary windings on each leg of the transformer. As indicated in Fig.5-1(e) the anode current flows in opposite directions through the secondaries of each leg and hence no saturation due to unidirectional current flow results. This is however accomplished at considerable expense since such a connection requires that the two secondaries on each leg be insulated from each other for a voltage equal to $1/\sqrt{3}$ of the peak anode voltage. More secondary turns per leg are required for the same anode voltage because two secondaries in series zigzag give only $\sqrt{3}$ times the voltage per secondary whereas two secondaries in series give double the secondary voltage. The zigzag connection is not frequently used, for with the additional cost of only three rectifying arms six phase diametric rectifier operation may be obtained.

5-3-6 Three phase bridge rectifier see Fig.5-1(f).

Fig.5-4 is an oscillogram of the open circuit voltage of a three phase bridge rectifier. The ripple factor is low, and the major ripple frequency is double that of the three phase wye rectifier; both these factors make filtering of the output power easier. The circuit has all the advantages

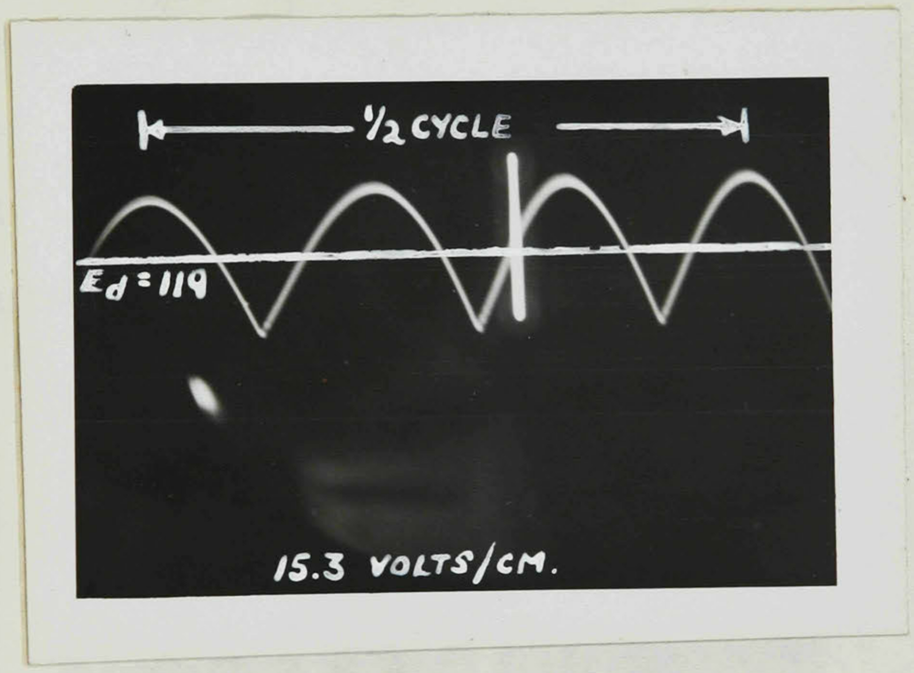


Fig.5-4 Three phase bridge selenium rectifier open circuit voltage.

of the single phase bridge rectifier plus the added advantage that each rectifying element conducts for 120 degrees per cycle instead of 60 degrees per cycle as is the case for the six phase diametric rectifier. The longer conducting period makes more efficient use of the rectifying elements; but this is counteracted by the fact that two arms always conduct in series. Since two elements are in series the voltage regulation is high. For tube rectifiers, which have a constant arc drop, this fact makes it impractical to use this circuit at low voltages because the efficiency would be low, even though the maximum theoretical efficiency is high. Another disadvantage of this circuit is that the cathodes may not be connected together, hence this circuit may not be used with multianode pool cathode tank rectifiers. However the above mentioned disadvantage is non-existent as far as dry disk rectifiers are concerned, and thus the three phase bridge circuit is frequently used in dry disk rectifiers.

5-3-7 <u>Six phase diametric rectifier</u> see Fig.5-1(g).

Fig.5-5 is an oscillogram of the open circuit voltage of a six phase diametric rectifier. This oscillogram indicates, when compared with Fig.5-4, that the voltage wave shape is similar to that of the three phase bridge rectifier. This

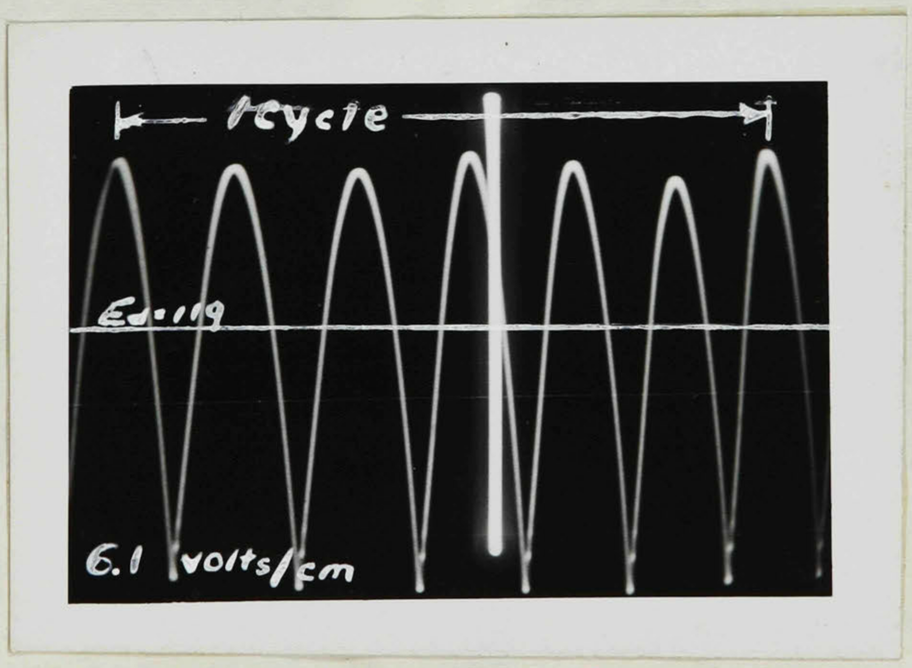
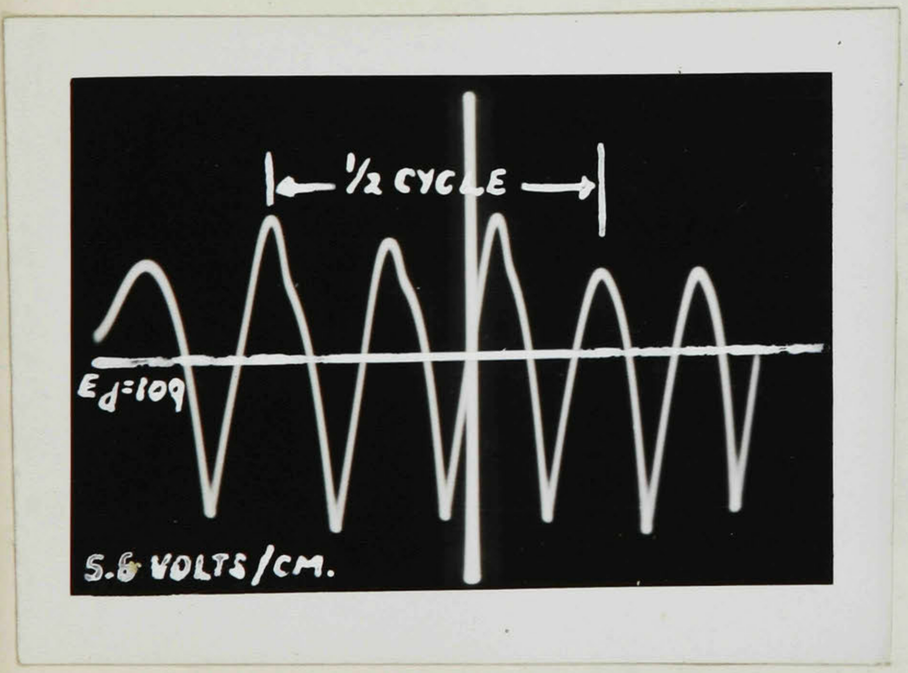


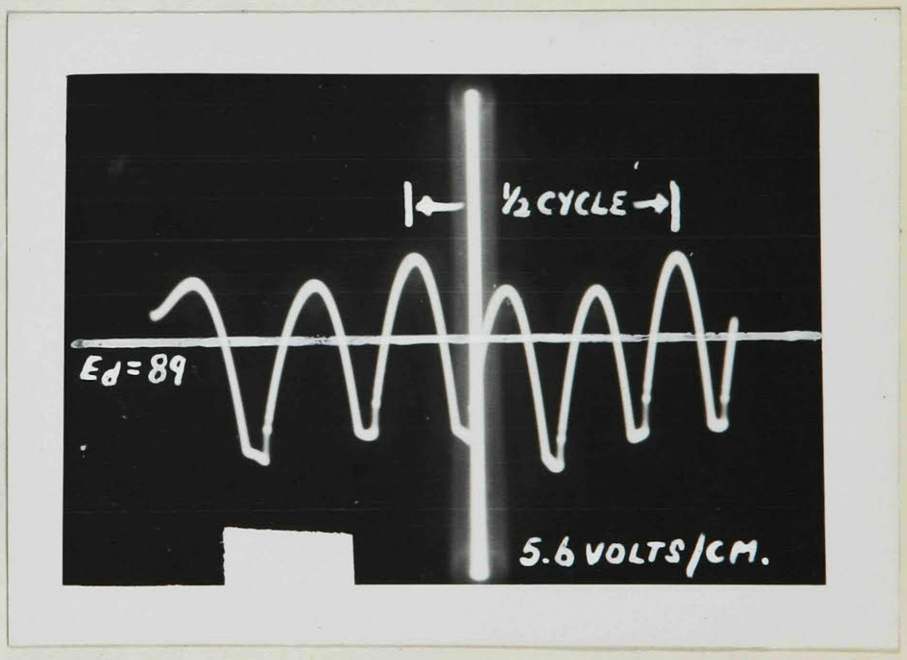
Fig.5-5 Six phase diametric selenium rectifier open circuit voltage.

circuit has the disadvantage of a low secondary utilization factor compared to either the three phase bridge or three phase wye circuits. Each anode conducts for only 60 degrees per cycle, thus the rectifying elements are only half as efficiently used as for the bridge circuit. Also, the peak inverse voltage is double that of the three phase bridge circuit. The chief advantage of this circuit is that the cathodes are connected together and thus the circuit is adaptable to multianode pool cathode tank rectifiers. No transformer saturation due to unidirectional current flow through the secondary windings results as long as the transformers used have twin secondaries.

5-3-8 Double wye rectifier see Fig.5-1(h)

Fig. 5-6(a) shows the output voltage wave form of a double wye rectifier. A comparison of this osccillogram with Fig.5-5 shows that the wave shapes of the output voltages from six phase diametric and double wye rectifiers are similar.





(a) (b)

Fig.5-6 Double wye selenium rectifier output voltages (a) at light load
(b) at $\frac{3}{4}$ rated resistance load.

This suggests that, under the load conditions noted, they must operate similarly. Under light load conditions the double wye rectifier's interphase transformer (subsequently abbreviated IPT) has insufficient current flowing through it to magnetize it. The neutral points of the two wyes must therefore be at the same potential. Under such conditions the potentials of any two of the anodes are only equal at the 60 degree intervals of each cycle, and hence only one anode may conduct at a time. This is simply six phase diametric rectifier operation. If the potentials of at least two of the anodes are made equal at all times then two anodes must conduct simultaneously; the wyes are now paralleled. This equalizing of anode potentials, and subsequent paralleling of the wyes, is brought about only if sufficient current flows in the IPT to magnetize it. Fig.5-7 shows the wave form of the voltage across the IPT when the current is too small to fully magnetize it. (The voltage wave form under load

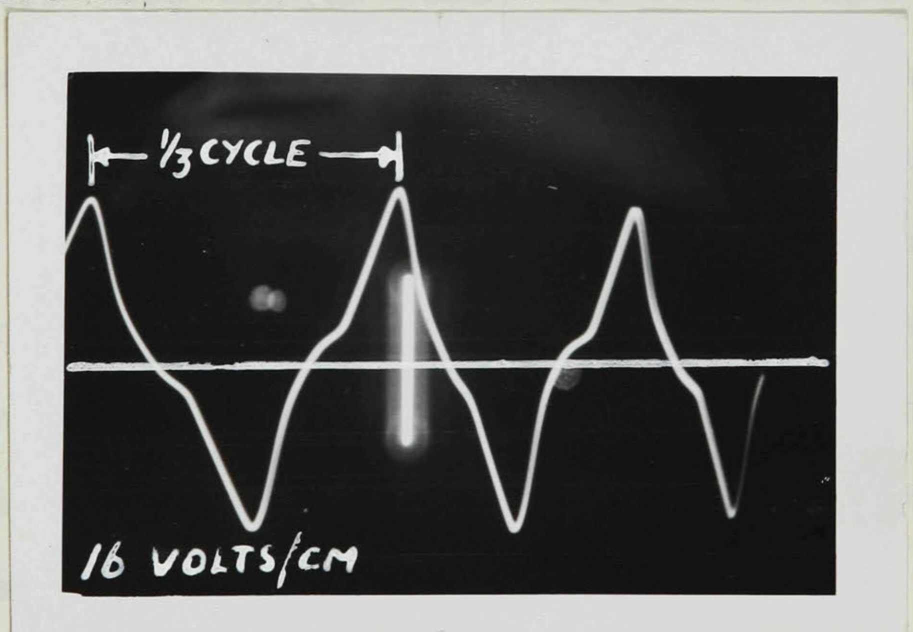


Fig.5-7 Wave shape of voltage across IPT on very light load.

is triangular, see ref. 6 for oscillogram.)

The advantage of double wye rectifier operation is that it combines the high secondary utilization factor characteristic of three phase star operation with the desirable wave form (low ripple magnitude and high ripple frequency) of a six phase diametric rectifier. This circuit is widely used in high current mercury arc rectifiers because the cathodes may be connected together and, since two wyes are paralleled, a greater load current may be carried, using tubes of a given rating, than would be possible with any other circuit discussed here.

Referring to Fig.5-6, it will be noted that the average output voltage decreases from 109 volts to 89 volts due to loading. Part of this regulation is due to the voltage drop in the rectifier and also due to the transformer leakage reactance; however it can be shown mathematically that 14 of this 20 volt regulation is caused by the voltage drop across the IPT. This then suggests that the double wye rectifier has the disadvantage of very high voltage regulation. However if the IPT is designed to have a very low exciting current the drop in D-C output voltage due to the IPT can be made to occur from no load to about 5 percent of rated load. By so doing the regulation over the greater portion of the loading will be due to the normal drops encountered in all rectifier circuits.

Table 5-1 shows, in tabular form, the advantages and disadvantages of each rectifier circuit previously discussed. No attempt has been made to list all the factors concerning the choice of a rectifier circuit, but rather to tabulate the more important ones and thus facilitate the comparison of different rectifier circuits. A table of numerical values of those factors of interest in rectifier design will be found in references 4,5,6,7.

TABLE 1 COMPARISON OF RECTIFIER CIRCUIT CHARACTERISTICS

Circuit	Advantages	Disadvantages
Half-wave	1. Only 1 rectifying arm. 2. Simplicity	1. Very high ripple factor. 2. Large fundamental frequency ripple 3. High inverse peak voltage. 4. Transformer secondary saturation. 5. High peak anode current. 6. Very low efficiency.
Full-wave	1. High secondary U.F.[x] 2. Only two rectifying elements. 3. Cathodes may be common. (Particularly adaptable to double diodes etc.)	1. High ripple factor. 2. Ripple frequency 2F.[xx] 3. High inverse peak voltage. 4. Centre tapped secondary.
Single phase bridge	1. Very high secondary U.F. 2. Primary and secondary U.F. same. 3. Elements conduct 180° per cycle. (Particularly adaptable to dry disk rectifiers.)	1. High ripple factor. 2. Ripple frequency 2F. 3. 4 rectifying arms. 4. Cathodes can not be common. 5. High voltage regulation.
Three phase wye	1. Only 3 rectifying arms. 2. Elements conduct 120°/cycle. 3. Simplicity. (Often used in low power tube rectifier-motor drives.)	1. Transformer secondary saturation. 2. Primary and secondary U.F. differ. 3. Secondary U.F. lower than bridge.
Three phase zigzag	Advantages same as for three phase wye.	1. Twin secondaries on each leg. 2. Secondaries well insulated. 3. More turns/leg than for wye.

x Utilization factor.
xx Fundamental frequency.

TABLE 1 CONTINUED

Circuit	Advantages	Disadvantages
Three phase bridge	1. Low ripple factor. 2. Ripple frequency 6F. 3. Very high secondary U.F. 4. Low inverse peak voltage. 5. Elements conduct 120°/cycle. (Particularly adaptable to dry disk rectifiers.)	1. High voltage regulation. 2. 6 rectifying arms. 3. Cathodes cannot be common.
Six phase diametric	1. Low ripple factor. 2. Ripple frequency[x] 6F.	1. 6 rectifying arms. 2. Elements conduct 60°/cycle. 3. Low secondary U.F. 4. Twin secondaries on each leg.
Double wye	1. Low ripple factor. 2. Ripple frequency 6F. 3. Elements conduct 120°/cycle. 4. Low peak anode current. 5. Cathodes may be common. (Particularly adaptable to multianode pool type rectifiers.	1. 6 rectifying arms. 2. Requires interphase transformer. 3. Very high inverse peak voltage at no load. 4. High regulation from no load to light load.

x Throughout this table 'ripple frequency' refers to 'major ripple frequency'

CHAPTER SIX

RECTIFIER D-C OUTPUT VOLTAGE CALCULATIONS

6-1 Ideal rectifier.

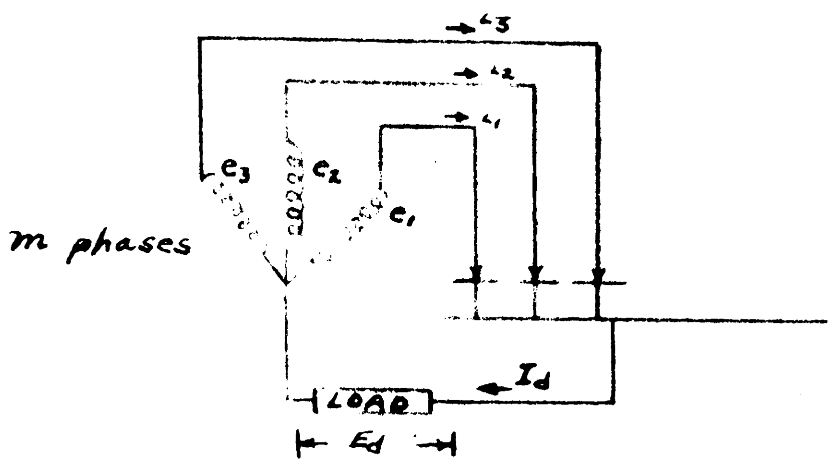
So far no mention has been made of the mathematical relationship existing between the peak anode voltage and the mean output voltage of a rectifier. Consider a rectifier having m phases, then the wave form of the rectifier output voltage, neglecting any drops in the rectifier and assuming the transformer leakage reactance to be zero, will be as shown in Fig.6-1(b), providing only one rectifying element conducts at a time. If the secondary transformer voltage is a sine wave of rms value E_s, then, considering zero time to occur at a voltage peak, the average or mean rectified voltage will be:

$$E_d = \frac{m}{\pi}\int_0^{\pi/m} \sqrt{2}\, E_s \cos(\omega t)\, d(\omega t)$$

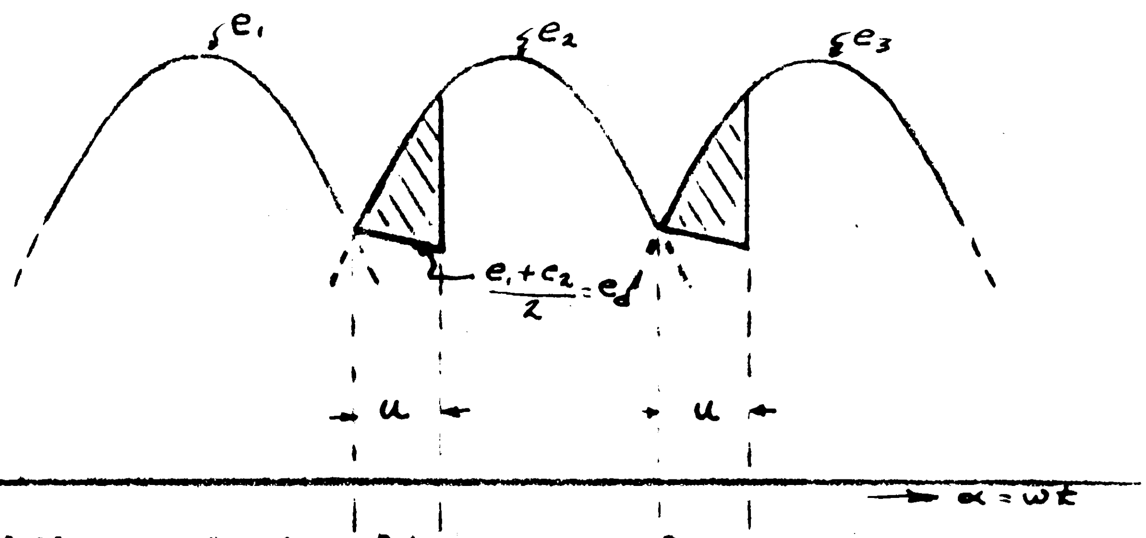
This equation when solved gives:

$$E_d = \sqrt{2}\, E_s \frac{\sin \pi/m}{\pi/m} \qquad \text{(Eqtn. 6-1)}$$

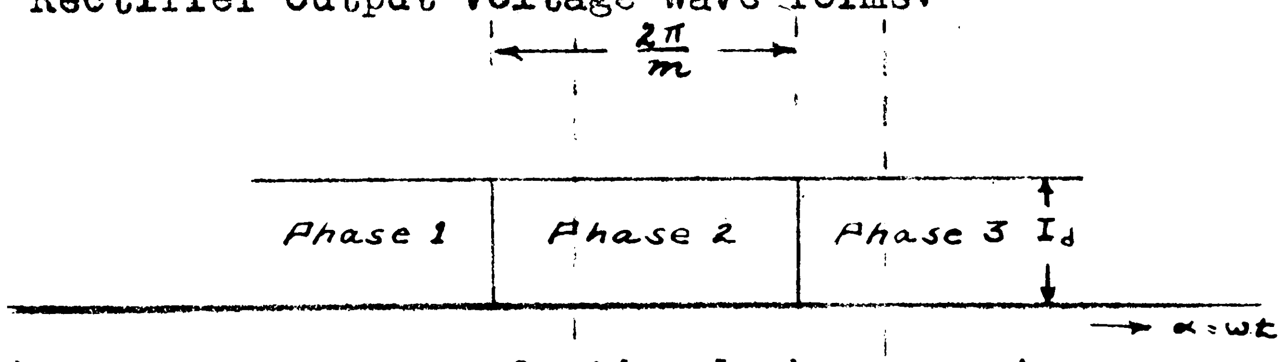
It is readily seen from this equation that as m increases the ratio of E_d to E_s increases and approaches a maximum value of $\sqrt{2}$. This means that the more phases employed in a rectifier the more closely the D-C output voltage approaches the peak secondary transformer voltage. Further, by Fourier analysis, it can readily be shown that the ripple voltage decreases and the major ripple frequency increases as m increases. However the rate of change of these factors with increasing m is very small for m greater than six. It is therefore impractical in most cases to use more than six rectifier phases.



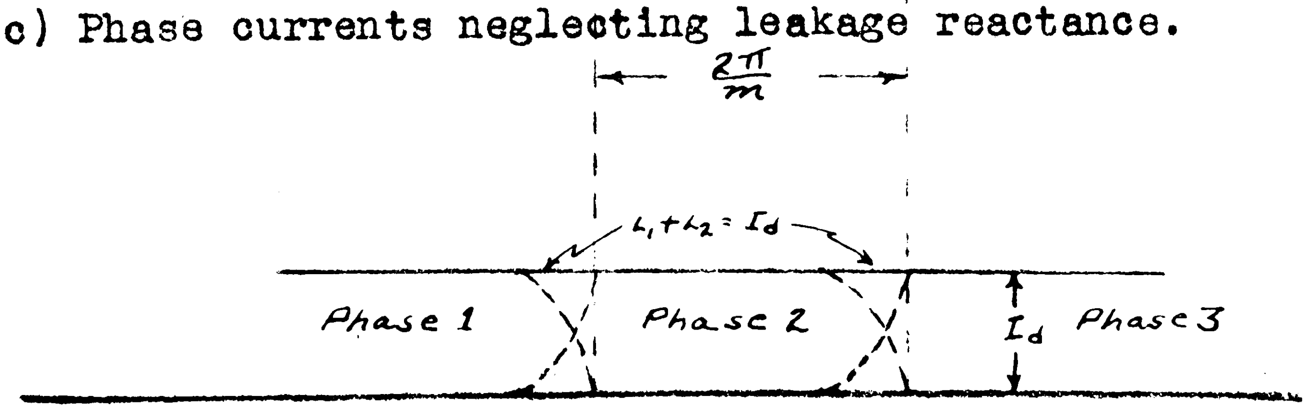
(a) m-phase star connected rectifier.



b) Rectifier output voltage wave forms.



(c) Phase currents neglecting leakage reactance.



(d) Phase currents considering overlap due to reactance

Fig.6-1 M-phase star connected rectifier voltage and current wave shapes.

6-2 Effect of transformer leakage reactance.

Equation 6-1 was derived on the assumption that the current through the rectifying arms transferred or commutated instantaneously from one arm to the other, see Fig.6-1(c). This infers an infinite rate of change of current with time exists for the currents in the commutating arms. This can only occur if the transformer secondary leakage reactance is ignored. The inductance of the transformer secondary forces the current to decrease or increase gradually, thus two rectifying elements must conduct simultaneously. Simultaneous conduction of two elements requires that their potentials be equal. This condition gives the equation:

$$e_1 - L\frac{di_1}{dt} = e_2 - L\frac{di_2}{dt} = e_d$$

where the symbols are defined in the appendix. If the load circuit is highly inductive the load current may not change, therefore $i_1 + i_2 = I_d$ (constant)

The solution of these two equations gives: (ref. 5 and 6)

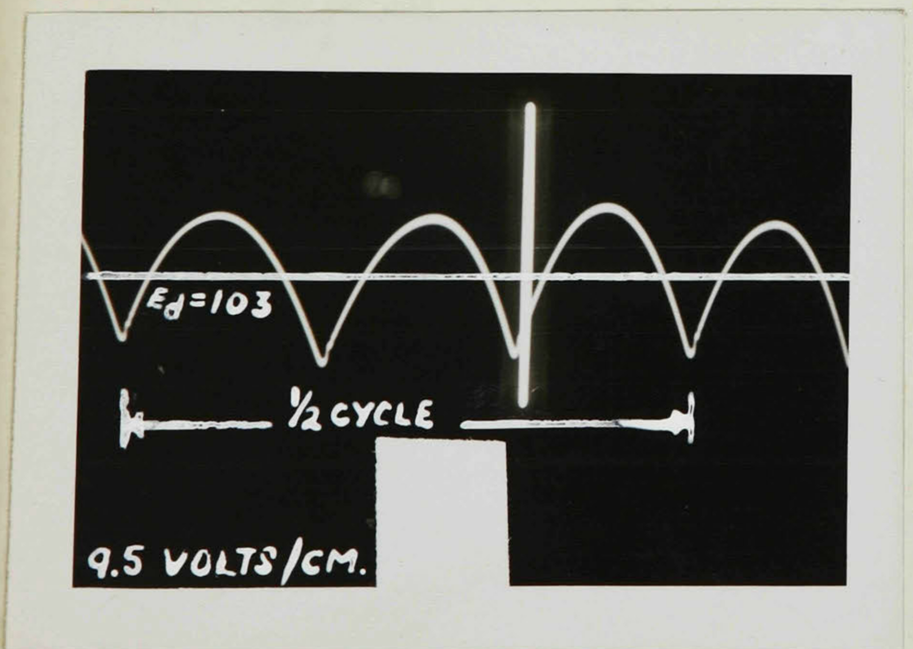
$$e_d = \frac{e_1 + e_2}{2} \qquad \text{(Eqtn.6-2)}$$

Equation 6-2 states that the instantaneous output voltage during the commutation period is the average instantaneous voltage of the simultaneously conducting rectifier arms The resultant output voltage wave shape is shown in Fig.6-1(b) where the shaded area divided by $\frac{2\pi}{m}$ represents the decrease in mean rectifier output voltage due to an angle of overlap u. E_c, the reduction in voltage due to transformer leakage reactance, may be readily derived (ref. 4) and gives:

$$E_c = \frac{m}{2\pi} X I_d \qquad \text{(Eqtn.6-3)}$$

where X is the transformer leakage reactance.

Equation 6-3 shows that the reduction in voltage due to transformer leakage reactance increases as the number of rectifier phases increases. In section 6-1 it was shown that, for any given transformer voltage, the output voltage increased as the number of phases increased. It then follows that there must exist an optimum number of phases, for any given value of leakage reactance, beyond which an increase in m results in a lower output voltage at rated load. Equation 6-3 also shows that the reduction of output voltage is directly proportional to load current, thus overlap increases the voltage regulation of a rectifier. Fig.6-2 shows oscillograms of six phase selenium rectifier output voltage at light load and half load; these clearly show the effect of overlap.



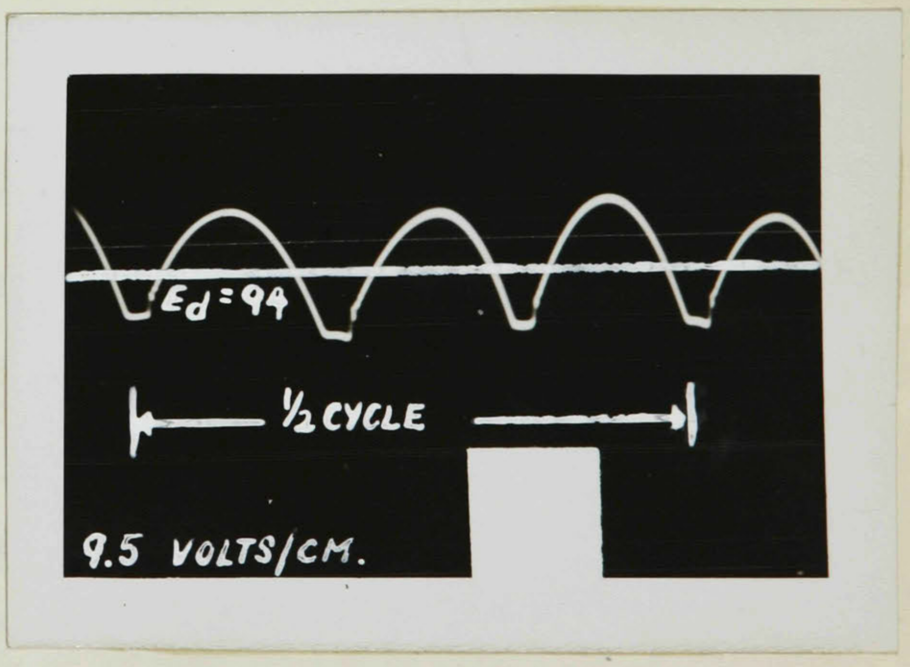


Fig.6-2 Six phase diametric selenium rectifier output voltage (a) light load
(b) half load.

This discussion of the effect of leakage reactance upon output voltage has assumed star connected phases, however a similar reasoning may be followed for bridge and double wye circuits. In fact, the double wye rectifier may be thought of as simply a six phase diametric rectifier which has reactance deliberately introduced in order to increase the angle of overlap so that two elements are always conducting in parallel.

This outline has assumed that at every instant no more than two elements are conducting. It is however possible with rectifiers having a large number of phases for three elements to conduct simultaneously. Such conditions may be analyzed in a manner similar to that discussed above.

It was assumed in the above discussion that because the load circuit was highly inductive the load current remained constant. If a resistance load is considered the determination of the reduction in output voltage due to transformer leakage reactance does not lend itself to a simple solution. However, if the rectifier has six or more phases little error results from use of equation 6-3.

6-3 Effect of IR drops.

Two voltage drops must be considered, firstly the equivalent IR drop in the transformer secondary and secondly the voltage drop across the rectifying element. The IR drop due to the transformer is equal to, if I_d is constant, the copper loss, P_r, divided by the mean load current I_d.

If the rectifying elements are of the type in which the drop across them is practically independent of current, see Fig.2-4, then the complete equation for the D-C output voltage will be: $E_d = \sqrt{2} E_s \frac{\sin \pi/m}{\pi/m} - \frac{m}{2\pi} X I_d - \frac{P_c}{I_d} - E_o$ (Eqtn.6-4)

If the rectifying elements are of the dry disk type, with characteristics as shown if Fig.2-3, then the last term in Equation 6-4 must be replaced by a term $I_d R$, where R is the resistance as determined from the volt-ampere characteristic at a current I_d. This is of course not strictly correct, since both R and the instantaneous current are not constant, however the error introduced in E_d by assuming the voltage drop equal to $I_d R$ is insignificant in most applications.

Fig. 6-3 shows the output voltage oscillograms for a six phase diametric selenium rectifier operating at no load and half rated load (motor load). Since the voltage gains

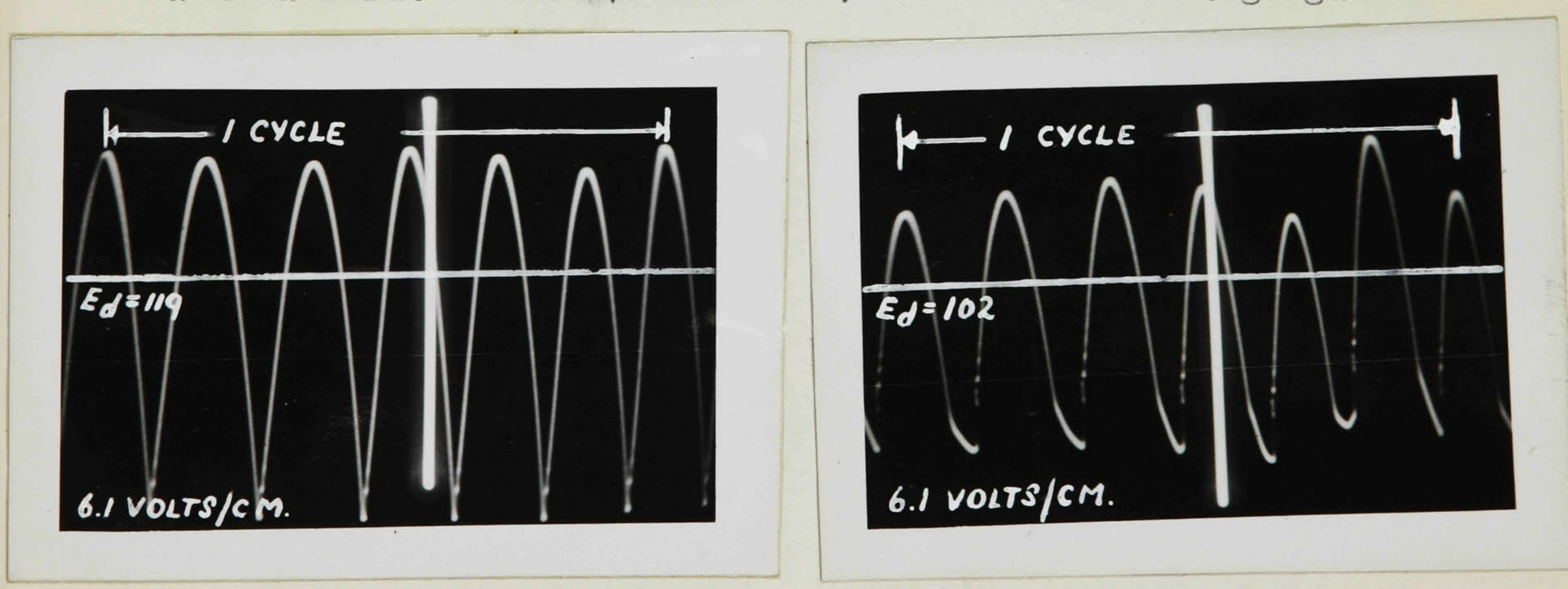


Fig.6-3 Six phase diametric selenium rectifier output voltages (a) open circuit
(b) half rated motor load.

are the same for both oscillograms it may be seen that the ripple voltage has decreased upon loading. It appears that this reduction in ripple voltage may be due to the variation in the instantaneous IR drop across the rectifying elements. During the period of overlap the current (which is practically constant due to the circuit inductance) is divided between the two simultaneously conducting elements, hence the IR drop is lower during overlap than when one element is carrying all the load current. The net effect then is to reduce the open circuit peak output voltage more than the instantaneous output voltage during overlap, thus reducing the ripple voltage.

Figs.6-2 and 6-3 both show the effects of overlap and IR drop across the rectifying arms, however in Fig.6-3 the amplification was increased in order the magnify the ripple component. The uneven voltage peaks in Fig.6-3(b) indicate that the IR drops across the rectifying arms are not all equal.

CHAPTER SEVEN

CHARACTERISTICS OF A RECTIFIER-MOTOR DRIVE

7-1 Circuit representation.

The rotating armature of a D-C motor, under steady state conditions, may be represented by a circuit consisting of a resistance R, inductance L, and back-emf E_g. Hence the determination of voltage and current magnitudes and wave shapes depends upon the solving of a circuit such as shown in Fig.7-1(a). In order to reduce the number of variables it will be assumed that the motor armature reaction is negligible and thus the operating flux is constant. It therefore follows, since $E_g = K\varphi n$, that E_g is entirely dependent upon motor speed for any given set of operating conditions.

7-2 Theory of discontinuous conduction.

Two modes of operation may exist for any rectifier-motor drive. They are characterized by either continuous of discontinuous conduction; discontinuous conduction resulting when periods of zero armature current occur and continuous conduction resulting when no zero armature current gaps occur.

7-2-1 Voltage and current wave shapes.

For discontinuous operating conditions only one phase of the rectifier need be considered to determine the current and voltage characteristics since each phase operates independently of the others for any given value of E_g. It then follows that the resistance and inductance of the

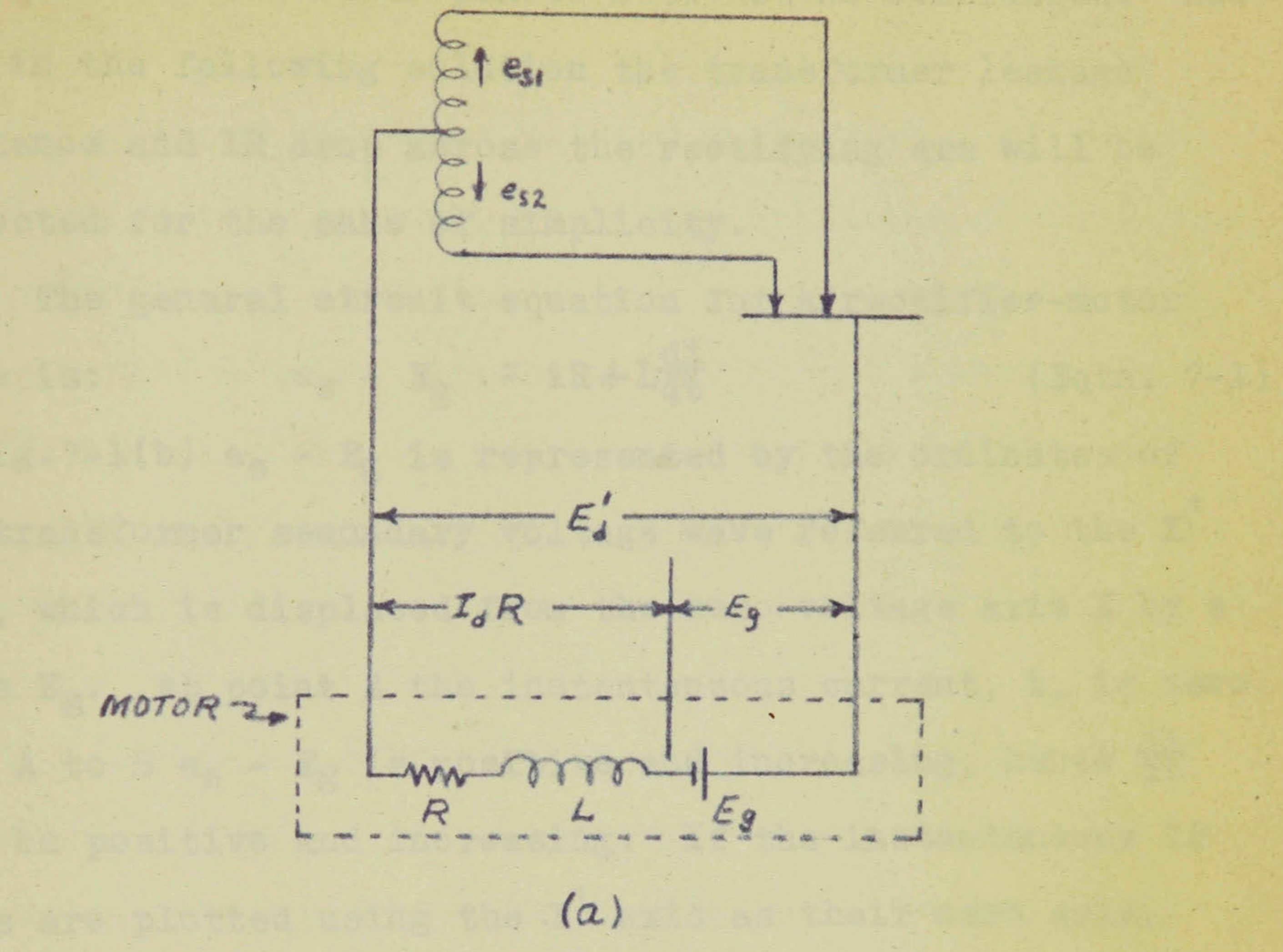


Fig.7-1 Full-wave rectifier-motor
(a) circuit representation
(b) voltage and current wave shapes.

conducting rectifier phase may be lumped with the resistance and inductance of the motor circuit; the resistance and inductance of the other phases need not be considered. However in the following solution the transformer leakage reactance and IR drop across the rectifying arm will be neglected for the sake of simplicity.

The general circuit equation for a rectifier-motor drive is:

$$e_s - E_g = iR + L\frac{di}{dt} \qquad \text{(Eqtn. 7-1)}$$

In Fig.7-1(b) $e_s - E_g$ is represented by the ordinates of the transformer secondary voltage wave referred to the X' axis, which is displaced from the zero voltage axis X by a value E_g. At point A the instantaneous current, i, is zero. From A to B $e_s - E_g$ is positive and increasing, hence $\frac{di}{dt}$ must be positive and increasing. If the instantaneous IR drops are plotted using the X' axis as their zero axis, then the ordinate between the resulting curve AGDE, and the voltage wave of e_s will be $L\frac{di}{dt}$. It then follows that at point D, since this ordinate is zero, $\frac{di}{dt}$ is zero. Also beyond point D the ordinates are negative and increasing, hence $\frac{di}{dt}$ must be negative and increasing. Therefore at the angle corresponding to point D maximum instantaneous current must occur. At point E the IR drop, and hence the current, becomes zero. However from points E to M, even though there is an emf tending to reverse the current, the current remains at zero because of the assumed infinite resistance of the rectifier to flow of current in the reverse direction. At point M the cycle begins again since conditions at points A and M are identical.

The voltage E_d', as measured by a D-C voltmeter across the rectifier terminals, will be the average ordinate, referred to the X axis, of the curve ABDFEM taken over one half cycle. The instantaneous rectifier output voltage can never be greater than e_s. It then follows that E_d' is not the average rectifier output voltage because such would make the instantaneous rectifier output voltage greater than e_s in the period E to M. The rectifier output voltage, E_d, is therefore defined as the average voltage across the load <u>during the period of conduction only</u>, that is, E_d equals the average ordinate, referred to the X axis, of curve ABDF taken over one half cycle.

The armature current wave shape will be that of the curve AGDEM referred to the X' axis. The average current, I_d, will be the average ordinate of this wave, over one half cycle, divided by R.

7-2-2 Current and voltage calculations.

An analytical method of determining I_d results if it is noted that the average armature current, I_d, is proportional to the average armature resistance drop I_dR. Since I_dR is equal to the average armature terminal voltage minus the back-emf of the motor it then follows that:

$$I_d = \frac{E_d' - E_g}{R}$$

$$= \frac{1}{\pi R}\int_{\alpha_f}^{\alpha_s} \sqrt{2} E_s \sin(\omega t) - E_g \, d(\omega t)$$ since E_d' equals

e_s during the conducting period of each phase. The necessary limits of integration are the angle of firing, , and the angle of extinction, . The solution of this integral is,

(ref. 8) $$I_d = \frac{\sqrt{2} E_s}{\pi R}\left[\cos\alpha_f - \cos\alpha_s - \frac{E_g}{\sqrt{2} E_s}(\alpha_s - \alpha_f)\right]$$ (Eqtn. 7-2)

The factor $\frac{E_g}{\sqrt{2}E_s}$ is directly proportional to motor speed if the operating flux is assumed constant and the voltage drop across the rectifying elements is assumed zero, therefore this factor is called the 'speed factor'. Putting $a = \frac{E_g}{\sqrt{2}E_s}$ equation 7-2 becomes:

$$I_d = \frac{\sqrt{2}E_s}{\pi R}\left[\cos\alpha_f - \cos\alpha_s - a(\alpha_s - \alpha_f)\right] \quad \text{(Eqtn. 7-3)}$$

An inspection of equation 7-3 will show that the value of I_d will be dependent upon α_f, α_s and a. However conduction always begins, if controlled firing is not used (as is always the case with dry disk rectifiers), at an angle α_f

such that $$E_g = \sqrt{2}E_s \sin\alpha_f$$

hence $$\alpha_f = \sin^{-1}\frac{E_g}{\sqrt{2}E_s} = \sin^{-1}a$$

Equation 7-3 may now be simplified and becomes:

$$I_d = \frac{\sqrt{2}E_s}{\pi R}\left[\sqrt{1-a^2} - \cos\alpha_s - a(\alpha_s - \sin^{-1}a)\right] \quad \text{(Eqtn. 7-4)}$$

As may be seen from the explanation of the current and voltage wave shapes shown in Fig.7-1(b), α_s depends upon the ratio of inductance to resistance for the circuit, and the value of the speed factor 'a'. The ratio of inductance to resistance may be represented by the power factor of the circuit, $\cos\theta$, taken at line frequency.

Vedder and Puchlowski (ref. 8) have constructed graphs giving values of α_s for different values of 'a' and $\cos\theta$. These graphs are primarily intended for solving controlled firing problems. The writer has attempted to simplify the graphs and make them easier to use for the case of uncontrolled firing which is of interest with dry disk rectifiers. Fig.7-2 is a plot of α_s against 'a', using $\cos\theta$ as a parameter. Such a graph greatly simplifies the determination of α_s and hence the solving of I_d from equation 7-4, when values

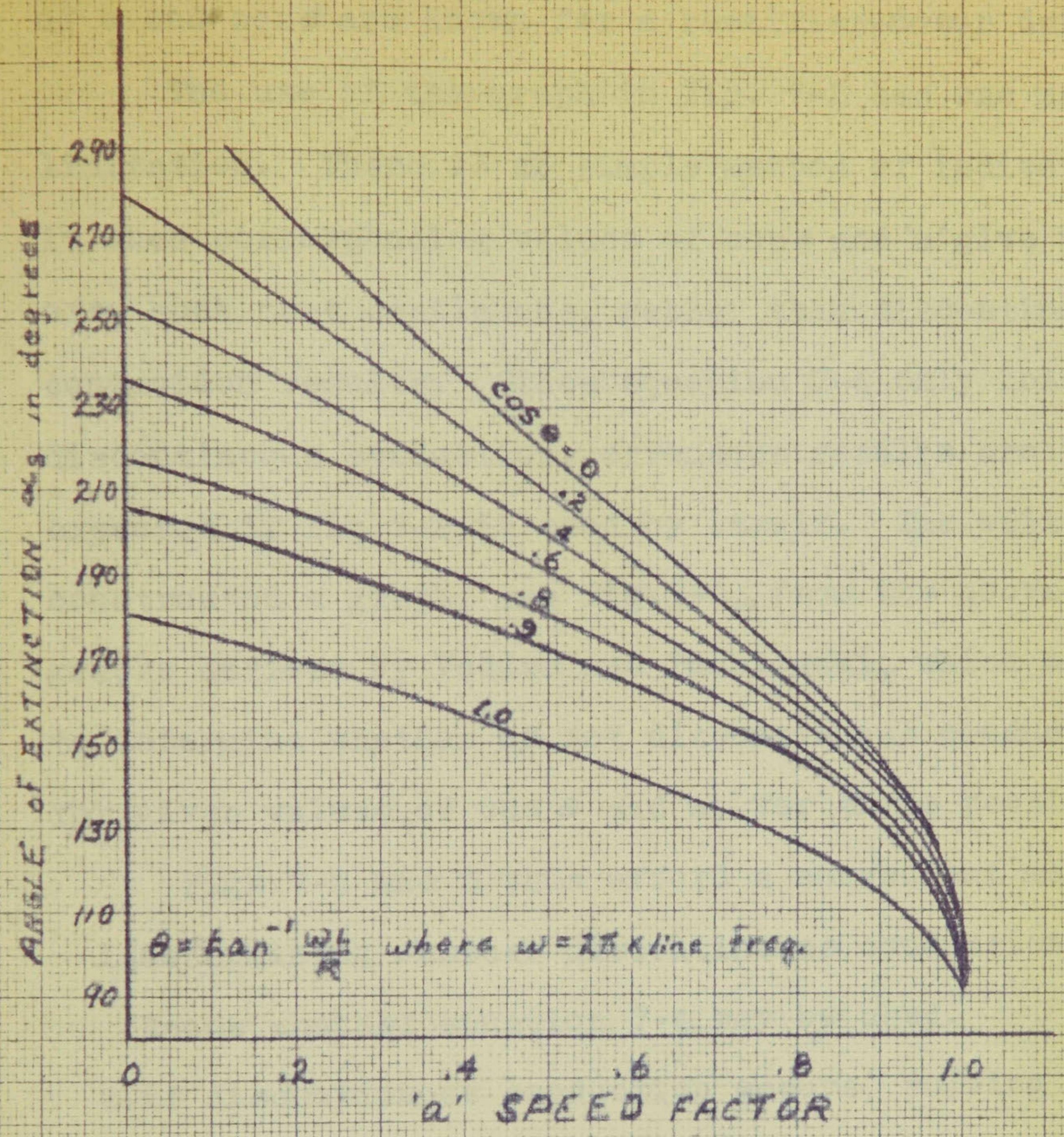


Fig. 7-2 Graph for determining α_s.

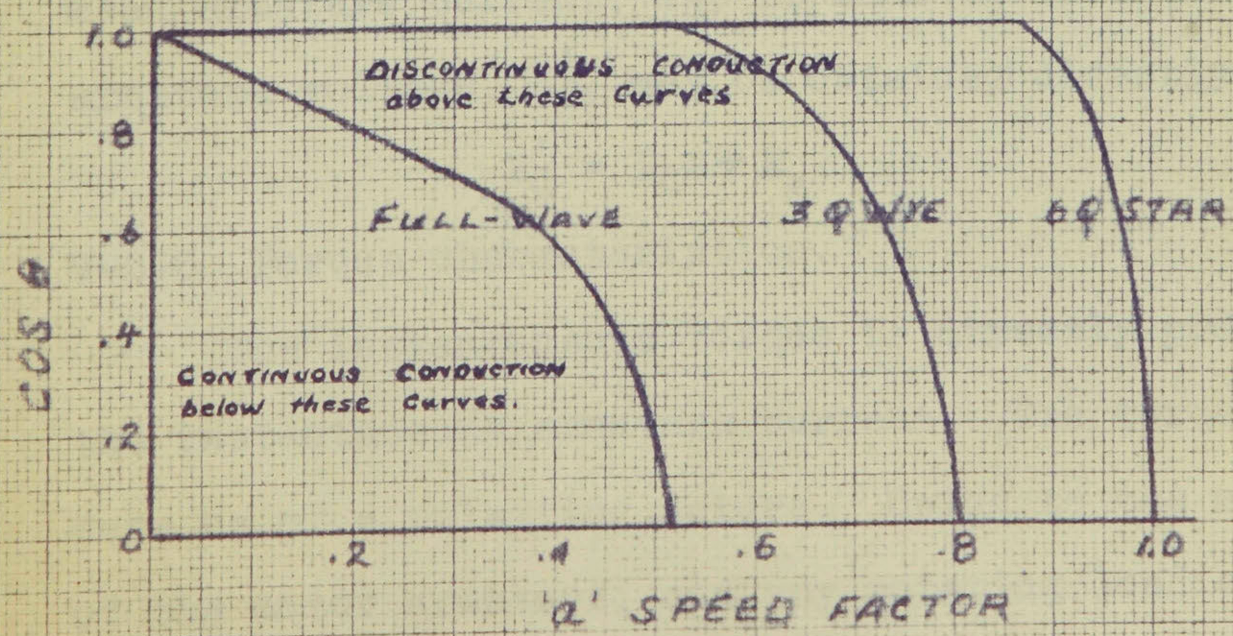


Fig. 7-3 Regions of continuous and discontinuous conduction.

of a and $\cos\theta$ are known for a rectifier-motor drive.

The use of the graph in Fig. 7-2 has one major limitation. There is no simple method of indicating on it when corresponding values of $\cos\theta$ and 'a' give values of α_s such that continuous, rather than discontinuous, conduction results. Since equation 7-4 only holds for discontinuous conduction, erroneous results are to be expected if Fig. 7-2 is used by itself. The writer has constructed a graph, see Fig. 7-3, from the above mentioned graphs derived by Vedder and Puchlowski, which may be used to determine whether or not discontinuous conduction occurs, for given values of $\cos\theta$ and 'a', for three rectifier circuits.

Figs. 7-2 and 3 thus afford a convenient method of:

1. determining whether discontinuous conduction occurs and hence whether equation 7-4 may be used.
2. if discontinuous conduction occurs, solving for α_s and thus reducing the work involved in solving equation 7-4.

Having indicated a simple method for determining the mean armature current, I_d, it then follows that the mean armature voltage, E_d', may be obtained directly from:

$$E_d' = I_d R + E_g \qquad \text{(Eqtn. 7-5)}$$

7-2-3 Torque characteristics.

The instantaneous torque is directly proportional to the instantaneous armature current. The torque will therefore be of a pulsating nature. Owing to the moment of inertia of the motor armature, and any rotating load connected to it, the instantaneous speed cannot change appreciably, so it is permissible to assume the speed, n, and the back-emf of the motor, E_g, are constant.

An increase in load torque is accompanied by an increase in armature current. For rectifiers having uncontrolled firing this increase in armature current may be obtained only by a decrease in E_g, which in turn is brought about by a decrease in speed. This process of taking on load is similar to that of a conventional D-C motor drive with one exception. The decrease in speed and E_g is larger for a discontinuously conducting rectifier-motor drive than for a conventional D-C motor drive under the same operating conditions. Since average torque is proportional to average armature current, for a given increase in shaft load a corresponding increase in average current must result. The magnitude of this increase is the same whether for a rectifier-motor drive or a conventional motor drive. However the required increase in instantaneous current during the period of conduction to produce a given increase in average armature current over one half cycle will depend upon whether or not the current flows continuously. For example, if the average current is to be doubled and current flows continuously, then the average current during conduction must of course double; however if current flows for only one half of each cycle then the average current during conduction must be quadrupled in order to double the average current over the whole cycle. In order to increase the instantaneous current a proportionate decrease in E_g, and hence speed, must occur. It is thus apparent that the speed regulation of a discontinuously conducting rectifier-motor drive will be greater than that of a corresponding conventional D-C motor drive. Also, for a rectifier-motor drive, as the load increases and continuous conduction is approached the rate of change of speed with load will decrease.

7-2-4 Experimental results.

The experimental wave shapes shown in Figs.7-4,5,6,and 7 serve to verify the theory outlined in this chapter and also to indicate any discrepancies that may exist between theoretical and practical operating characteristics. Fig.7-4 shows the armature voltage wave shape obtained across a full-wave selenium rectifier-motor drive running at no load.

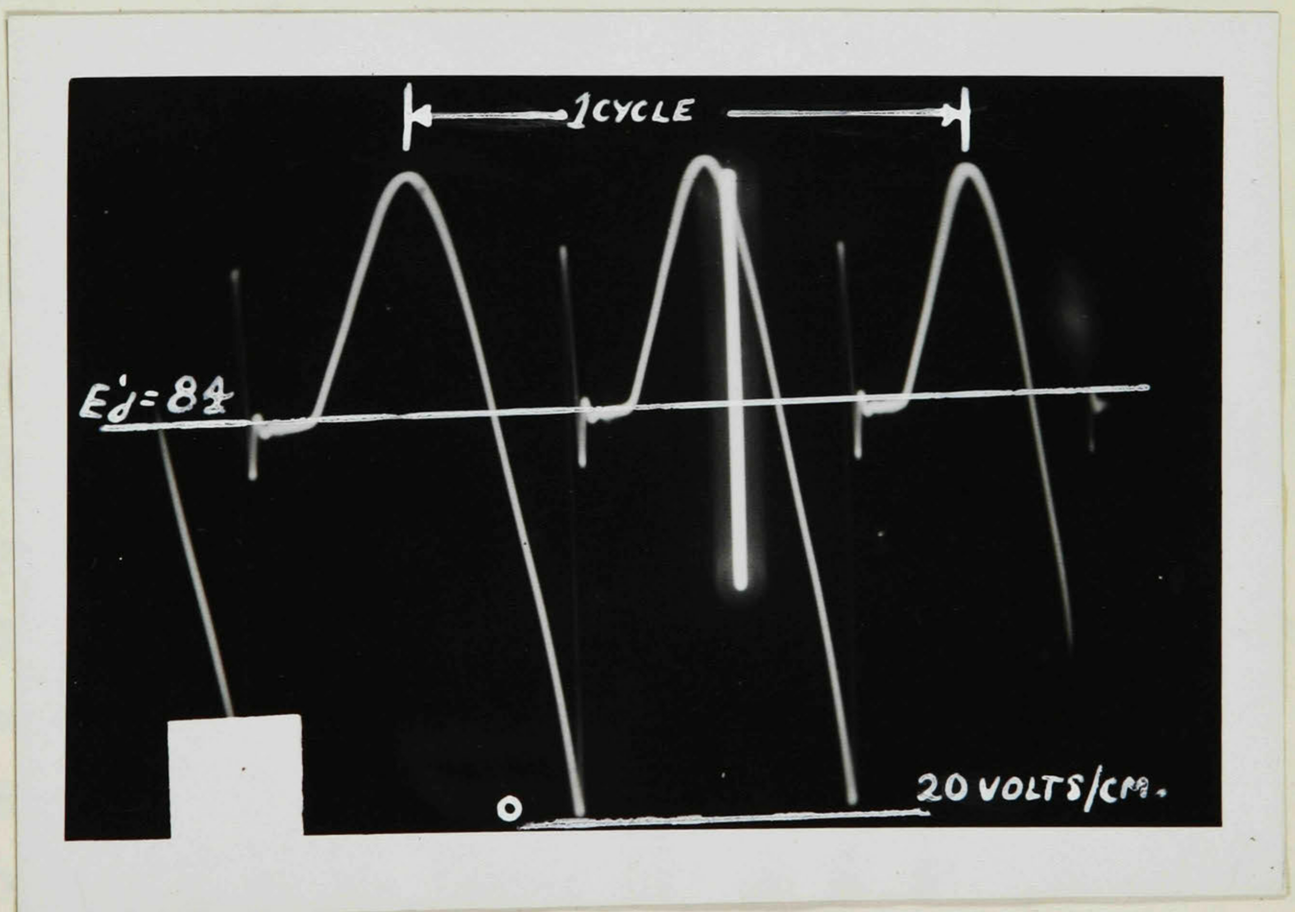


Fig.7-4 Armature voltage, E_d', wave shape of a full-wave selenium rectifier-motor drive at no load.

A comparison of this wave shape with the theoretical wave shape shown in Fig.7-1(b) indicates complete agreement between theory and practice with the exception of the oscillations superimposed upon the portion of the wave whose voltage is equal to E_g.

Lee (ref. 9) describes the existence of a large backswing of voltage in transformer circuits when sudden voltage changes occur in the circuit. This is due to the leakage reactance and distributed capacitance of the transformer. Lee also states that a resonance voltage may also be produced by leakage reactance of the transformer and other capacitance in the circuit. Steinmetz (ref. 10) outlines the same idea and shows an oscillogram of an oscillatory voltage pulse.

The capacitance of selenium rectifier disks may be as high as 0.02 microfarads per square centimeter of rectifying area (ref. 11). It is then apparent that the capacitance of a number of large disks in parallel is appreciable. Nevertheless, in order to prove that the rectifier capacitance was the cause of the oscillations, a comparison of the frequencies of oscillation, before and after paralleling each rectifying arm of the rectifier with a 0.1 microfarad condenser, was made. The decrease in the frequency of oscillation was of the order anticipated.

From the above it is then apparent that the capacitance of selenium rectifiers is not always negligible. However, as may be seen from the wave forms in Fig.7-4, the oscillation is rapidly damped out, the initial backswing in voltage being the only cycle of appreciable magnitude. Fig.7-5 indicates that such oscillations are obtained only for discontinuous conduction. Since discontinuous conduction for dry disk rectifiers occurs only at light loads no major difficulty in motor commutation was anticipated; such was found to be true.

Fig.7-5 shows the change in motor armature voltage wave shape of a single phase bridge selenium rectifier-motor drive upon loading the motor. This radical change in wave shape may be readily explained from Fig.7-3 which shows that discontinuous conduction no longer exist for values of speed factor below about 0.5, regardless of the circuit power factor. (Cos θ is generally of the order of 0.4 for ordinary D-C motors, ref. 8)

Worthy of note is the fact that the armature voltage regulation from no load (0.6 amps) to light load (1.2 amps) is 9 volts, whereas from light load to full load (7.2 amps) there is only 15 volts decrease in armature voltage. This agrees with the previously outlined theory that the regulations of E_g and speed are higher in the region of discontinuous conduction than in the region of continuous conduction.

Fig.7-6 shows that similar results to those shown in Fig.7-5 for a single phase bridge rectifier-motor drive are obtained with a three phase wye rectifier-motor drive. The major difference in operation is that continuous conduction occurs at a much lighter load than for the single phase bridge or full wave rectifier-motor drives. This conforms

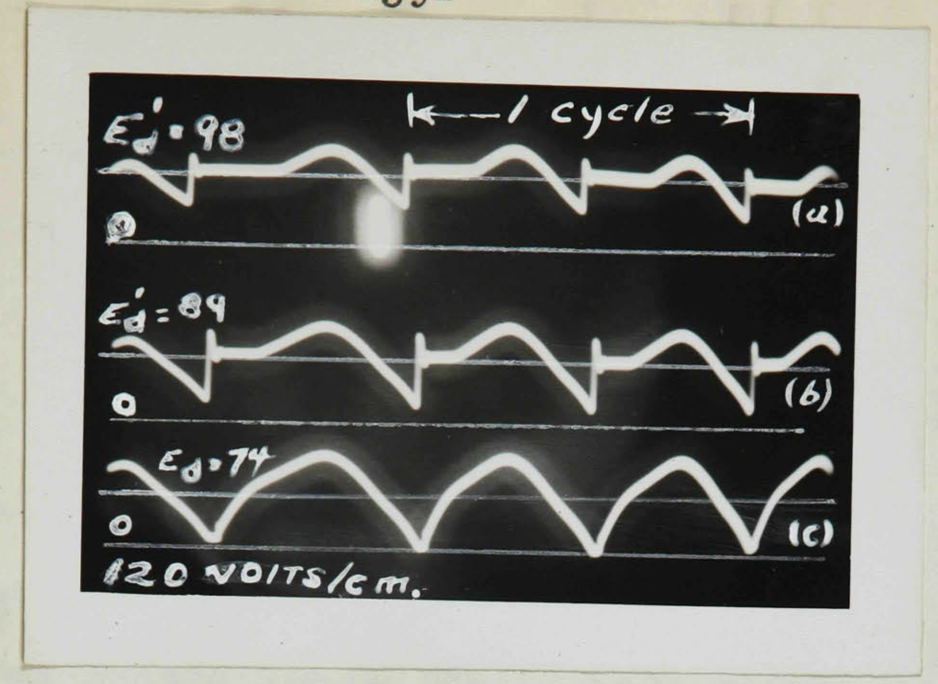


Fig.7-5 Single phase bridge selenium rectifier-motor drive armature voltages (a) no load--0.6 amps
(b) light load--1.2 amps
(c) full load--7.2 amps

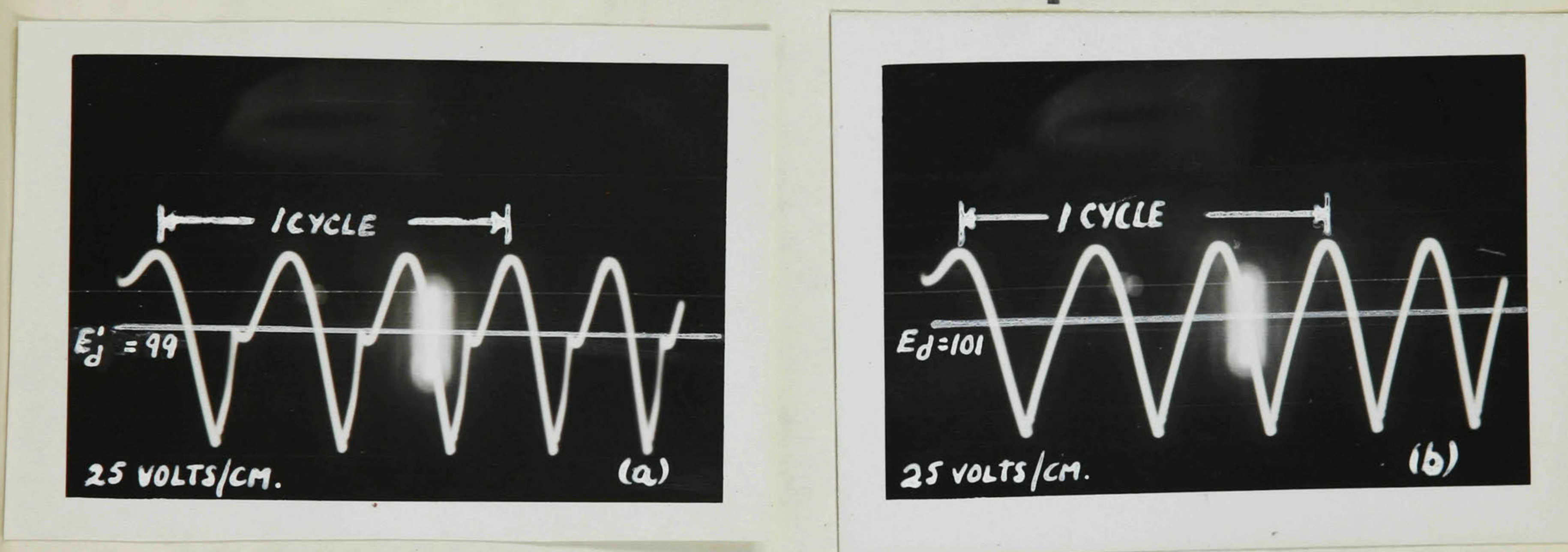


Fig.7-6 Three phase wye selenium rectifier-motor drive armature voltages (a) no load--0.6 amps
(b) light load--0.8 amps

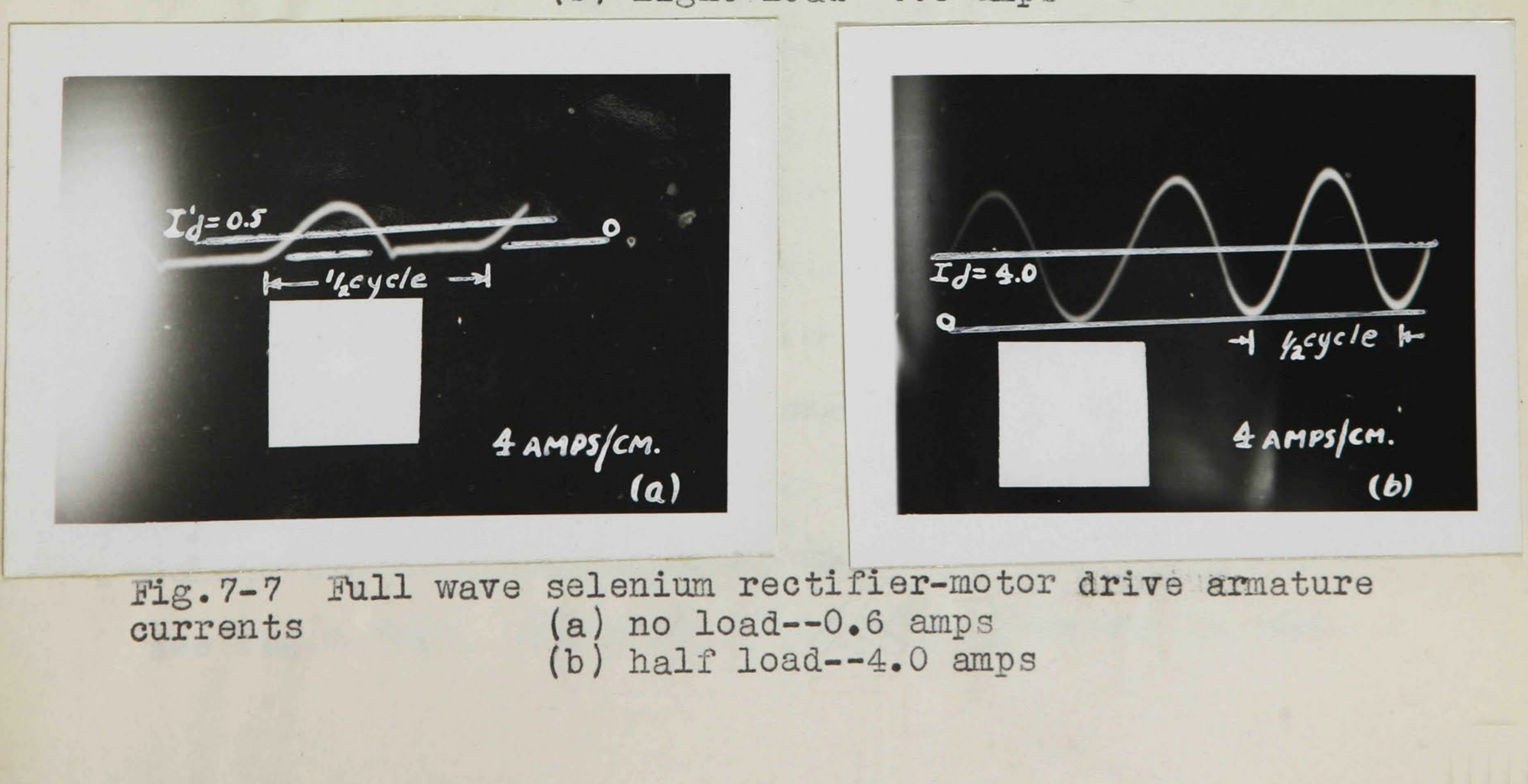


Fig.7-7 Full wave selenium rectifier-motor drive armature currents (a) no load--0.6 amps
(b) half load--4.0 amps

with the information available in Fig.7-3 concerning the values of cos θ and 'a' at which discontinuous conduction ceases.

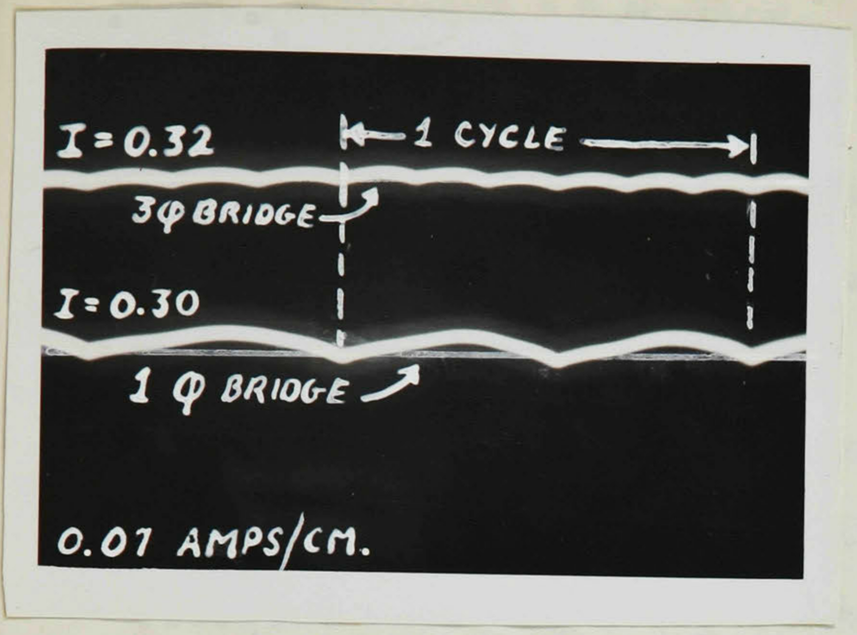
Fig.7-7 compares armature current wave shapes for a full-wave selenium rectifier-motor drive at no load (discontinuous conduction) and approximately half load (continuous conduction). Fig.7-7(a) agrees with the theoretically derived current wave shape for discontinuous conduction, as showns in Fig.7-1(b), with the exception of the small negative current pip. It was previously noted that the selenium rectifier possesses considerable capacitance, and that due to this the voltage at the end of conduction does not rise to a value E_g and remain constant but overshoots and oscillates about this voltage. Effectively then a reverse current does flow during a small portion of the cycle due to the charging and discharging of this capacitance. In the wave shape shown in Fig.7-7(a) only one pulse of reverse current is discernible; other reverse current pulses do exist but since the oscillations are rapidly damped out by the circuit resistance only the first pulse is of appreciable magnitude. (By increasing the vertical gain on the oscilloscope these other pulses becames apparent.)

The negative current pulse produces a negative torque pulse, however it is of such small magnitude that no practical difficulties are caused by it. Upon loading continuous conduction soon occurs and no such reverse current flows, see Fig.7-7(b). This follows because there are no rapid changes, during continuous conduction, in the potential across the rectifying arms to start oscillations.

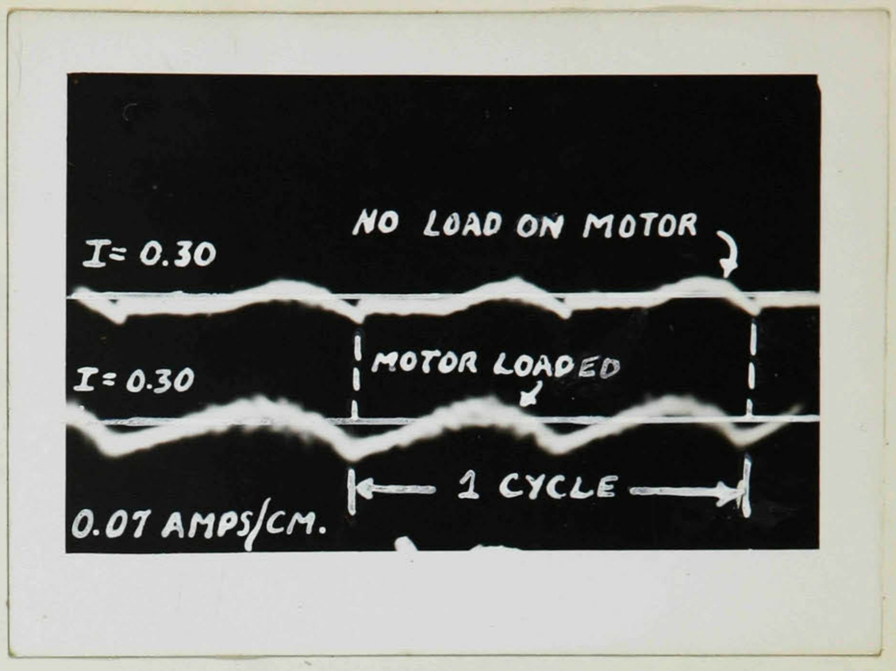
Fig.7-7(b) is included here to indicate the large difference in armature current form factor (ratio of rms current to average current) during discontinuous and continuous conduction. The greater the form factor of the armature current the greater the heating losses in the motor. It then follows that at light loads the overall efficiency and the temperature rise of the motor may be improved if a choke were placed in the circuit; the choke would decrease cos θ and hence force continuous conduction to occur at much lighter load, see ref.12.

Throughout this discussion it has been assumed that the motor flux remained constant. This infers that armature reaction is neglected and that the field current is pure D-C. All the oscillograms were obtained using a compounded D-C motor, hence this compounding tends to keep the field current of constant magnitude. It is generally assumed that the inductance of the field circuit is sufficient to completely smooth out the field current, however rarely are oscillograms shown in the literature on this subject to indicate how accurate this assumption actually is. Fig.7-8 shows oscillograms of the field current wave shape for single phase bridge, three phase wye, and three phase bridge selenium rectifiers.

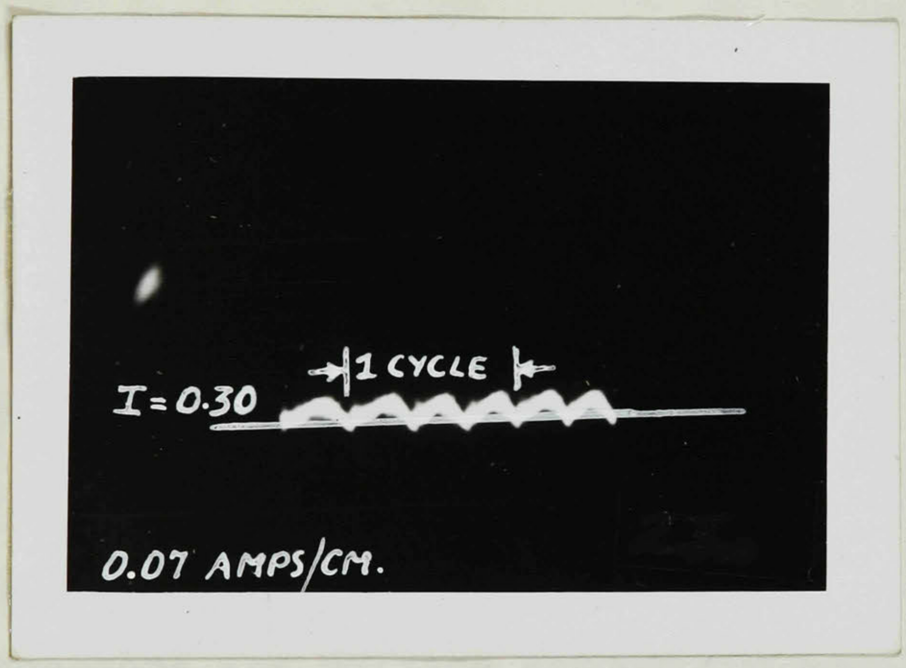
Fig.7-8(a) permits comparison of the ripple currents produced by single phase and three phase bridge rectifiers. It will be seen that only a small ripple current exists even



(a)



(b)



(c)

Fig.7-8 Rectifier-motor field currents.
(a) Single phase and three phase bridge-(motor stationary)
(b) Single phase bridge rectifier-(continuous and discontinuous conduction.
(c) Three phase wye-(discontinuous conduction).

for the single phase bridge rectifier and that the use of the three phase bridge rectifier decreases the ripple only slightly. This then suggests the reason single phase rectification is commonly used in industry to supply field current to rectifier-motor drives.

Fig.7-8(b) shows the field current wave shapes for a single phase bridge rectifier-motor drive during discontinuous and continuous conduction. (Note that discontinuous and continuous conduction refer to the flow of armature current, and not field current.) The variation in the field current wave shape is due to the change in the wave shape of the voltage across the field as discontinuous armature conduction becomes continuous conduction, see Fig.7-5.

The superimposed ripple on the oscillograms of field current when the motor is running is due to pick up from the motor commutator.

From the above it may be concluded that the assumption that the field current is pure D-C introduces a very small error even for single phase rectifier-motor drives.

7-3 Continuous conduction.

7-3-1 Voltage wave shapes.

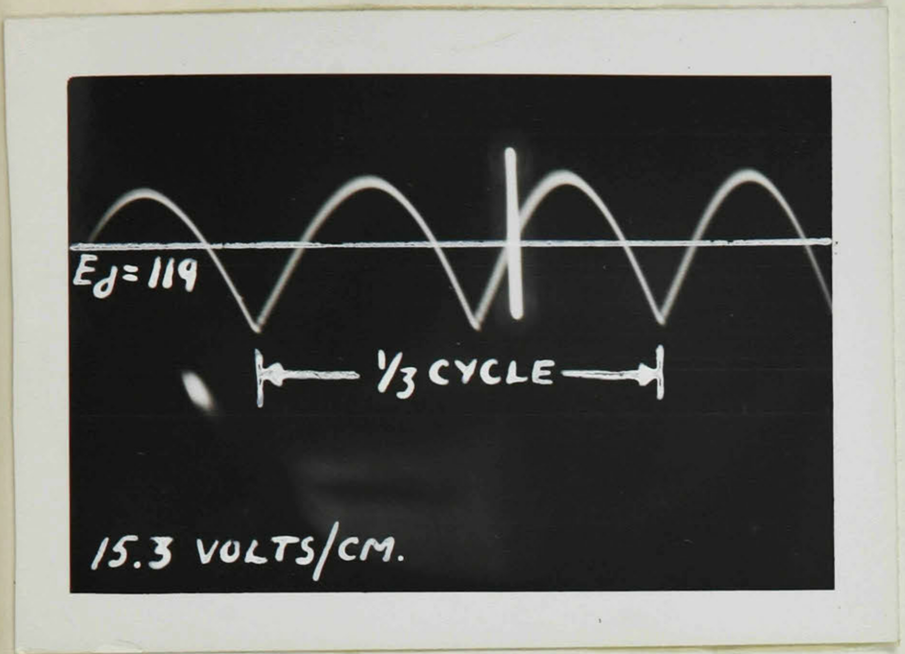
If the rectifier of a rectifier-motor drive is continuously conducting the rectifier current never becomes zero. Therefore the voltage across the armature (or rectifier) must depend only upon the transformer secondary voltage and the voltage drop through the rectifier. This then means that the armature voltage is independent of the back emf of the motor, E_g, and also that the rectifier output voltage and the motor armature voltage are equal. Both these statements do not apply to discontinuously conducting rectifier-motor drives as was explained on page 52. (E_g does not directly affect the armature voltage, but indirectly it does by virtue of its effect upon the magnitude of the rectifier current and consequently the magnitude of the voltage drop across the rectifier.)

Fig.7-9 shows oscillograms of the rectifier output voltage of a three phase bridge selenium rectifier-motor drive for various loads. With reference to Fig.7-9, several points of interest are listed below:

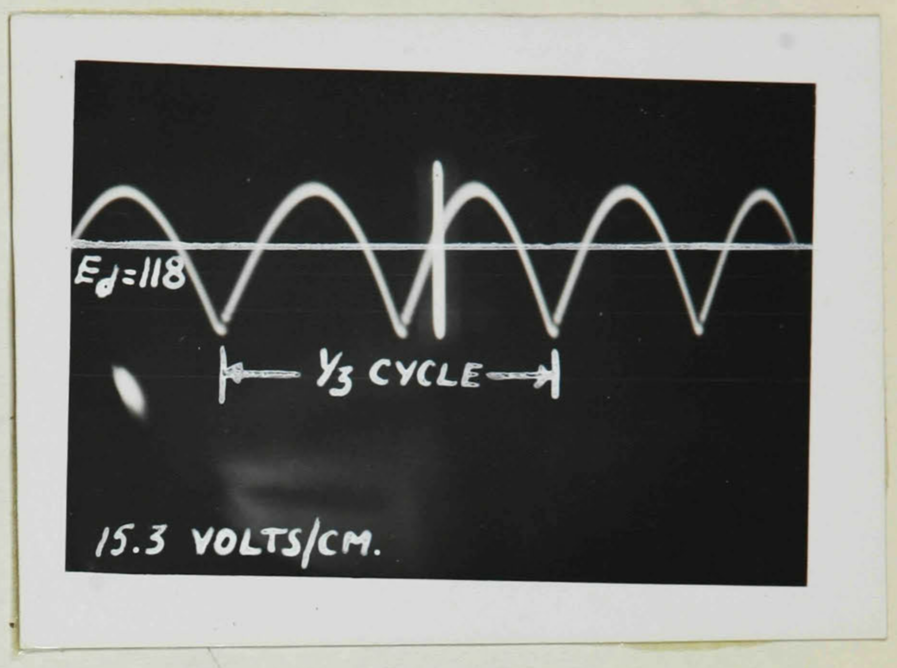
1. Wave shapes of armature voltage shown in (a) and (b) are almost identical even though in (a) E_g was zero and in (b) E_g was large. This then is experimental verification that armature voltage is independent of E_g for a continuously conducting rectifier-motor drive.
2. (b) also indicates, since there are no periods of constant voltage, that for the three-phase bridge rectifier-motor drive continuous conduction occurs even at no load. (If friction and windage were reduced sufficiently discontinuous conduction would occur, see Fig.7-3.)
3. Comparison of (c) and (d) indicates that armature voltage wave shapes on resistance and motor loads are alike, variations being mainly due to the different values of load current.
4. Comparison of all four oscillograms shows that the ripple voltage is only slightly reduced upon loading. This reduction of ripple voltage upon loading was explained on page 49.

7-3-2 Current wave shapes.

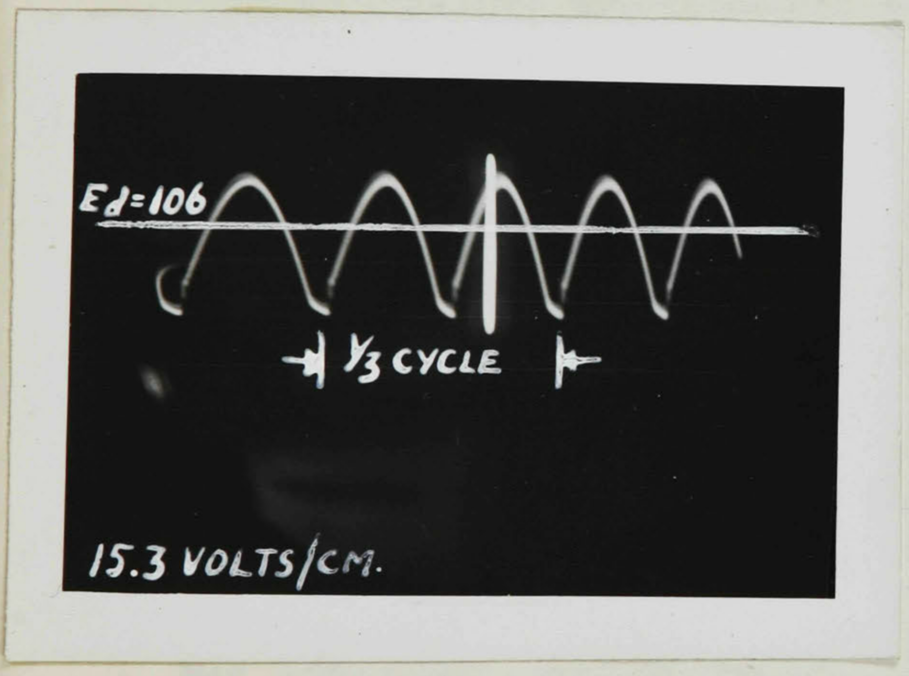
It was previously shown that the armature current form factor was lower if conduction was continuous rather than discontinuous, see Fig.7-7. The form factor has a definite



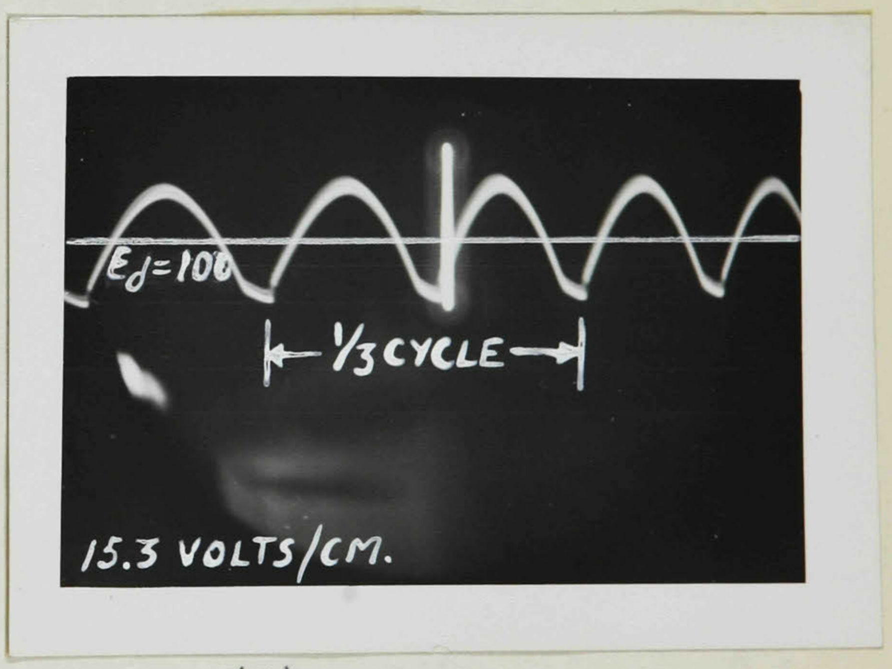
(a)



(b)



(c)



(d)

Fig.7-9 Armature voltage wave shapes for a three phase bridge selenium rectifier-motor drive.

(a) open circuit.

(b) motor on no load--rectifier current 0.6 amps.

(c) motor on rated load (approx.)--rectifier current 8.0 amps.

(d) motor replaced by resistance load--rectifier current 12.0 amps.

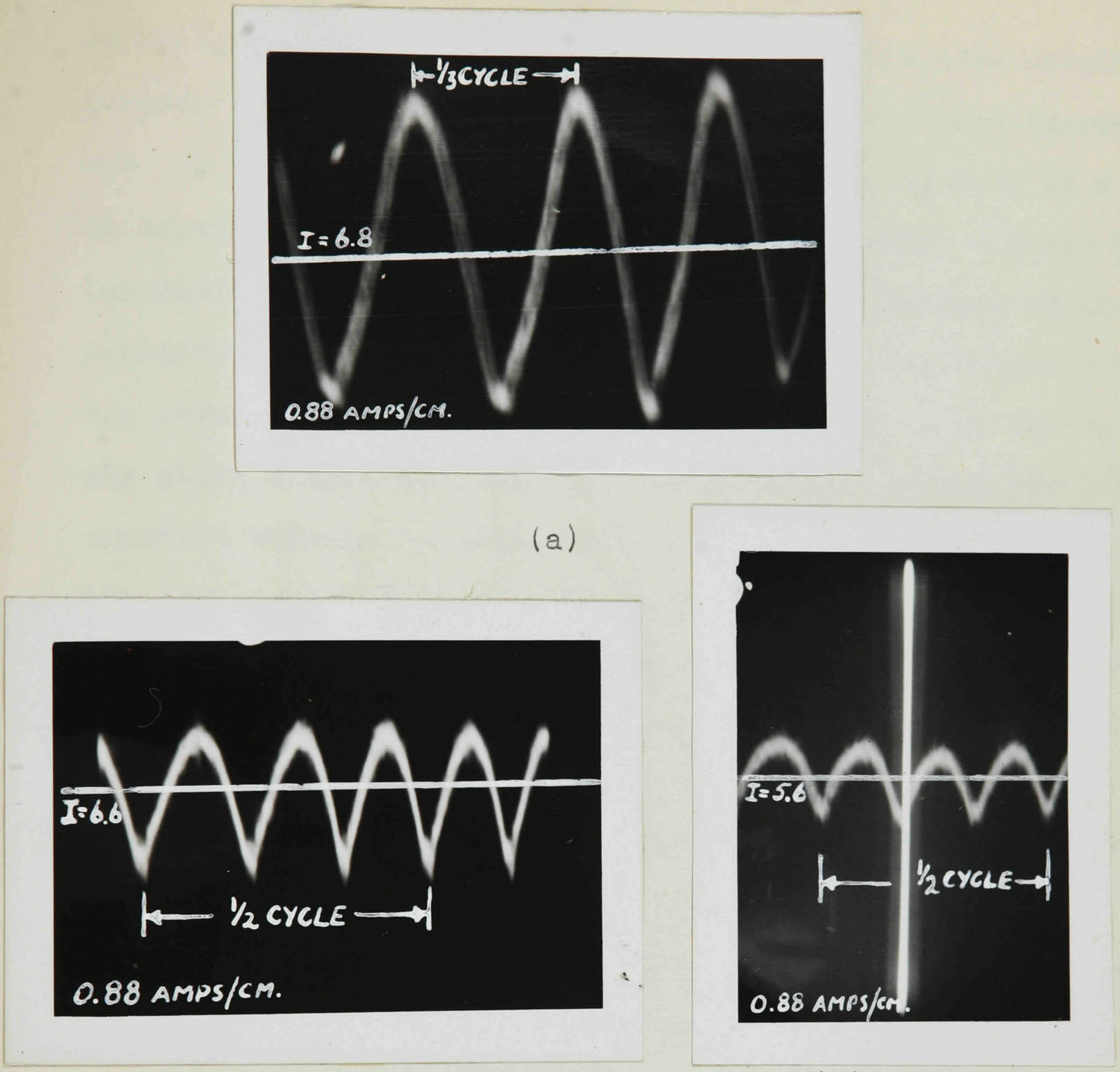
effect upon the efficiency and heating of a motor. For a given torque a certain average current is required, however, since at high form factors the corresponding rms current is larger than would exist if the form factor were unity, the I^2R losses are excessive. Excessive I^2R loss may result in a temperature rise of the motor above the specified limits with the result that the motor rating must be decreased. Also the armature current form factor of a rectifier-motor drive is a rough measure of the ratio of maximum to minimum instantaneous armature current and hence is also an indication of the amount of torque pulsation. Further, high form factors mean high peak current which are detrimental to good motor commutation.

It can be mathematically proven, ref.7, that for discontinuous conduction the armature current of a rectifier-motor drive has a form factor always greater than 1.11; for continuous conduction the form factor is always between 1.0 and 1.11. The value of 1.11 is of course the form factor of a sine wave, hence the above limit of 1.11 applies only if the rectifier transformer secondary voltage is a sine wave and the voltage drops are neglected, or are of constant magnitude. For dry disk rectifiers the voltage drop across the rectifying arms is not constant. In fact Richards (ref. 3) states that due to this variation of the instantaneous IR drop the form factor limit for dry disk rectifiers is increased from 1.11 to 1.15. However this increase in form factor will be negligible for other than single phase rectification.

The minimum value of current form factor will be obtained when the ripple current is small compared to the average current value. The ripple current is reduced by the inductance of a circuit, see oscillograms of field current in Fig.7-8. However the inductance of a motor armature is low and, as illustrated in Figs.7-7 and 10, very little smoothing is obtained except for single phase rectification where the ripple is very large. (Note that Fig.7-10 shows oscillograms of rectifier current, not armature current, for a shunt motor. However, since for rectifier circuits having three or more phases the field current is almost D-C, and also because the magnitude of the field current is small compared to the magnitude of armature current, little error results if the armature and rectifier currents are assumed to have similar wave shapes.) Since the inductance is low, cos θ for the circuit may be assumed unity and hence the ripple current will be proportional to the rectifier ripple voltage.

An increase in the number of rectifier phases will decrease the rectifier output ripple factor and will thus decrease the armature current form factor, see Fig.7-10--(a) compared with (b) and (c).

For a rectifier-motor drive, if the ratio of E_g to mean armature voltage decreases, then the ratio of ripple voltage to the D-C voltage drop through the armature (due to the armature resistance) will decrease. Further, since the value of cos θ for the circuit is assumed unity, the ripple current will be a smaller percentage of the armature current. This effectively means the form factor of the armature current decreases. (Note: the above applies to continuous conduction



(a)

(b) (c)

Fig.7-10 Rectifier current wave shapes for various rectifier-motor drives at approximately the same speeds.
(a) three phase wye rectifier----6.8 amps 88 volts D-C
(b) three phase bridge rectifier-6.6 amps 107 volts D-C
(c) double wye rectifier---------5.6 amps 95 volts D-C

only.) Thus for a given armature voltage an increase in load current will be accompanied by a decrease in form factor, because E_g must decrease in order to allow the armature current to increase.

If the armature voltage is decreased, but the speed kept constant by decreasing the flux, then it follows that the value of E_g must decrease. If the average armature current, I_d, increases in order to deliver the same output torque, then the I_dR drop through the armature must increase, but the reduction in armature voltage is accompanied by a decrease in ripple voltage. The ratio of ripple voltage to I_dR must therefore decrease and hence the resulting armature current will have a lower form factor. It then follows that the lowest possible value of armature current form factor, for any given output torque, will result if the lowest possible armature voltage is used. The motor temperature rise and the efficiency of a rectifier-motor drive will therefore be improved by lowering the transformer secondary voltage and decreasing the flux, for any given speed and torque output.

The oscillograms in Fig.7-10 are difficult to compare because so many factors are variable. However it is apparent from them that a variation in load current and armature voltage does affect the form factor of the armature current.

From the above discussion of armature current wave shapes it is evident that whereas on resistive and inductive loads the current form factor is very nearly unity for multiphase rectification, on motor loads this is not true because of the effect of the back emf of the motor.

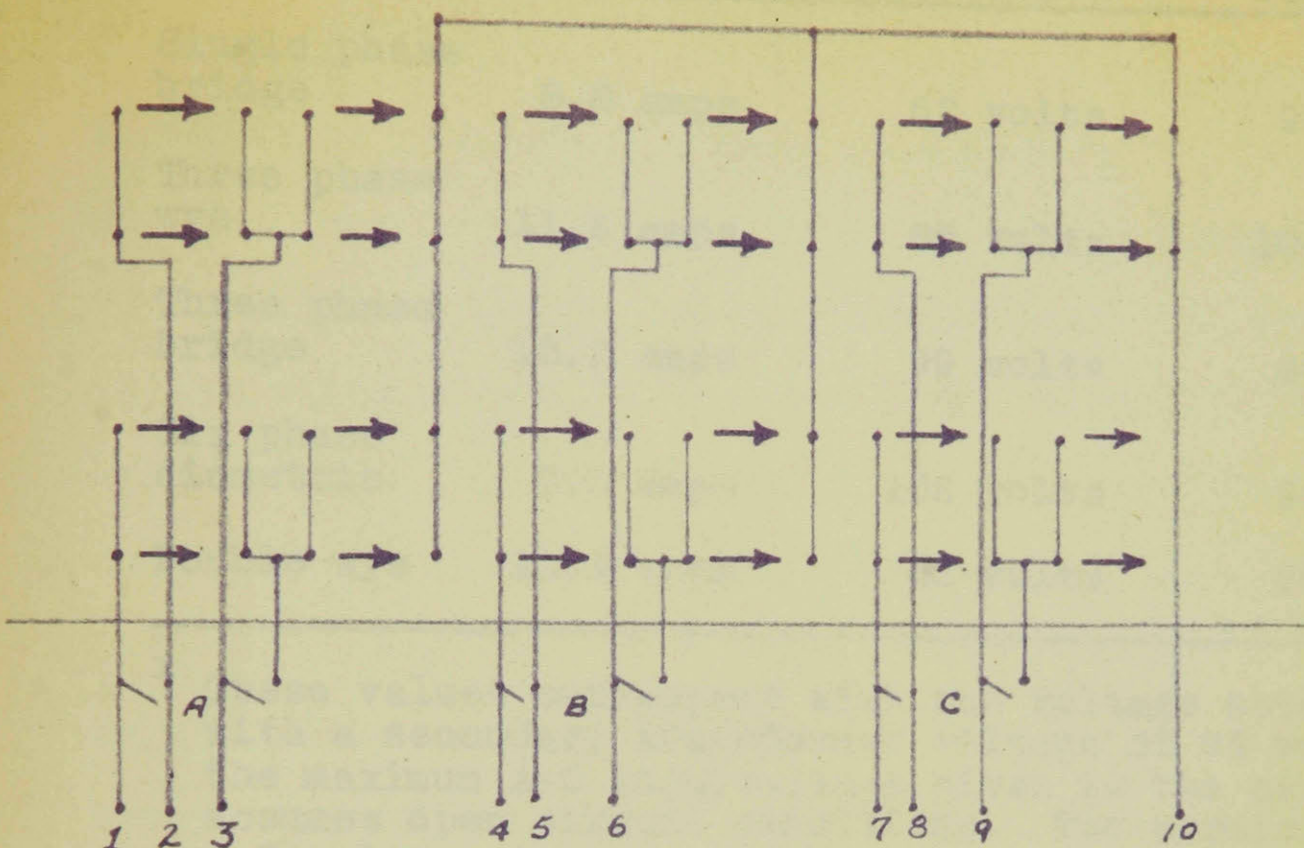
CHAPTER EIGHT

EXPERIMENTAL RESULTS ON SELENIUM RECTIFIER-MOTOR DRIVES

8-1 Design of a selenium rectifier.

The selenium rectifier used to obtain the experimental data in this thesis was not designed in the normal manner. A limited number of selenium rectifier disks was available. There was no convenient source of variable A-C voltage for use with the rectifier, since such a source had to have low voltage regulation and a good sinusoidal wave form. Because of these limitations the design of the rectifier used consisted of choosing an A-C voltage to apply to the rectifier and then determining the output voltage and current ratings for different arrangements of the rectifier disks on hand. This procedure was carried out for all the types of rectifier circuits to be studied and then a simple switching arrangement was worked out to enable the use of the same rectifier disks rearranged to form different rectifier circuits. Fig.8-1 shows the wiring diagram for the resulting rectifier board, and Fig.8-2 shows a picture of the board connected as a three phase bridge rectifier. Fig.8-3 is a table giving the voltage and current ratings for each rectifier circuit; it also indicates the switch positions and necessary transformer and lead connections for the various rectifier circuits.

The rectifier transformer used was originally a three phase transformer. It was reconnected to give six phases,



Notes: Switches A,B, and C are single pole double throw.
represents two selenium disks in series.

Fig.8-1 Wiring diagram for multi-circuit selenium rectifier board.

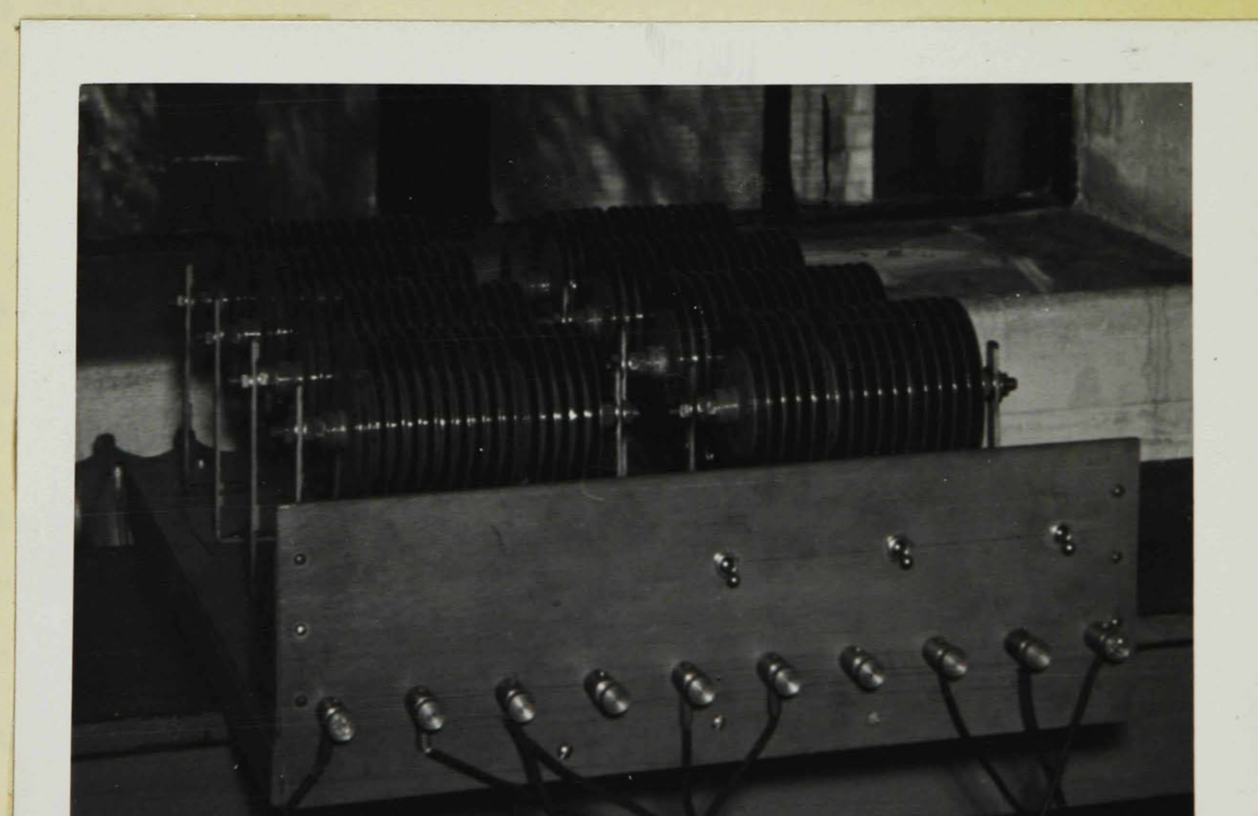


Fig.8-2 Picture of selenium rectifier board connected as a three phase bridge rectifier.

	Full load D-C current	Full load[x] D-C voltage (approx.)	Maximum A-C input voltage
Single phase bridge	8.8 amps	62 volts	90 volts
Three phase wye	11.6 amps	85 volts	104 volts(phase)
Three phase bridge	13.2 amps	99 volts	90 volts(line)
Six phase diametric	8.0 amps	102 volts	90 volts(phase)
Double wye	11.6 amps	82 volts	90 volts(phase)

[x] These values correspond with the voltage obtained, Fig.8-5,6, with a secondary transformer voltage of 92 volts- the maximum A-C input voltage given in the next column assumes open circuit conditions. The permissible A-C voltage increases upon loading due to the rectifier IR drop which reduces the inverse peak voltage.

(a) Rectifier Ratings

	Switches	Bus terminals	Secondary phases to:
Single phase bridge	all closed	2 & 5	3 & 6
Three phase wye	all closed	---	1, 4, 7
Three phase bridge	all closed	2, 5, 8	3, 6, 9
Six phase diametric	all open	---	1,2,4,5,7,8
Double wye	all open	---	1,2,4,5,7,8

Switches are closed in 'down' position.

Terminal 10 is always the positive terminal of the output.

(b) Table of connections for rectifier board.

Fig.8-3 Ratings and connections for rectifier board.

and the effective number of turns per secondary was changed in order to obtain one transformer suitable for use with all the rectifier circuits studied. The transformer rating far exceeds the rectifier rating, as a result the voltage regulation of the transformer is negligible in most calculations.

A sample design for a selenium rectifier whose rating is 110 volts output at a rated load current of 12 amps will be carried out. The circuit is to be connected six phase star. The disks available are such that on six phase star operation they will carry 4.2 amps. (The current rating of the disks is available from manufacturers' literature.) (Note that the current rating of the disks depends upon the circuit they are to be used in. For example--a disk that will carry 4.2 amps in a six phase star circuit will carry only 2.2 amps in a single phase bridge circuit. This difference results from the fact that the disks conduct a greater percentage of the time when used in the single phase circuit than in the six phase circuit and hence cooling is better for the latter.) Knowing the load current and the current rating of the disks it is then apparent that three disks must conduct in parallel. In order to determine the number of disks required in series per arm the peak inverse voltage must be determined, and this in turn depends upon the peak value of the output voltage. It may be easily shown that for six phase star rectification the ratio of peak output voltage to average voltage is 1.04. Therefore the peak inverse voltage across each rectifying arm is 2 x 1.04 x 110 = 230 volts. (The factor 2 arises from the fact that the inverse voltage is double the phase voltage.)

Since each disk may withstand an inverse peak voltage of 25 volts, 10 disks in series per arm might appear satisfactory. However up to now no account has been taken of the voltage drop across the rectifying arm, and also the reduction in voltage due to overlap. As a result 11 disks per arm will be tried. From the manufacturer's volt-ampere characteristic for the disks, see ref.3 and 11, the drop per disk is 1.8 volts at rated current. Therefore the voltage drop per arm will be 11 x 1.8 = 20 volts. Then the transformer secondary voltage must be such as to give 110 + 20 = 130 volts D-C volts output. Therefore the secondary transformer voltage must be 1.04 x 130 = 135 volts.(peak). The actual peak inverse voltage is then 2 x 135 = 270 volts which is less than the maximum allowable peak inverse voltage of 11 x 25 = 275 volts. (Note that the inverse peak voltage under load will be less than 270 volts by the voltage drop across one rectifying arm. That is, under load the inverse peak voltage is 250 volts.) The rectifier then must consist of six arms, each comprised of 33 disks having 3 parallel arms of 11 disks in series. The transformer secondary voltage must be at least 135 volts peak, and should be variable over a small range in order to adjust the voltage to take care of aging of the disks and also the loss in output voltage due to overlap.

In practice the current rating of the selenium rectifier disks is slightly reduced from its rating on resistive load when operating on a motor load. This reduction is necessary because of the higher current form factor on motor load. However, if the ambient temperature is well below the rated

35°C as was the case in the experimental work outlined in this article, then only the rating for the single phase circuits need be reduced. The single phase circuits are particularly affected by motor operation because they tend to operate discontinuously over a considerable portion of their rating.

8-2 Voltage regulation on resistance and motor loads.

Figs.8-5 and 6 are experimental voltage regulation curves obtained on resistance and motor loads. It will be noted that for the three phase bridge, six phase star, and double wye rectifiers there is no difference between their regulation curves on resistance or motor loads; however for the three phase star and single phase bridge rectifiers a difference does exist.

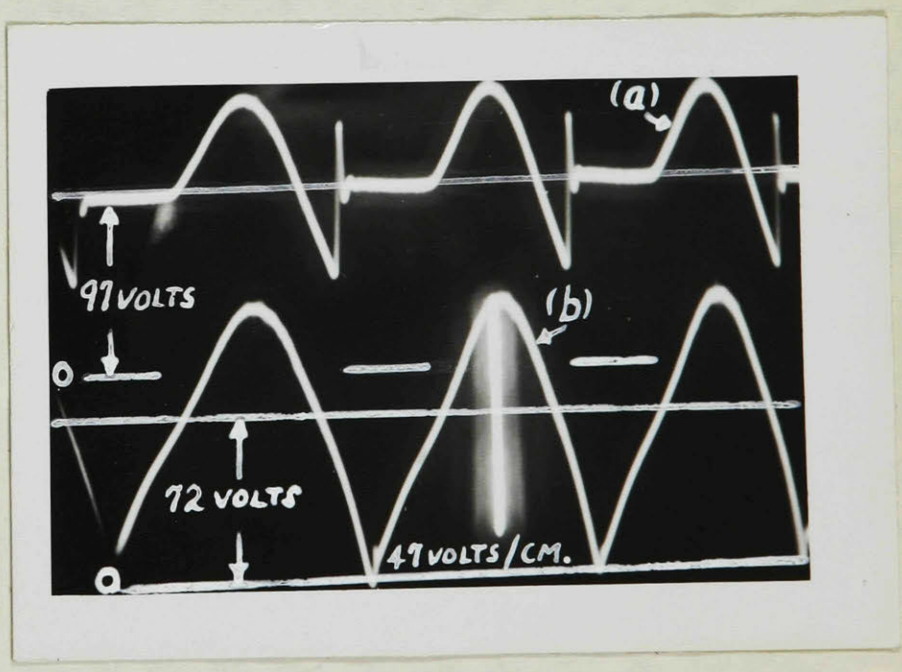


Fig.8-4 Single phase bridge rectifier-motor drive armature voltage oscillograms-
(a) no load--0.6 amps, 97 volts
(b) light load--2.6 amps, 73 volts.

Fig.8-4 shows the radical change in wave shape over the range of load current from 0.6 to 2.6 amps for a rectifier-motor drive using single phase bridge rectification. This figure indicates that continuous conduction begins at a load current of about 2.6 amps. This value corresponds exactly with the load current at which the voltage regulation curve (Fig.8-5) levels off. The reason the output voltage is so

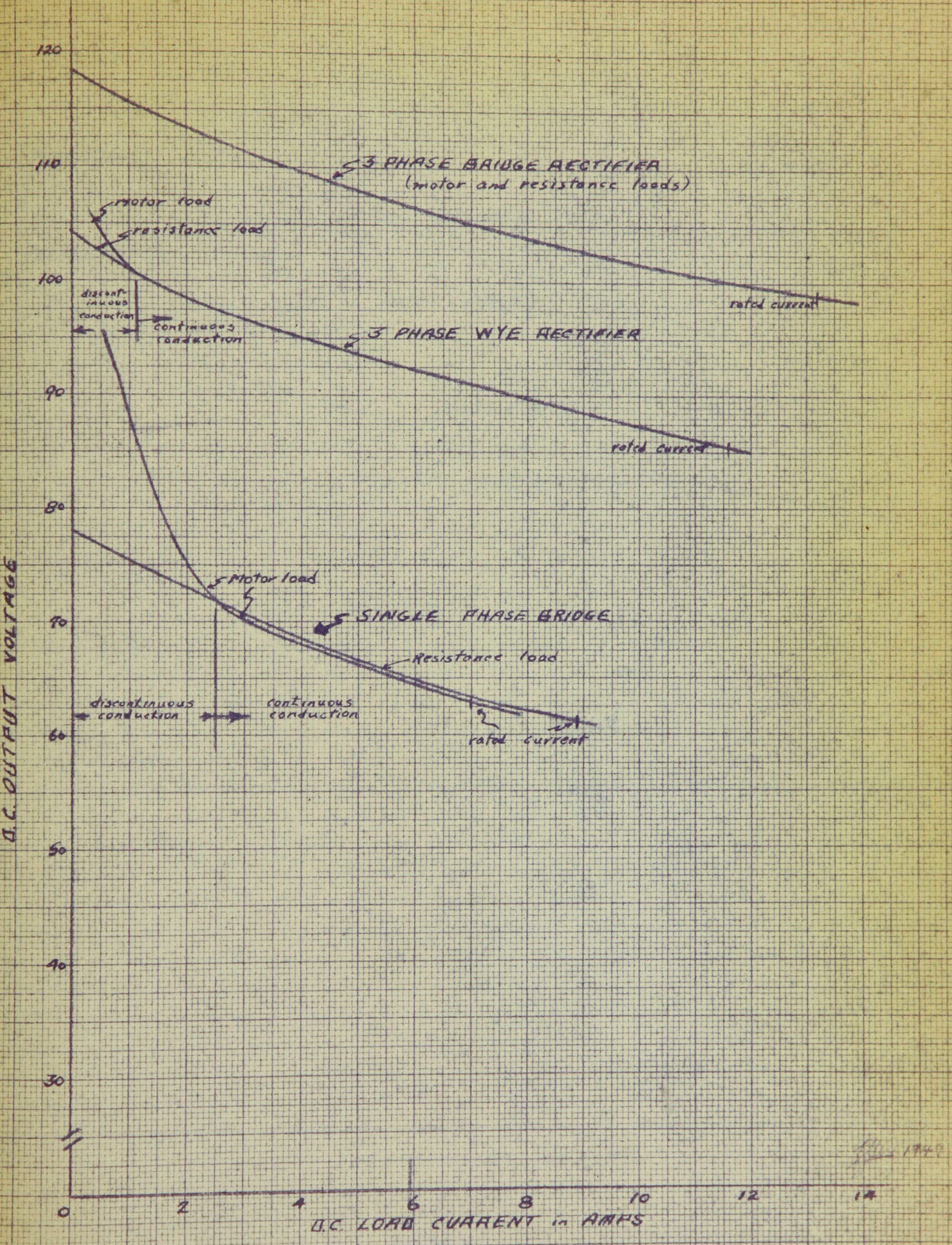


Fig.8-5 Rectifier voltage regulation curves on resistance and motor loads.

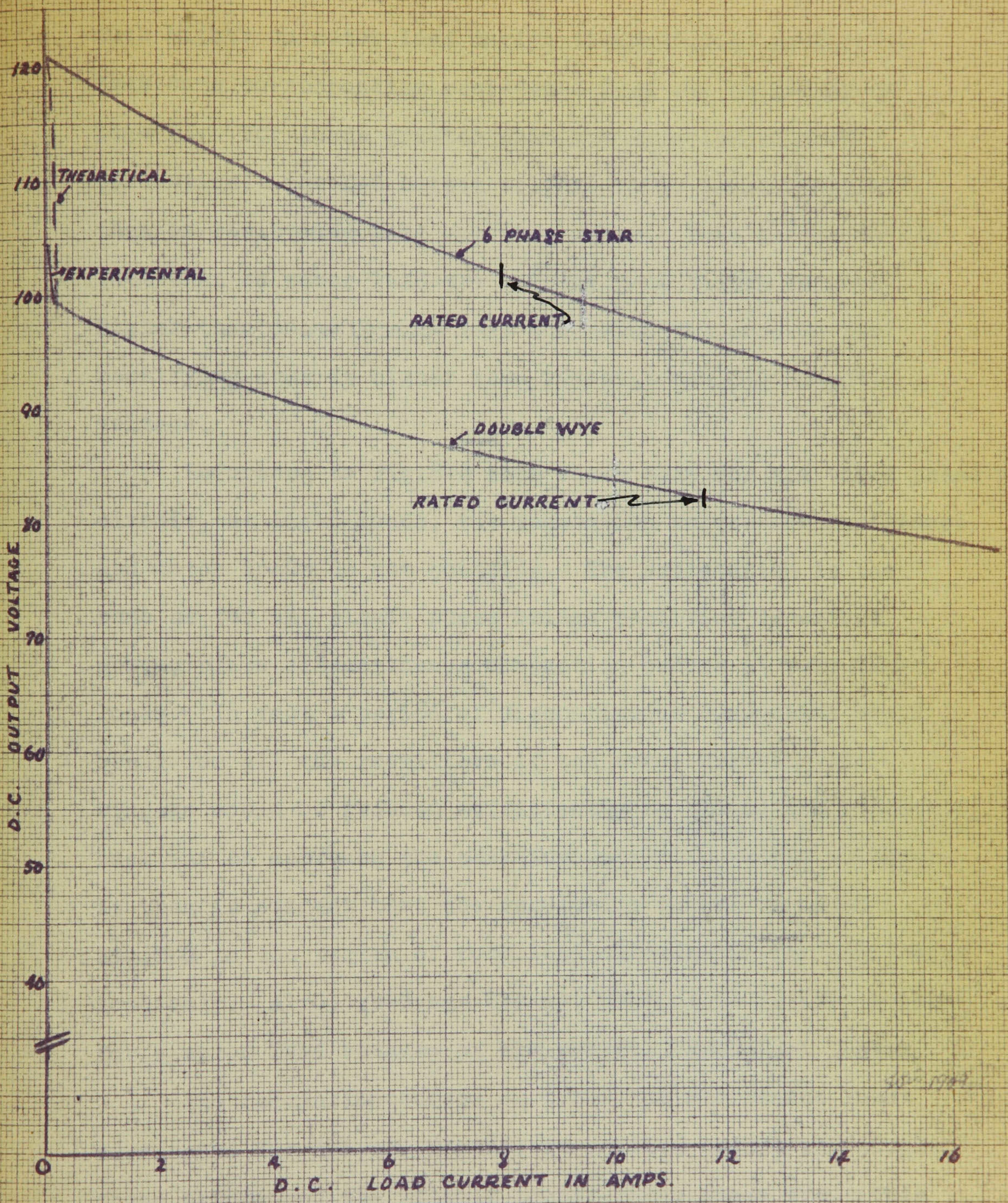


Fig.8-6 Rectifier voltage regulation curves.

much higher on motor load during discontinuous conduction than on a corresponding resistance load was explained on page 51. For loads greater than 2.6 amps (continuous conduction) the D-C output voltage is no longer greater than on resistance load but vice versa. This is due to the fact that on motor load the current form factor is much higher than on resistance load and hence the drop in the rectifying arms is higher thus reducing the D-C output voltage.

Reference to Fig.8-6 also shows that for the three phase wye circuit, at light loads, the regulation curves for resistance and motor loads do not coincide. The explanation is the same as for the single phase bridge rectifier described above, since discontinuous conduction occurs at very light loads. In fact a period of discontinuous conduction would occur for all the rectifiers if the motor friction and windage could be reduced sufficiently to enable the motor back emf to approach the peak instantaneous output voltage. It then is evident that the regulation curves shown in Fig.8-6 in the region of zero load current are for resistance load only. Also, readings are not obtainable in this region for a motor load because of the motor's mechanical losses.

The regulation curves on motor and resistance loads correspond for all the rectifiers studied except the single phase bridge and the lightly loaded three phase wye. This may be explained by noting the form factor does not increase appreciably for these circuits when a resistance load is replaced by a motor load; consequently the voltage drop across the rectifying arms does not vary appreciably with the type of load for these rectifier circuits.

Rated current values for each rectifier are noted on the regulation curves. The following table lists the voltage regulations for the different rectifiers as calculated from Figs.8-5 and 6.

Rectifier Circuit	% Voltage Regulation (motor load)
single phase bridge.............	51
three phase bridge..............	19
three phase wye.................	22
six phase star..................	22
double wye......................	22 (light load to full load)
	27 (no load to full load)

From the above table it may be seen that the regulation of the double wye rectifier from no load to light load is only 5%. For tube rectifiers the corresponding regulation is theoretically 15.4% (see ref. 4). The dotted line in Fig.8-6 shows the regulation as it would occur for tube rectification. The theoretical regulation of 15.4% depends upon the fact that no current is flowing through the IPT at no load. For dry disk rectifiers a reverse current does flow even at no load, and since the magnetizing current of the IPT used was very low, this reverse current enables a potential to exist across the IPT, see Fig.8-7.

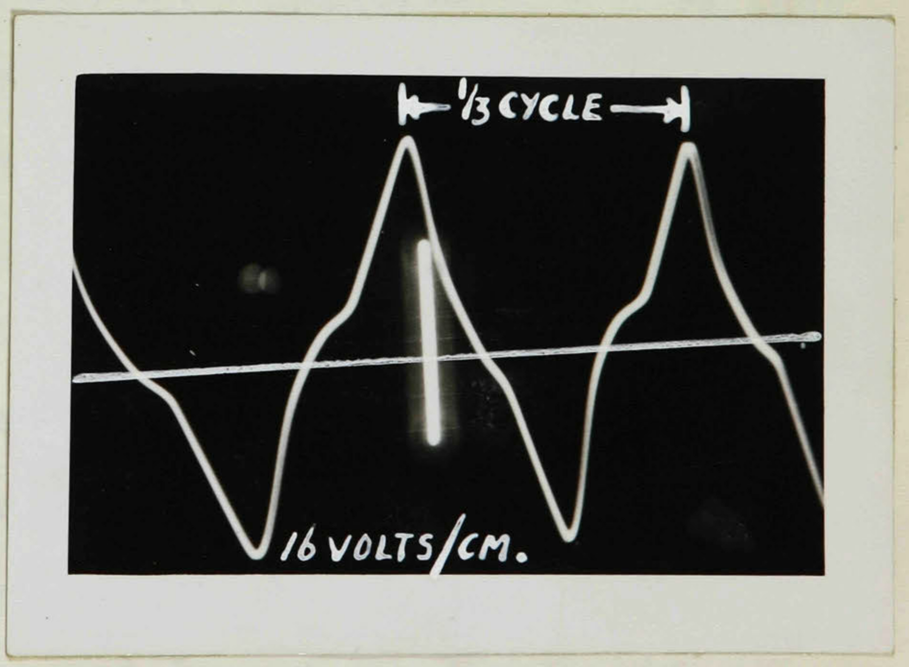


Fig.8-7 Voltage wave shape across IPT of double wye rectifier on open circuit.

Thus at no load the double wye selenium rectifier operates more nearly as double wye rectifier under load than as a six phase star rectifier. This then explains the relatively low voltage regulation of the double wye selenium rectifier compared with the double wye tube rectifier.

The table of voltage regulations on the previous page shows that the percent regulation is approximately equal for all the rectifiers with the exception of the single phase bridge rectifier. An inspection of the wiring diagram in Fig.8-1 will show that the voltage regulation for all the circuits results from the same number of disks in series per arm. Also, as previously noted, the rated current of a disk depends upon the type of rectifier it is used in. Both these factors account for the fact that the percent regulation is the same for all the rectifier circuits with the exception of the single phase bridge rectifier. A portion of the voltage regulation will be due to overlap, however, as indicated by Figs.6-2(b) and 6-3(b), the reduction due to overlap is small compared to the resistance drop.

8-3 Speed regulation of rectifier-motor drives.

In Fig.8-8 are shown the corresponding speed regulation curves for the rectifier-motor drives whose voltage regulation curves are shown in Figs.8-5 and 6.

In order to indicate what portion of the speed regulation of these drives is due to the voltage regulation of the rectifiers, speed regulation curves for the same motor, operating on constant D-C voltage, are also shown. These

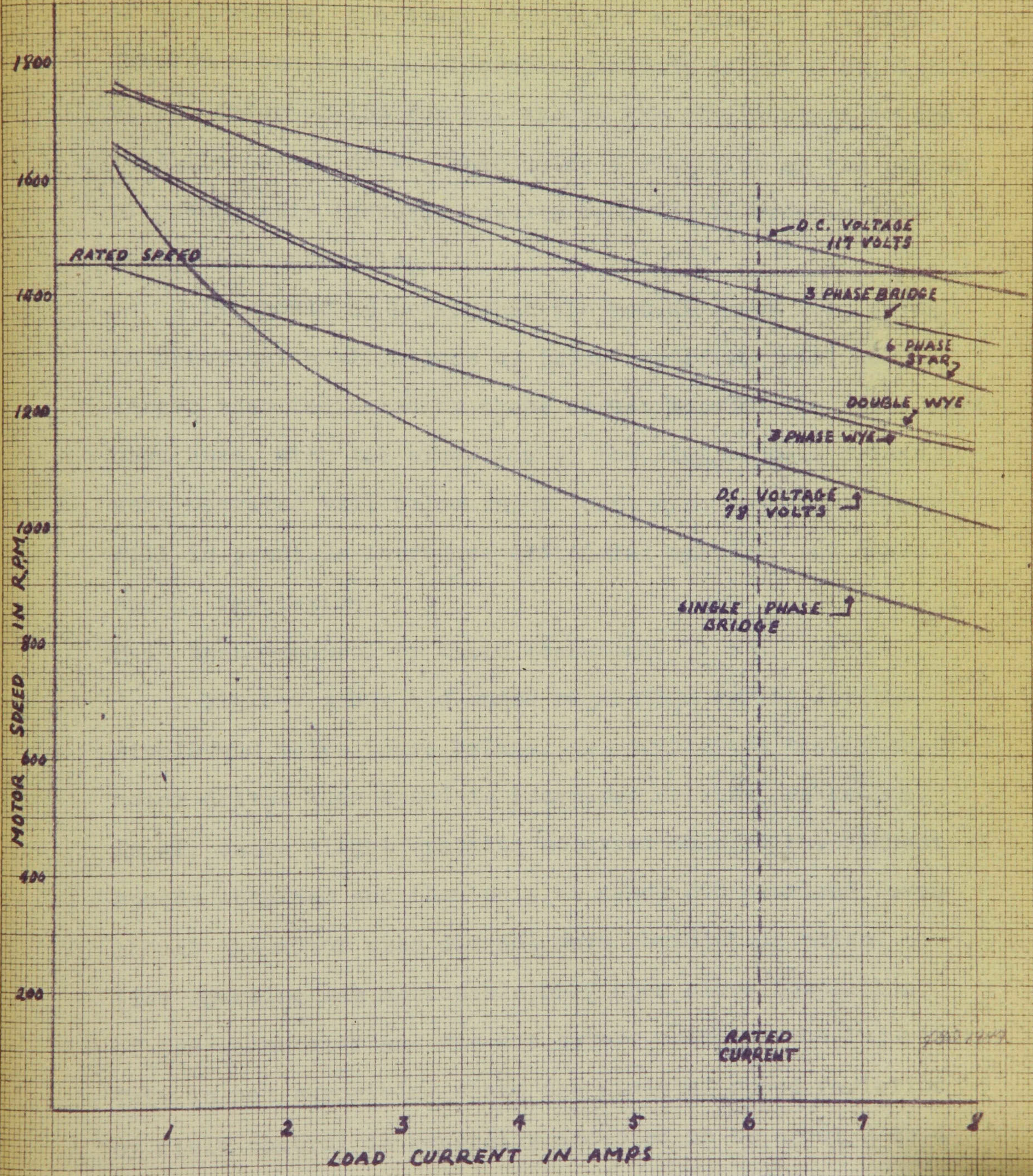


Fig.8-8 Rectifier-motor speed regulation curves.

curves verify that the motor is compounded and that, typical of such motors, the speed regulation on pure D-C is high. However there is a considerable increase in speed regulation, of the order of 15% for all except the single phase bridge rectifier-motor drive, when using a rectifier as the source of power; this increase results from the IR drop in the rectifier and overlap.

It should be noted that the actual speed regulation in practical applications of these rectifiers will be larger than indicated by these curves because the rectifiers used here, with the exception of the single phase bridge, were operated well below rated load; also the transformer will in practice introduce additional voltage, and hence speed, regulation.

8-4 Speed control by field weakening.

Fig.8-9 shows the speed regulation curves for the single and three phase bridge, and double wye rectifier-motor drives when speed is increased by field weakening. In all cases slight sparking occurred only at the highest speeds obtained and then only at about 30% overload, even though the motor used did not have commutating poles. (The sparking was noticeable only upon close inspection of the commutator and was not severe enough to be injurious.) This is not surprising since the limit of speed variation by field control is generally accepted to be about 3 to 4 times motor base speed whereas the curves indicate results up to double base speed were the limit obtained in these

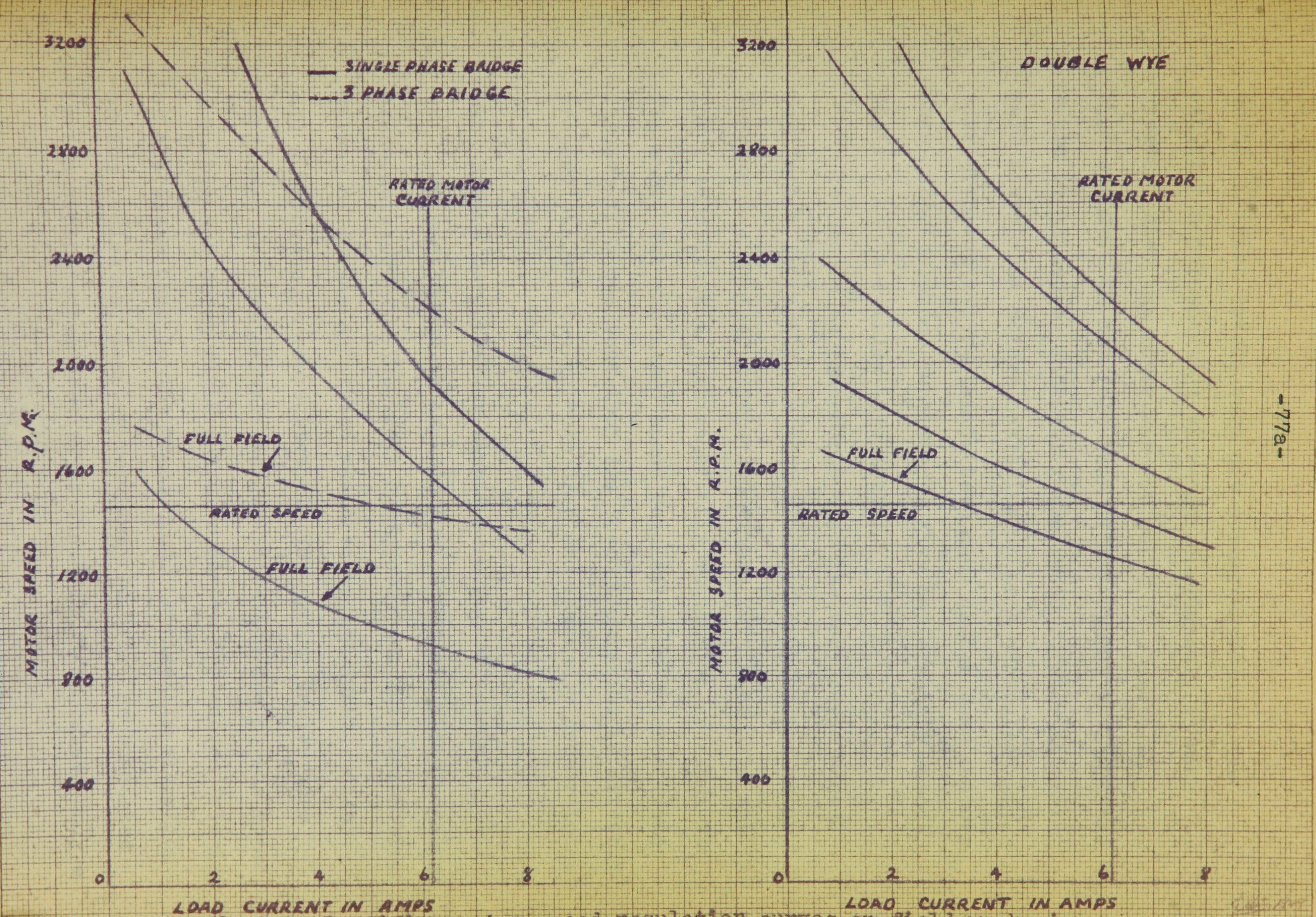


Fig.8-9 Rectifier-motor speed regulation curves on field weakening.

tests. Higher speeds were not attempted because the existing motor mounting vibrated considerably at high speeds. Also the motor was not rated to operate at high speeds. It was felt that little useful information would be gained by increasing the speed further as it is well known that motors operating on grid controlled thyratron rectifiers, which have much higher form factors than these selenium rectifiers, give satisfactory speed control up to 4 times base speed.

It should be remembered that the very large speed regulation is partly due to the compounding of the motor, however the voltage regulation of the rectifier does account for a considerable portion of this regulation as shown in Fig.8-8. The increased speed regulation at reduced field results from the fact that the speed regulation is directly proportional to the voltage drop and inversely proportional to the flux.

8-5 Effect of rectifier ripple on motor efficiency.

Figs.8-10 and 11 are plots of motor efficiency against brake horsepower. The brake horsepower was calculated from values of torque and speed measured by two spring scales and a stroboscope respectively. The spring scales were subjected to considerable torque pulsation due to the motor mounting not being rigid and also due to the uneven friction of the brake band on the brake drum. Noticeable vibration of the indicating needles resulted, however, as suggested by the experimental results in Fig.8-11, this caused only a

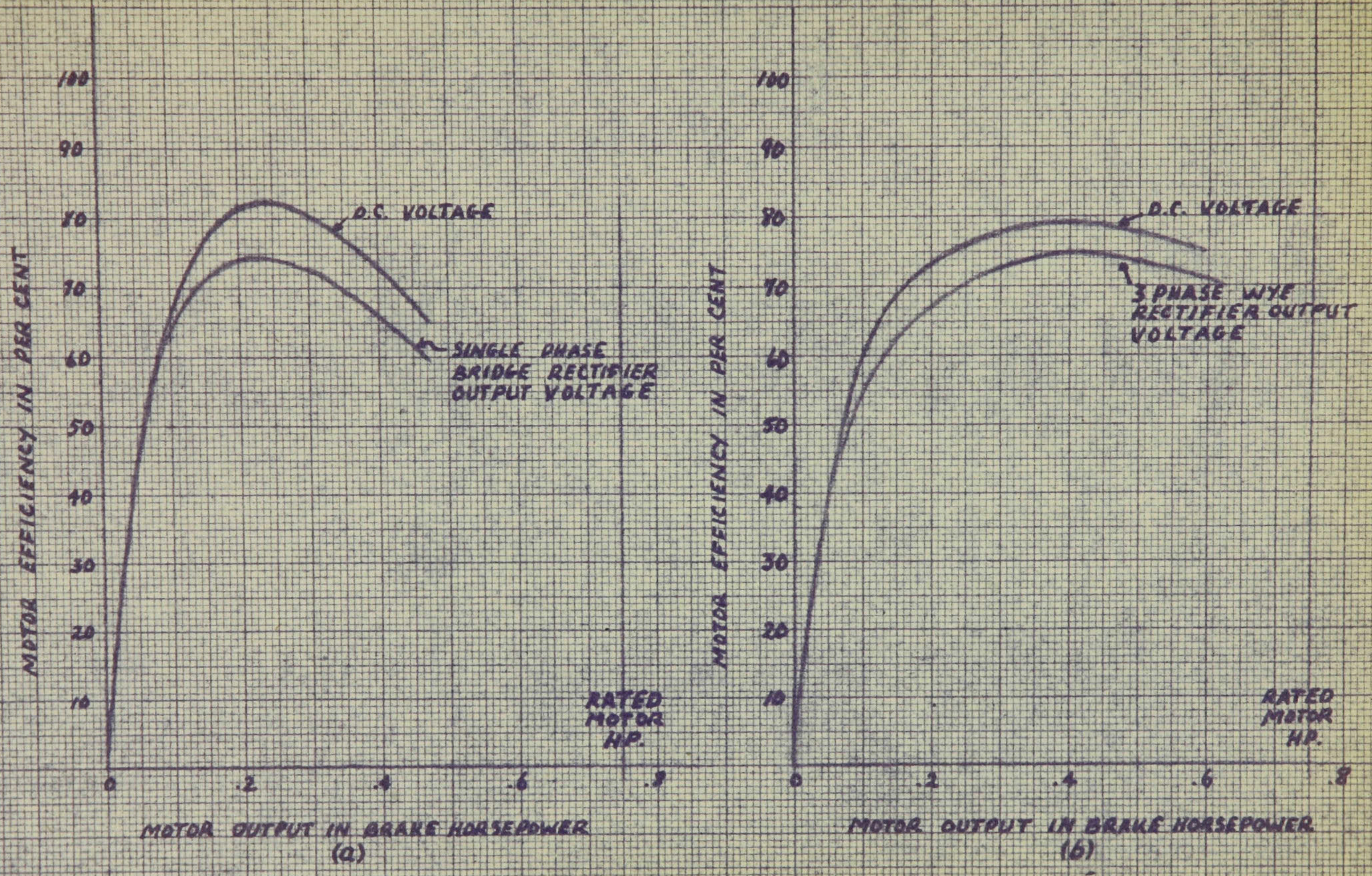


Fig.8-10 Motor efficiency curves on rectifier voltage and corresponding D-C voltages.

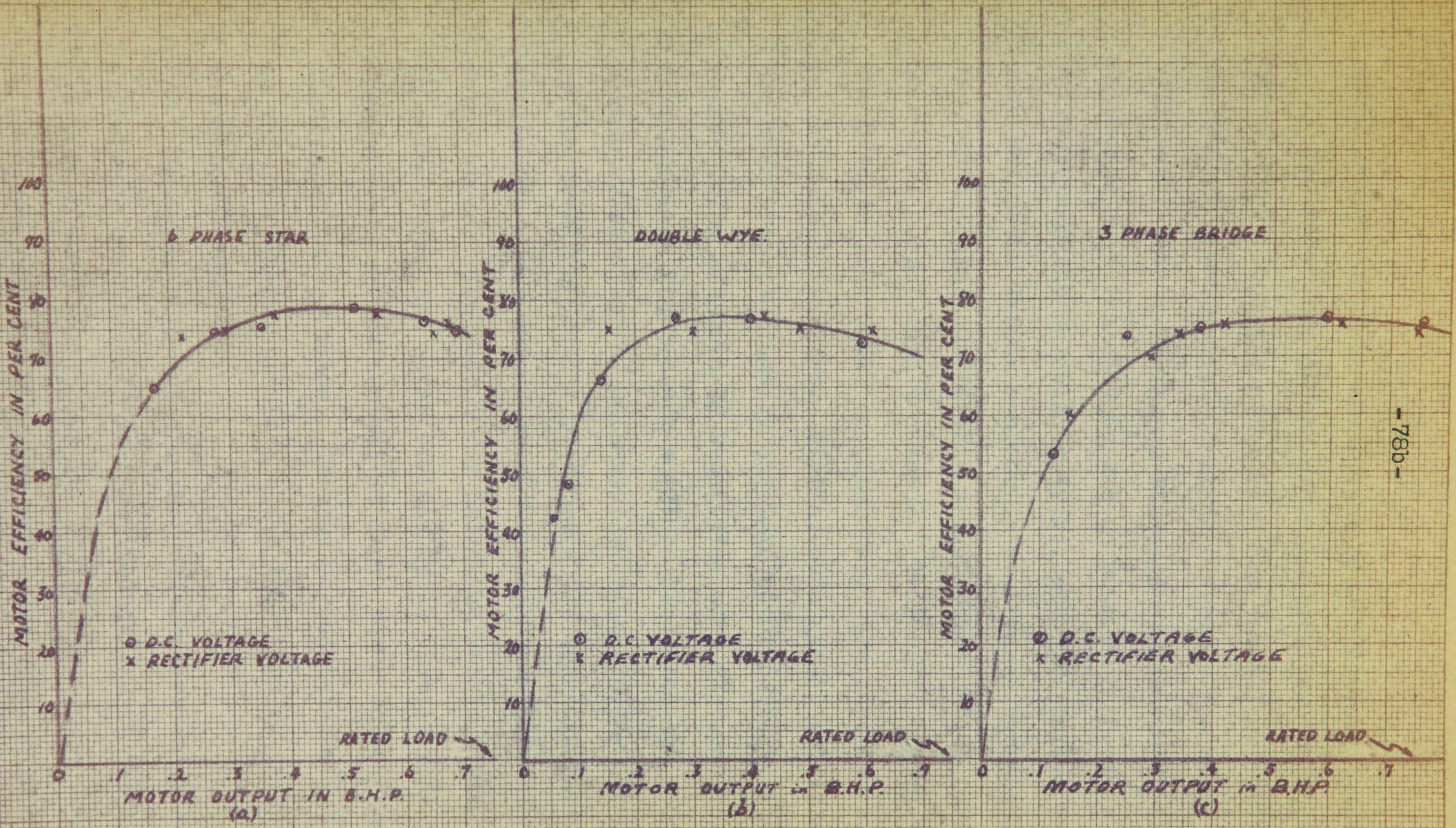


Fig.8-11 Motor efficiency curves on rectifier voltage and corresponding D-C voltage.

small random error in the torque and efficiency calculations.

The motor efficiency was calculated as the equivalent watts output from the motor over the watts input to the motor as read by a wattmeter. This then assumes the brake is 100% efficient. Since the motor input power measured by the wattmeter must include the A-C component of power it then follows that the calculated efficiency will depend not only upon the motor losses ordinarily considered but also upon the added losses due to this A-C component which produces no useful output from the motor. This is in contrast to the results that would be obtained if the input power used in the calculations were that as obtained by multiplying the mean motor voltage by the mean motor current, these values being measured by D-C moving coil instruments. In this case the input power would be less than the corresponding wattmeter readings by an amount equal to the A-C component of the rectifier output power, and the resulting motor efficiency would depend upon the characteristics of the motor alone. The reason for using the method first mentioned in calculating the motor efficiency is that it will give a true picture of the percent of input power which must be dissipated in the motor. This is of course of prime interest to the motor designer since it is this loss which determines the motor frame size.

In order to ascertain the actual decrease in motor efficiency attributable to the fluctuations in the rectifiers' instantaneous output power the efficiency of the motor at corresponding D-C voltages and loads is also plotted on the graphs in Figs.8-10 and 11.

The difference between the efficiencies of the motor when operated on pure D-C power and on power from a rectifier must be due to increased losses such as:

1. Higher I^2R loss in the armature due to the current form factor now being higher than on D-C current.
2. Higher I^2R loss in the armature due to the increase in effective armature resistance because of the increase in stray load loss, see ref. 13.
3. Increased eddy current and hysteresis loss due to the pulsating armature flux resulting from the alternating component of armature current.

A comparison of the motor efficiencies for single phase bridge and three phase wye rectifier-motor drives with the efficiencies of the same motors operated on equivalent D-C voltages, see Fig.8-10, shows that a considerable decrease in motor efficiency results when rectifiers are used as the source of power. This decrease in efficiency is of the order of 10% for the single phase bridge power source and about 5% for the three phase wye power source. (Note that a decrease in motor efficiency of 10% means an increase in motor losses of approximately 50%.) These figures however serve only as an estimate of the actual decrease encountered in practice because the motor was operated considerably below its rated voltage of 115 volts. (With the available number of rectifier disks it was impossible to construct a rectifier having the required voltage and current rating to operate this motor.)

In Fig.8-11 are shown motor efficiency curves for six phase star, double wye, and three phase bridge rectifier-motor drives. It was here deemed unwise to attempt to draw two separate curves, one for the rectifier source of power and the other for the D-C source of power. The possible error in the determination of the brake horsepower and the efficiency by the method previously mentioned is of such magnitude as to warrant the drawing of only one best fit curve to satisfy both sets of points. This does not infer that there is no increase in the motor losses when the motor is operated on these rectifiers, but rather that the increase in the loss is so small as not to be discernible by the experimental methods used in this study. It is then reasonable to assume that the increase in loss is so small as to be of little or no practical concern in the design of motors to be used on rectifier-motor drives.

The shift in the value of brake horsepower at which the peak motor efficiency occurs for the various rectifier-motor drives results from the fact that the rectifiers have different output voltages.

8-6 Rectifier efficiency.

The rectifier efficiencies plotted in Figs.8-12 and 13 were calculated as the ratio of the product of the rectifier mean output voltage and mean current, as read by D-C moving coil instruments, to the A-C power delivered to the rectifier, as read by a wattmeter. From practical considerations this is of more interest than the efficiency based on wattmeter

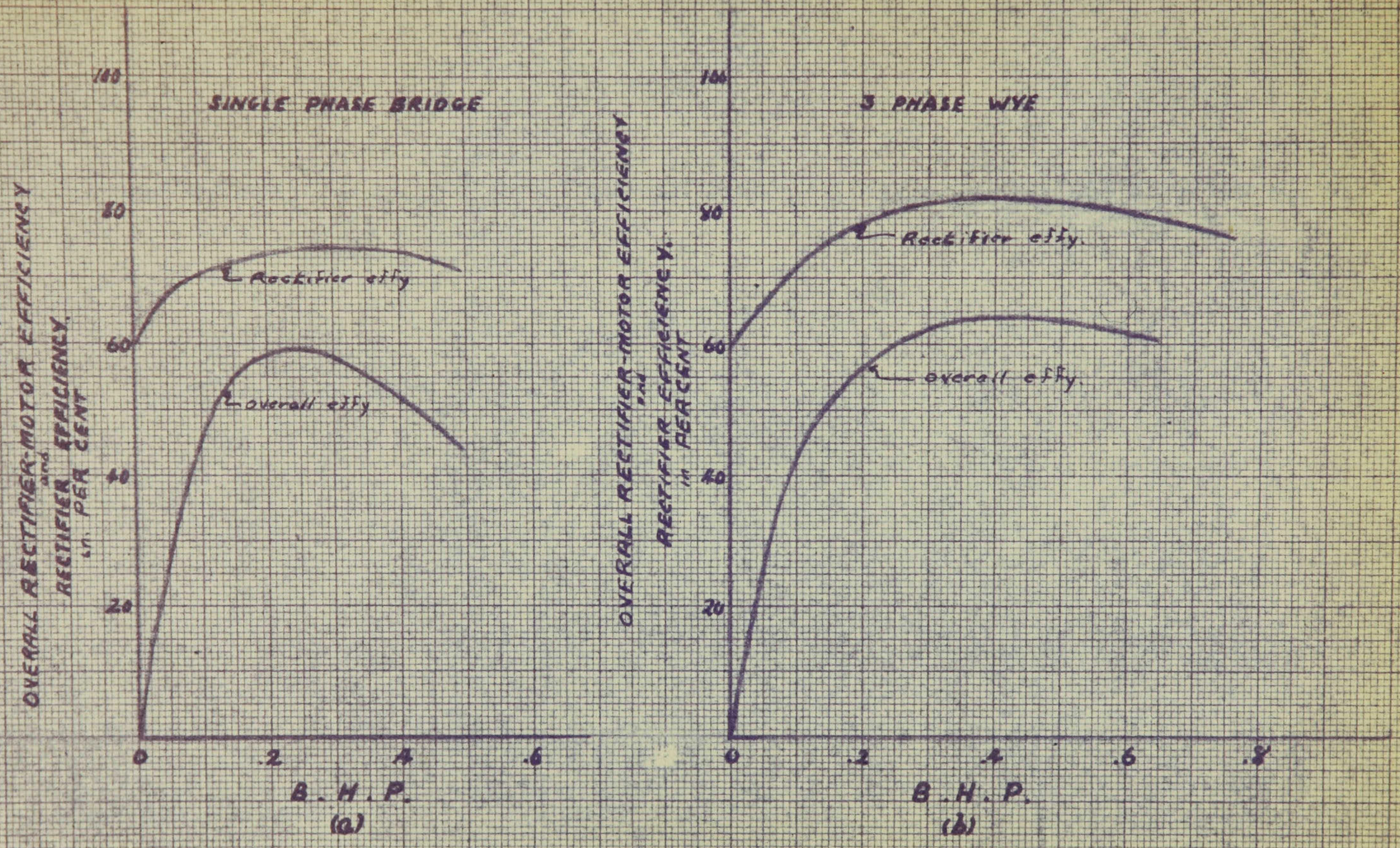


Fig.8-12 Rectifier efficiency and overall rectifier-motor efficiency curves as a function of brake horsepower.

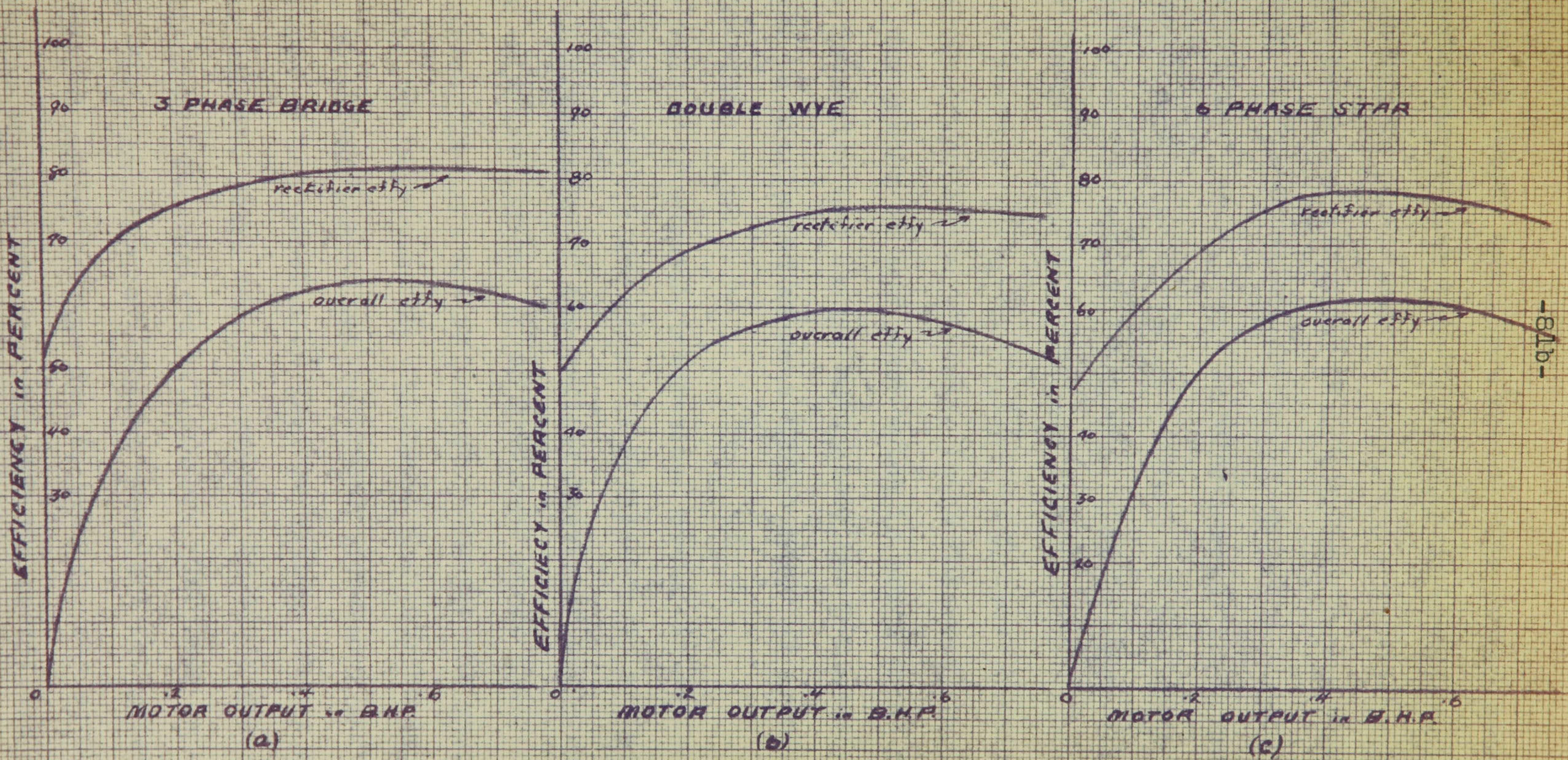


Fig.8-13 Rectifier efficiency and overall rectifier-motor efficiency as a function of brake horsepower.

readings of output and input power. The former method may be considered to give the 'efficiency of rectification', and as such may be considered as a measure of how efficiently the A-C power is converted to D-C power. However it should be noted that even if the rectifier resistance were zero the efficiency could never be 100% because there always exists an A-C component in the output power. Hence the rectifier efficiency as calculated from the mean volt-amps output over the watts input is a measure of:

1. the losses in the rectifier which cause heating of the rectifier disks and hence limit the rectifier rating.
2. the amount of A-C power which is transferred through the rectifier and cannot be used by the D-C motor. This power is dissipated as heat in the motor as previously mentioned.

Values of maximum theoretical efficiencies for the various rectifiers are given in references 4, 5, and 6.

A comparison of the various rectifier efficiencies shown in Figs.8-12 and 13 is difficult since their voltage and current ratings are not equal. However the graphs do indicate the magnitude of efficiency that may be expected.

An inspection of the rectifier efficiency curves leads one to the conclusion that an optimum number of rectifier phases exists. This results because the three phase wye rectifier has the highest efficiency. This may be caused by the fact that the more phases there are the greater the loss in D-C output voltage due to overlap, see eqtn.8-3 and discussion on page 46, and that for the rectifiers studied in this experimental work the optimum rectifier efficiency is obtained with three phase wye rectification.

It will be noted that the efficiency of the double wye rectifier is lower than that of the six phase star or three phase bridge rectifiers. This may be explained by the fact that the increased overlap (for effectively that is what the IPT of a double wye rectifier accomplishes) reduces the D-C output voltage below that value which would exist were the IPT removed. Hence the efficiency of converting A-C power to D-C power is reduced.

Also of interest is the fact that the efficiency of the dry disk rectifiers is reasonably constant from about 25% rated load to beyond rated load. This characteristic is not typical of motor generator sets, where the efficiency is definitely peaked at rated load, (see ref.14 for comparison).

8-7 Overall efficiency of Rectifier-motor drives.

The overall efficiency of the rectifier-motor drives is plotted in Figs.8-12 and 13. This overall efficiency is calculated from watts input to the rectifier over the equivalent watts output from the motor. The losses in the transformer have not been included because the rating of the transformer used was so much greater than that necessary to operate the rectifier-motor drives being studied that its losses are not representative of the transformer losses encountered in practice. Also, since the rectifiers were in most cases operating below their rated current, and the motor below its rated voltage, the overall efficiencies plotted in Figs.8-12 and 13 are not to be considered accurate, but rather indicative of the range of efficiency that may be expected from each type of rectifier-motor drive. The overall efficiency may appear rather low, being of the order of 50%, however it should be remember that the overall efficiency of a drive using a motor generator set as a source of power is also about 50%.

8-8 Across the line starting.

Figs.8-14 and 15 are motor starting current wave shapes during across the line starting. These wave shapes were obtained using a mirror type deflecting galvanometer. Each film was exposed twice, once when the motor was started on three phase bridge rectified D-C voltage, and once when started on D-C line voltage. The wave shapes in Figs.8-14 and 15 were obtained when starting on no load and full load respectively. (The loading of the motor was accomplished in the same manner as used to obtain the data plotted in Figs.8-8 to 13.) The following table summarizes the results obtained from the experimental wave shapes in Figs.8-14 and 15.

Across the line motor starting on:

	Three phase bridge rectified D-C	D-C line voltage
open circuit voltage	120 volts	112 volts
voltage on rated load[x]	111 volts	112 volts
peak starting current on: no load	12 amps	14 amps
full load	12 amps	16 amps
approximate duration of starting current on: no load	0.19 sec.	0.13 sec.
full load	0.68 sec.	0.45 sec.

[x] Motor rated current-6.2 amps.

The relatively low peak current when starting on the D-C line voltage probably results from the fact that the motor used was compound wound. Of particular interest is the existence of a peak starting current for the rectifier-motor drive which is apparently independent of load; whereas the starting current on D-C line voltage increases upon increasing the load, as would be normally expected. These results verify the idea set forth previously (page 27) that, for across the line starting on a rectifier source of power, the regulation of the rectifier voltage would limit the peak starting current. This is in contrast to the ordinary across the line start where the inductance, resistance, and inertia of the armature limit the starting current.

Actual values of starting current for the rectifier, given in the above table, are not in themselves significant because the rectifier rated current was 13.2 amps compared with 6.2 amps for the motor. Had the rectifier and motor been of equal rating the peak starting current on rectified D-C would have been still lower; this follows from the fact

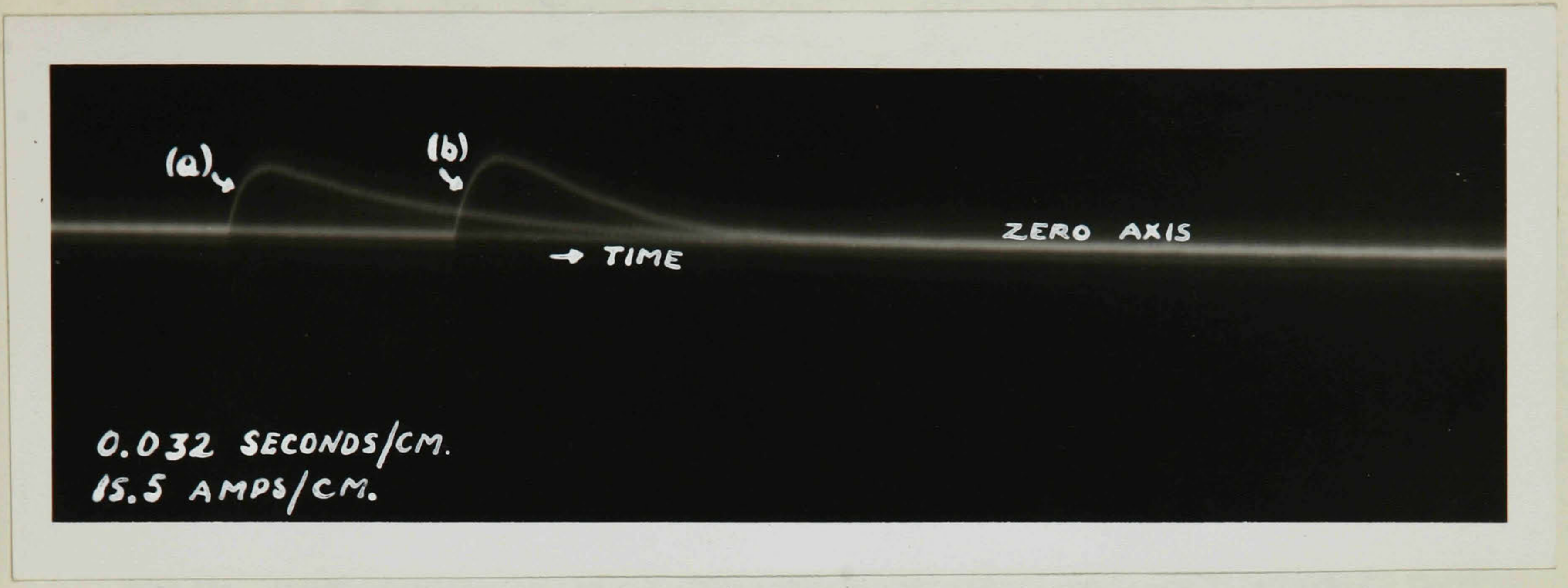


Fig.8-14 Across the line motor starting current wave shapes on no load for (a) three phase bridge rectified D-C. (b) D-C line voltage.

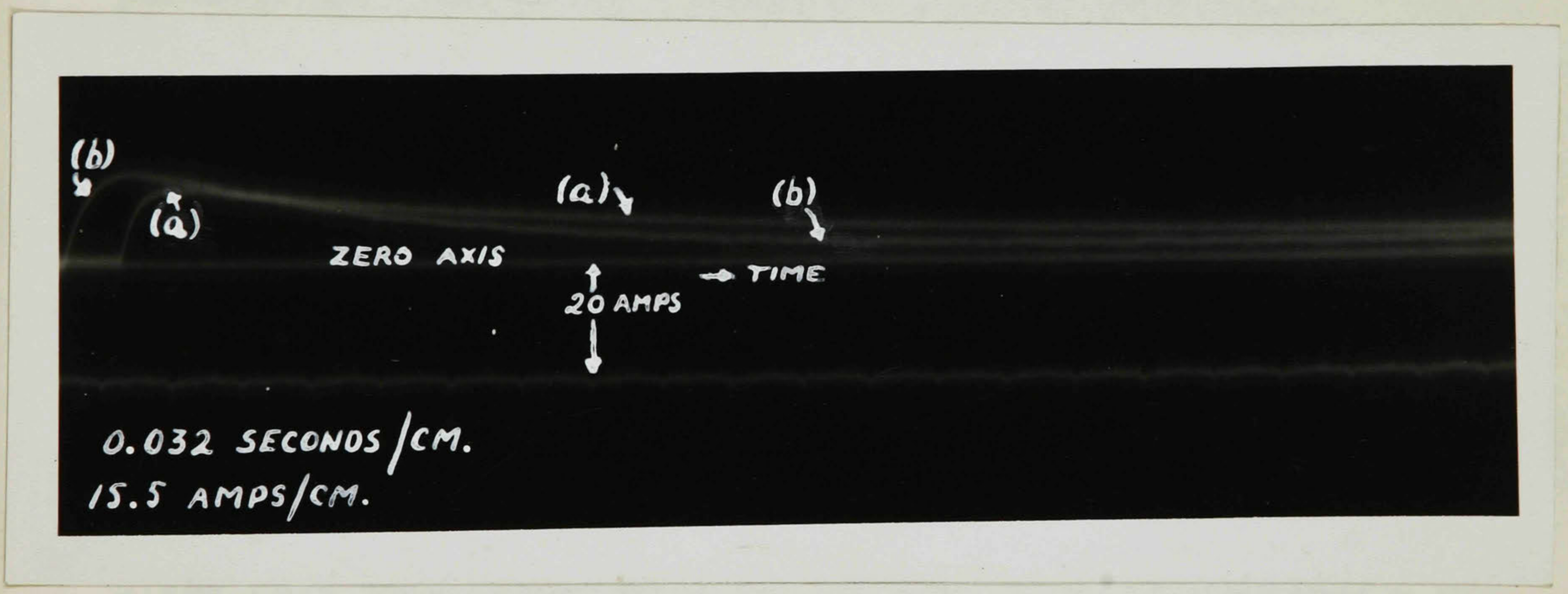


Fig.8-15 Across the line motor starting current wave shapes on full load for (a) three phase bridge rectified D-C. (b) D-C line voltage.

that the current density of the rectifier disks would have been higher and hence the output voltage would have had a still higher regulation.

The starting period using the rectifier source of power was greater than when the D-C line was used. This is as expected. The very short time duration of the overload suggests that the rectifiers will probably withstand across the line starting, see Fig.4-4 showing the permissible overload characteristics of selenium rectifiers. It should be pointed out that in practice, since the rectifier rating would be lower compared to the motor rating than was the case in this experimental work, the starting time would be greater. However from the overload characteristics in Fig.4-4 it is seen that the selenium rectifiers will withstand $5\frac{1}{2}$ times their rated current for 60 seconds, providing the rectifier is at the normal ambient temperature. Comparison of this permissible overload with that actually obtained on across the line starting suggests that the selenium rectifier-motor drive is well suited to this type of operation. The chief advantage of the rectifier drive would be that, since the starting current is lower than for an ordinary across the line start, the line disturbances would be less than normally encountered with present day equipment. However the data on across the line starting given here is incomplete since the inertia of the load was very low compared with that encountered in some types of applications.

CHAPTER NINE

APPLICATIONS OF DRY DISK RECTIFIER-MOTOR DRIVES

9-1 Practical considerations.

The dry disk rectifier-motor drive has not been developed to the same degree of perfection as the tube rectifier-motor drive for two chief reasons:

1. Until recently the low inverse peak voltage of dry disk rectifiers has made their cost prohibitive in the ratings required for motor operation. Since 1930 however the advent and improving of the selenium rectifier has brought into industry a dry disk with a much higher inverse peak voltage.
2. Improvements in the design of saturable core reactors have only recently opened up the field of controlled dry disk rectification.

The previous chapter outlined some of the more important characteristics of a selenium rectifier-motor drive. It was shown that in general the speed regulation of such drives is high, hence unless some type of regulator is to be used to hold the motor speed constant such a drive will not be applicable where constant speeds are required. The use of a magnetic amplifier (saturable core reactor) to adjust the voltage applied to the rectifier transformer has improved the rectifier-motor drive in two ways:

1. The range of speed control has been increased because economical armature control is made available as well as field control, ref. 15. This form of armature control

does not increase the form factor of the armature current as is done with thyratron grid controlled rectifiers.

2. The effects of rectifier voltage regulation may be overcome. Therefore the dry disk rectifier-motor may be applied to constant speed drives.

The prime advantages of the selenium rectifier-motor drive are:

1. Low weight to horsepower ratio. (ref. 16) Whether this ratio is lower than that for drives using contact rectifiers is not known by the writer as it is only since the war that contact rectifiers have come into the field at all.

2. Low space requirements. (ref. 16) The space requirements are appreciably less than for motor generator sets. This is particularly true if the rectifier is fed directly from the line and the transformer is not used. This is only possible however for the single phase and three phase rectifier circuits. If the advantages of six phase rectification are of more importance than the saving on space, and also weight, then the rectifier transformer must be used.

3. Dry disk rectifiers have been proven to be exceedingly rugged, hence maintenance of these drives is low, and their reliability is better than for tube rectifier drives.

4. These drives in industry have the advantage over tube rectifiers of not requiring special staff to install and service them as is the case with electronic equipment.

5. The overload capacity of these rectifiers is greater than tube rectifiers and hence rapid motor acceleration, and in particular cases plugging, is permissible. As mentioned on page 87 this overload capacity of selenium rectifiers permits using them for across the line starting of motors on some types of loads. Across the line starting is not feasible with tube rectifiers because controlled acceleration must be used to limit the peak tube current at all times.

Several other factors must be considered in the application of a rectifier-motor drive. Because of the high ripple content of the line current drawn by the rectifier-motor drive, heating of the generator supplying this current may result if the rectifier capacity is large, see ref. 4 and 17. Also as a result of this high ripple content, in some cases where power and telephone lines run parallel, the problem of inductive coordination must be considered. Further, the line power factor resulting from a large capacity of rectifiers on a line may be low; in exceptional cases this may require power factor improving equipment. The pulsations of the armature current will sometimes cause excessive vibration, particularly if less than six phase rectification is used.

9-2 A multi-rectifier-motor drive.

So far some of the practical advantages and disadvantages of rectifier-motor drives have been outlined. In the previous chapter the characteristic curves typical of selenium rectifier-motor drives have been shown and discussed. With this material in mind it appears practical to consider the possibility of designing a multi-rectifier-motor drive that would give a considerably greater range of speed than that available by field control alone.

In many applications the motor drive must not necessarily be controlled over a wide range while in operation, however one drive must be applicable to different uses and hence an arrangement whereby the motor base speed is adjustable would be satisfactory. As an example of this consider the requirements of a lathe motor or spooling machine motor. The same motor during the course of one day may be required to operate over a wide range of speeds, however for any given operation the range of speed control necessary is easily achieved by field control.

The ratios of rms voltage per secondary leg of a rectifier transformer to the D-C output voltage from a rectifier depends upon the type of circuit being used. For example, (ref. 6) assuming the load on a rectifier is highly inductive and ignoring any losses in the rectifier, then if the transformer voltage per leg is 100 volts rms the D-C output voltage from the various rectifier circuits will be :

single phase bridge	89.5	volts
three phase bridge	202	volts
three phase half wave	117	volts

It then is readily seen that by simply changing the connections to the rectifier and the arrangement of the rectifying disks a variation of output voltage of approximately 2 to 1 is obtainable. It then follows that, with this control of output voltage as well as the normal range of field control, the speed variation of a selenium rectifier-motor could easily be 8 to 1. Such control of course can be obtained by using voltage taps on the transformer. However, as shown in Figs.8-8 and 9, different speed regulation curves are obtained with each rectifier circuit. It then appears possible that in some applications such as the winding of spools and reels where the linear speed of the material must be approximately constant, that this combined control of base speed and speed regulation may automatically adjust the speed to give the desired regulation over the whole process. If such a scheme could be applied to an industrial drive then no regulator would be required as the control is inherent in the drive itself. It is obvious that such a drive would be only applicable to processes where accurate speed adjustment is not essential.

9-3 Conclusions.

The use of selenium rectifiers as a source of D-C power has been well established. This is indicated by the varied fields in which they are used, see refs. 3,11,12, 14, 16, 18. However it has not as yet been proven that they are economical and practical as sources of power for D-C motors. The writer has attempted to show that the selenium rectifier-motor drive has many desireable characteristics, see chapter 8, which will make it a serious industrial competitor of the tube rectifier-motor drive. For closely controlled drives the dry disk rectifier-motor drive cannot compete, as yet, with the tube rectifier-motor drive. However for many variable speed motor drives where close control of speed is not required, it is felt that the dry disk rectifier will replace the tube rectifier. Proof of this statement can only be obtained from trial installations in industry. Up to now such experimenting has been hindered by high costs of selenium rectifiers, but as their use increases the prices will drop to the point where they will compete favorably with tube rectifiers.

LIST OF SYMBOLS

e -instantaneous applied A-C voltage.

e_1, e_2, etc.-instantaneous transformer voltages of secondaries 1, 2, etc.

e_b -instantaneous voltage drop across rectifier.

e_d -instantaneous output voltage from rectifier during commutation.

e_r -instantaneous voltage across resistance load.

E_o -arc drop of rectifier (considered constant).

E_c -loss in rectifier output voltage due to overlap.

E_d -mean rectifier output voltage.

E_d' -mean armature terminal voltage during discontinuous conduction.

E_g -motor back emf.

E_m -peak instantaneous output voltage.

E_s -rms transformer secondary voltage.

i -instantaneous current.

i_1, i_2, etc.-instantaneous currents in phases 1, 2, etc.

I_a -mean armature current.

I_d -mean rectifier load current.

L -equivalent transformer leakage reactance per phase referred to the secondary.

L_m -motor armature inductance.

m -number of rectifying phases.

n -motor speed.

P_r -transformer copper loss.

R -armature resistance.

R_o -rectifier resistance.

u -angle of overlap.

α -firing angle of rectifier.

α_f -angle of firing.

α_s -angle of extinction.

θ -power factor angle of rectifier-motor circuit at line frequency.

ω -$2\pi f$-where f is the fundamental frequency of the applied voltage.

BHP -motor brake horsepower.

IPT -interphase transformer.

SCR -saturable core reactors.

APPENDIX

I Motor Rating.

All experimental data for D-C motor operation included in this thesis was obtained using the same motor. The motor was made by the Electric Tamper and Equipment Company; it is rated at 1450 r.p.m., $\frac{3}{4}$ BHP, 115 volts, 6.2 amps, continuous rating. The motor, No. D21060, is compounded but has no commutating poles.

II Rectifier Disk Ratings.

The rectifier disks used were I. T. and T. (International Telephone and Telegraph Corporation) selenium rectifiers and were manufactured by Federal Telephone and Radio Corporation. The disks are Type No. 13, (2 5/8 inches diameter using aluminium cooling fins of 4 3/8 inches diameter.) Their rating (see manufacturer's pamphlet) is:

Max. rms A-C volts reverse per disk 18

Max. continuous D-C amps for one disk per arm at 35^{o} C. ambient, inductive or resistance load. for:	
single phase bridge circuit	2.2
full wave	2.2
three phase wye	2.9
bridge	3.3
six phase diametric	4.0

Note: Several manufacturers are now producing selenium rectifier disks having an inverse voltage rating of 26 instead of the former 18.

III Oscillograms.

The oscillograms, with the exception of those for across the line motor starting, were obtained by photographing the screen of a Dumont cathode ray oscilloscope. The screen was 5 inches in diameter, and had a green trace. (A blue trace is better for photographing but no such trace was available.)

The 35 m.m. camera was mounted on a tripod with the lens 11 inches from the screen. A 3 diopter portrait lens was used in order to permit such short object distances. An exposure time of 0.1 seconds at f 3.5, and Ansco Supreme film were used.

The oscillograms were calibrated by exposing the film a second time with the oscilloscope sweep set at zero and a known A-C voltage or current on the screen. The vertical gain of the oscilloscope was of course kept constant for each picture. The occasional blurring of this calibration marker resulted from the failure to reduce the beam intensity when photographing the screen.

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