Operation of D. C. Shunt Motors

on

Half Wave Rectified Power

Dissertation submitted in partial fulfilment of the
requirements for the Degree of

MASTER OF ENGINEERING
IN
ELECTRICAL MACHINE DESIGN

by

R. N. GOYAL

DEPARTMENT OF ELECTRICAL ENGINEERING

UNIVERSITY OF ROORKEE

CERTIFICATE

CERTIFIED that the dissertation entitled " OPERATION OF D.C.SHUNT MOTORS ON HALF WAVE RECTIFIED POWER" .... which is being submitted by Sri R. N. Goyal in partial fulfilment for the award of the Degree of Master of Engineering in Electrical Machine Design of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of three and a half months from 1-5--63 to 15-8-63, for preparing dissertation for Master of Engineering Degree at the University.

Signature

Designation of
the Supervisor .. Reader

Dated August 16 ,1963.

Seal

ACKNOWLEDGEMENTS

The author wishes to express his profound sense of gratitude to Sri J. L. Jethi, Reader in Electrical Engineering for his valuable advice and suggestions at every stage of the preparation of this dissertation.

The author wishes to thank Prof. C. S. Ghosh, Head of the Electrical Engineering Department, for the various facilities afforded in the department in connection with this work.

Sincere thanks are also due to Sri K. B. Verma, and Sri M. M. Gupta, for their valuable advice and help throughout the experimental work.

CONTENTS

SYNOPSIS

The scope of this dissertation extends only to the ? operation of d-c shunt motors on half-wave rectified power. A general mathematical analysis of the problem has been given and the results from theoretically derived equations are shown to be comparable with the experimental results. An approximate method of analysis has also been given and is shown to be quite quite accurate. Apart from this various usual performance tests, both under steady state and transient conditions are also given. The various methods of controlling the methods ? and details of auxiliary equipment are also given. The various operational problems are discussed.

NOMENCLATURE

a = speed coefficient of the motor when fed on half-wave rectified power.

a' = ratio of voltage generated in motor armature to the peak value of transformer secondary voltage

a_o = ratio of rectifier drop to the peak value of transformer secondary voltage

a_{dc} = speed coefficient (in d.c. operation of motor)

C = ratio of compole to armature turns

E = motor terminal voltage when on d-c supply

e_a = instantaneous value of anode supply voltage

E_{br} = brush contact drop

E_d = total back emf in rectifier-motor circuit

E_{dc}' = d-c voltage at load terminals

E_G = voltage generated in motor armature

? E_g = r.m.s. value of control grid voltage

E_L = line voltage

E_m = peak value of transformer secondary voltage to neutral

E_o = voltage drop across rectifier

E_s = r.m.s. value of the transformer secondary voltage to neutral

f_f = form factor of rectified armature current

f_m = peak-coff. of armature current

I_{d-c} = d-c value of motor armature current

I_L = line current

K_n = speed constant

K_f = excitation constant

L = inductance of armature winding

m = ratio of peak 60 cps ripple to d-c current

n = speed of the motor

P = h.p. rating of the drive

p = number of phases of the rectifier

p_L = number of phases of the a.c supply line

R = total resistance of motor armature circuit

T_L = load torque

t_f = torque factor

t_{fdc} = torque factor (in d-c operation of motor)

v_a = armature voltage coefficient

V_d = output d.c. voltage of rectifier at full grid control

x = percentage bucking of compole winding current

y = percentage boosting of compole winding current

x_m = time angle for peak value of motor armature current

ϕ, α = angle of phase-shift

β = angle of tube breakdown

γ = angle of extinction of rectifier tube

θ = $\tan^{-1} \frac{\omega L}{R}$ = impedance angle of motor armature circuit

ϕ = operating magnetic flux in motor

ω = angular frequency

INTRODUCTION

Motor-generator sets have been the normal source of power for large d-c motors for many years. The first application of rectifiers to large motors occured in the steel industry. A study of the evolution of rectifier-motor drive systems reveals a marked change in system characteristics over the past few years. Thus, it is necessary to investigate some simple and effective system using rectifiers which may be a possibility in power supply applications.

A historical review of the application of power rectifiers for large motors reveals that power rectifiers were first used for this application nearly two decades ago. Around 1940 a steel company wanted to increase the power to an existing hot strip mill. Due to considerations of available space, installation time, etc., power rectifiers were added in parallel with the existing generators. As the system employed a common bus power supply the influence of the rectifiers caused little disturbance of the input to the motors. On later hot strip mills, it becøme a common practice to use rectifiers as the sole power source. Here, again, the limits were paralleled on a common bus and particular care was taken to maintain the proper phase relationship among the static units to obtain the minimum disturbance on the power system.

In 1954, the first individual motor-rectifier powered hot strip mill was put into operation in the united states. The full impact of the rectifier voltage variations appeared at the terminals of a large motor for the first time. The motors were rated 5000 h.p. and operated through a 2 to 1 field weakening range from base speeds 125, 150 and 175 rpm. This type of power system is used for modern hot strip mills and → differs considerably from that first employed nearly 20 years ago.

Now-a-days, the use of rectifiers is becoming popular in electric traction also where the traction motors are d-c series motors. Various authors have investigated the choice of single-phase full-wave rectifier d-c motor system. But the single-phase half-wave rectifier system requires the least number of tubes. So it might be of some interest to study the half-wave rectifier d-c motor system, and to investigate the performance. Generally in traction, series d-c motors are used as a rule, whereas in many other applications as in steel industry, d-c motors with shunt excitations are used. So the problem under investigation was limited to the half-wave d-c motor system with separate d-c excitation. The various other combinations, as that of series motor on half wave rectified power, are still to be investigated and may become an interesting problem for future workers.

Still the problem of half wave rectifier d-c shunt motor system is in its initial stage and there are various drawbacks in the system. So before this system becomes an economic possibility, much of research work is needed.

CHAPTER - I

AUXILIARY EQUIPMENT FOR HALF-WAVE RECTIFIED POWER SUPPLY

When a d.c. motor is fed from rectified a.c. power, various types of equipments are to be used to make a link between the a.c. busbars and the d.c. motor. These equipments rectify the a.c. power to d.c. power. It is very important to be careful in the selection of these auxiliary equipments as their characteristics affect the overall performance of the system consisting of auxiliaries, d.c. motors and the load. In the following paragraphs an exhaustive discussion is being given.

(1.1) The Transformer.[1,2]

The transformer is the heaviest single item of equipment in the rectifier scheme, and it is, therefore, worth giving every consideration to means of attaining the minimum possible weight and size which is important in many applications of rectifier fed drives.

(1.1.1) Insulation and Cooling.

For voltages upto about 15 KV it is practicable to use air as the insulating and cooling medium, and this promotes lightness and a low fire risk. For higher voltages the greater electrical clearance and creepage distances needed would cause an air insulated transformer to be excessive in size. For high voltage systems (say upto 30 KV), therefore, it is normal to use a liquid as the insulating medium.

In order to achieve the desired low weight it is customary to use a current density several times greater then would be normal for a conventional substation transformer. This results in correspondingly high copper losses which must be accepted as the penalty to be paid for lightness and smallness which are very important in certain cases as in the case of rectifier locomotives. The high losses could not be dissipated by natural cooling, and forced oil circulation is therefore adopted in order to circulate the oil between the transformer and a separate radiator and to obtain better heat-transfer factors.

Thus a small light transformer (with high losses) will probably necessitate additional weight in the case of rectifier locomotives and other such applications owing to the space occupied by the large radiator. The best compromise between transformer size and radiator size is a design problem.

Generally the core is built up from laminations of grain-oriented silicon-iron alloy, which can be operated at flux densities near to saturation (B_{max} - 1.8 Wb/m^2) without excessive losses or magnetizing current. This reduces the transformer weigh appreciably. The core is designed with high flux density at the nominal system voltage; when the voltage rises above the nominal system voltage; when the voltage rises above the nominal value, the increased losses and magnetizing current are accepted as a short term condition.

For high voltage control systems the rectifier transforme and the autotransformer are built with one yoke common to both. This yoke carries only the difference in flux of the two transfor-

-mers, so that the iron section is reduced with a corresponding weight reduction.

(1.1.2) Shell-Type versus Core-Type Transformers.

The shell-type transformer is usually preferred to the core-type mainly because it provides constructional advantages. In shell transformers the core, in effect, surrounds the coils. The main advantages of the shell-type are:

(i) The shape permits a simple design of tank to fit closely round the active parts, thus avoiding wasted space and reducing the volume and weight of oil.

(ii) The oil flows in clearly defined paths in close contact with the coils, thus promoting effective heat transfer.

(iii) The core laminations can be clamped together by the two halves of the tank, thus avoiding the use of clamping bolts passing through the core.

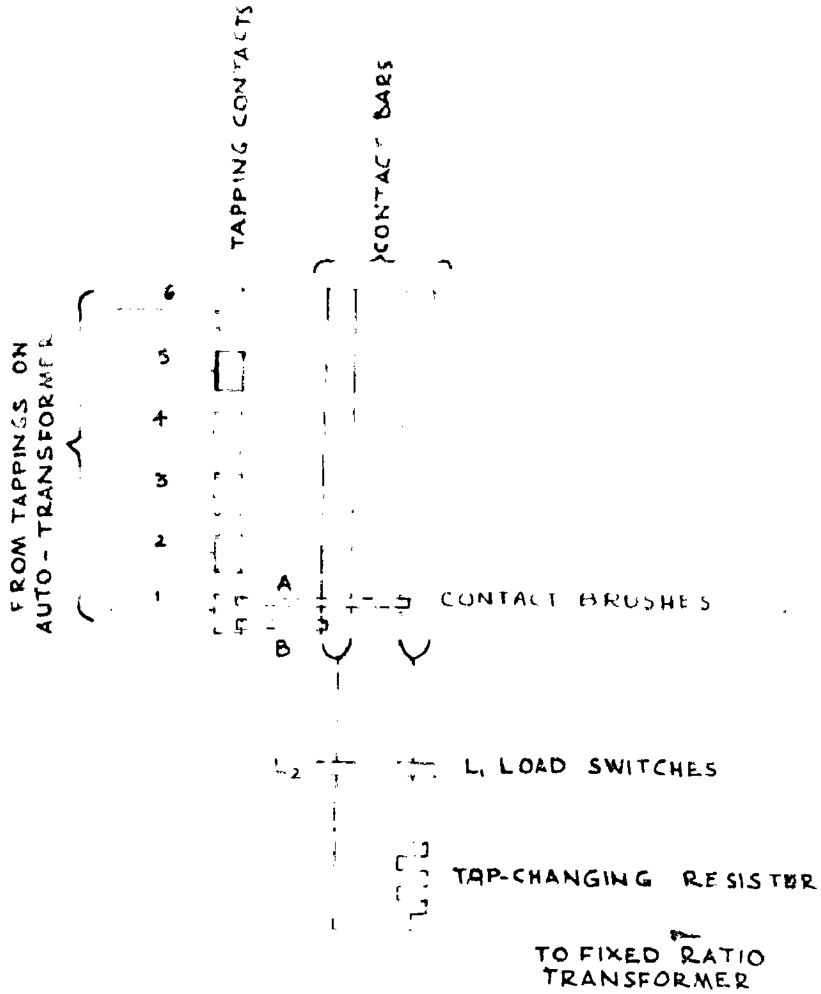
(iv) The shell-type is more flexible in shape, as all three dimensions are more or less independent of one another.

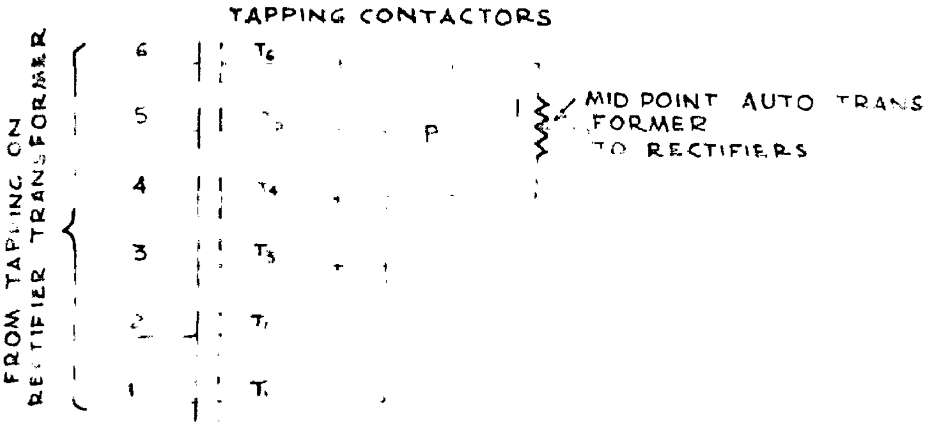
In the simplest shell construction there are only two loops of iron core around the rectangular-shaped coils, but this could obviously be increased to four loops.

With circular coils the number of loops can be increased to as many as are desired - this arrangement leading to the radial core design.

(1.1.3) Voltage Control Gear.

(i) H.V. Control:- Fig. 1.2 shows the connections for a typical h.v. tap-changer. The contact brushes A and B operate off-load and are mounted on a chain-driven carriage, which


TAPPING CONTACTS
CONTACT BARS
FROM TAPPINGS ON AUTO-TRANSFORMER
6
5
4
3
2
1
A
B
CONTACT BRUSHES
L2
L1 LOAD SWITCHES
TAP-CHANGING RESISTOR
TO FIXED RATIO TRANSFORMER


TAPPING CONTACTORS
FROM TAPPING ON RECTIFIER TRANSFORMER
6
5
4
3
2
1
T6
T5
T4
T3
T2
T1
P
MID POINT AUTO TRANSFORMER
TO RECTIFIERS

together with the contact blocks and contact bars, is housed in an oil-filled casing. Electrical clearances are therefore small, leading to a compact design. All current-making and breaking is handled by the two load switches L_1 and L_2, which are mechanically operated from the mechanism which drives the carriage. The load switches are air-break units and are thus readily accessible for maintenance. The tap changer may be operated by a pilot motor or by direct manual drive.

The tap-changing impedance is a resistor, which may be fan-cooled.

(ii) L.V. Control:- The connections for a typical l.v. tap-changer are shown in Fig. 1.3. This particular tap-changer uses a mid-point auto-transformer as the tap-changing impedance.

All the contacts operate on-load and are of the air break type; they may be operated by a camshaft or they may be in the form of unit switches-usually operated electro-pneumatically

Off-load tapping selector contacts, with separate contactors for current making and breaking are not common in rectifier transformers.

(1.1.4) Effect on Transformer Design.

The transformer for a rectifier/inverter scheme must be designed so that under the worst conditions of inverter operation the firing limits are never exceeded. These adverse conditions occur when peak loads coincide with a low supply voltage. This results in a transformer 10-20 percent larger than that necessary for the equivalent free-firing rectifier duty, and always involves operation during rectification with some firing delay.

Normally, the determination of kva rating of the polyphase power transformer is based on the continuous rating of the drive, without taking into account the starting and overload conditions. The kva of the secondary polyphase winding of the power transformer can be calculated from the formula:[10]

$$KVA = E_s \; I_{d-c} \; f_f \; \sqrt{p} \qquad (1.1)$$

where E_s = r.m.s. value of the transformer secondary voltage to neutral.

I_{d-c} = rated value of motor armature current.

f_f = form factor of the rectified armature current at the lowest operating speed and full rated torque.

p = number of phases of the rectifier

For a rough estimation, the approximate kva of the power transformer for drives up to 15 horse power can be obtained as[10]

$$kva = 2.5 \; P \qquad (1.2)$$

where P = horse power rating of the drive.

(1.2.1 Rectifiers.[1,2,3,4.]

Rectifiers play the most important role in the rectifier-motor installations. There are many types of rectifiers available and each type has got its own limitations. The most important type of rectifiers are:

(1.2.1) Semi-Conductor Rectifiers.

Semi-conductor rectifiers, although not competitive in price at present, are being developed rapidly and have a promis

-ing future for traction applications. The greatest asset is simplicity, owing to the absence of preheating, excitation and ignition equipment.

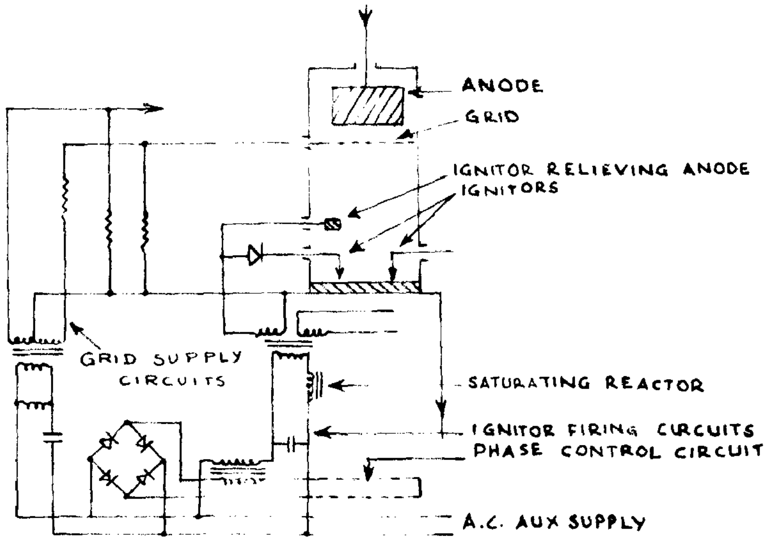
Germanium rectifiers do not show any really significant reduction in size compared with the mercury - arc rectifier at the voltages which can be used for industry, and there is very little gain in efficiency. Silicon rectifiers, however, can operate up to much higher temperatures than germanium and show considerable savings in space and weight. A set of semi-conductor rectifiers is more flexible in dimentions than a mercury arc rectifier.

Semi-conductor rectifiers have very short heating time-constants and hence need to be continuously rated for operation at the accelerating current. Fuses are needed to obtain sufficiently high-speed protection to prevent damage to the rectifiers due to faults.

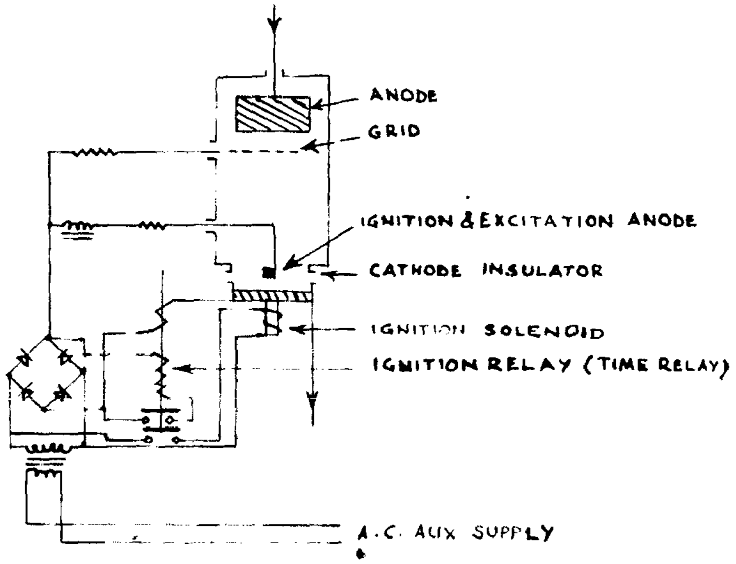
(1.2.2) Mercury-Arc Rectifiers.

Thyratrons and other types of mercury-arc rectifiers are generally used for the power rectification. The thyratron is limited to the life of its cathode and by warm - up time. Its grid power requirements are low. Little commercial experience has been obtained with large thyratrons.

The other types of mercury arc rectifiers are either single anode or multianode. The single anode rectifiers are ~~either~~ known as excitron and ignitron. These two types differ in construction and method of operation, but not in application. The fig. 1.4(a) and 1.4(b) indicate the essential difference between ignitrons and excitrons. In the former a cathode is


ANODE
GRID
IGNITOR RELIEVING ANODE
IGNITORS
GRID SUPPLY CIRCUITS
SATURATING REACTOR
IGNITOR FIRING CIRCUITS
PHASE CONTROL CIRCUIT
A.C. AUX SUPPLY

(a)


ANODE
GRID
IGNITION & EXCITATION ANODE
CATHODE INSULATOR
IGNITION SOLENOID
IGNITION RELAY (TIME RELAY)
A.C. AUX SUPPLY

(b)

initiated once in every cycle at the correct instant for the firing of the main anode, this spot being formed at the junction of the stationary ignitor and the mercury surface when a pulse of current is passed from the ignitor to the mercury. The pulse is obtained from static circuits. The excitron, however, has a cathode spot initiated on the mercury surface by one of the methods normally used in multi-anode rectifiers, and this spot remains burning continuously, the main anode firing whenever it becomes positive relative to the cathode.

Ignitrons are used for large currents and have shown little sign of being used below 200 to 300 amps in competition to rotating machinary. The firing power is generally large and requires devices having large time constant. For rapid response this is a difficult obstacle electrically. The excitron has not been produced in size small enough to be applied to the lower horsepowe drives. Grid power requirements are approximately those of the thyratron.

An ignitron design suitable to withstand forward voltages reliably and to have fast deionization characteristics is best designed with two or more grids. A tube with double grids for inverte requirements inherently has a lower allowable current density than that of a single grid tube of about the same physical size. Therefore, it is desirable to apply the double-grid type of tube at rectifier voltages above 1200 volts in order to obtain the optimum kilowatt output for given size of tube. Although a double-grid ignitron is better for most applications requiring inversion, a single grid tube is suitable for applications requiring only a limited amount of inversion. It may be possible to apply low-voltage single-grid ignitrons to many applications.

If the invertor requirements prevent the use of low-voltage single-grid ignitrons, it will be necessary to use double grid economically at higher motor voltages.

During the last two decades, the design of pumpless rectifiers has progressed so far that this type is being employed increasingly in many drive applications. Its main advantages are, no doubt, the omission of the vacuum equipment, which renders it extremely simple to maintain, and the ability to fill it with inert gas, which conduces to a most favourable run-up, even at low surrounding temperatures. Moreover, the temperature-control equipment has also been developed which ensures a perfectly stable control temperature even when the room temperature fluctuates widely. The optimum temperature is obtained by varying the velocity of the fans according to the control temperature, for which purpose chokes premagnetised by direct current are employed.

A further advantage attending the choice of pumpless rectifiers for medium capacity drives, is that a number of smaller tanks connected in parallel comply with the principle of back-up power, thus this type of rectifier finds increasing application in medium and high capacity drives.

(1.3) Busbar connections.

Many types of busbar connections can be possible. But in the interest of increased flexibility it might prove necessary to split up the busbars into a number of sections. Plants of this nature are provided with an auxiliary busbar, and a spare group which is dimentioned so as to normally feed in to the most heavily loaded section. Should the need arise the group can,

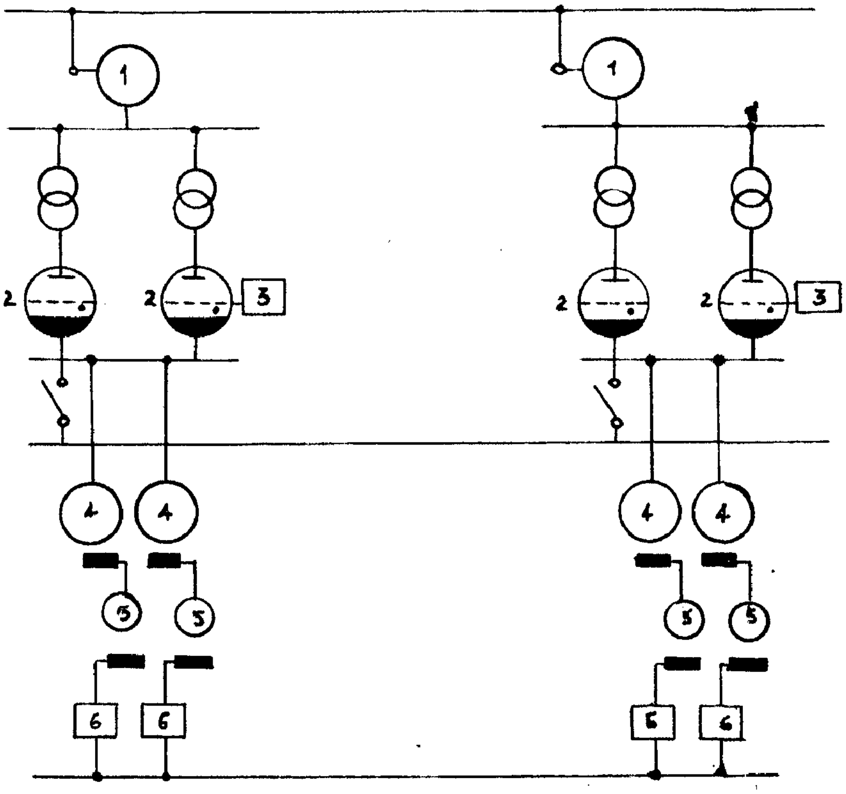


Fig. 1.5: TYPICAL BUSBAR CONNECTIONS

1. Transformer
2. Mercury Rectifier
3. Grid Control set for voltage regulation
4. Driving motors
5. Exciters
6. Speed regulators

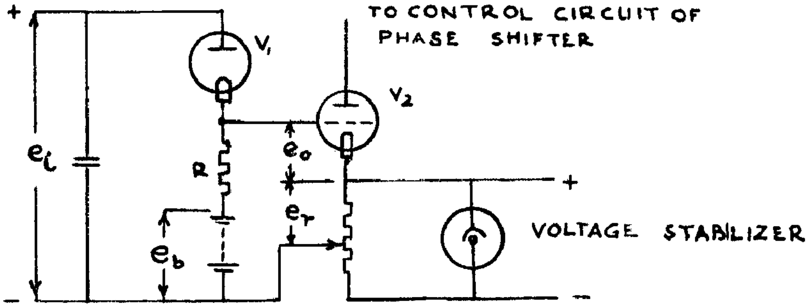


Fig. 1.6: CIRCUIT ARRANGEMENT FOR ELECTRONIC CURRENT LIMITER.

however, be changed over to any other section. Fig. 1.5 shows one good type of busbar scheme.

(1.4) Rectifier Faults and Protective Devices.[3,6.]

In the event a fault occurs during the operation of a rectifier fed motor, it is desirable to clear the fault and restore normal operation within a few cycles so as to have minimum effect on the motor operation.

The various types of rectifier faults and the devices adopted to clear them out are described in the following paragraphs

(1.4.1) Arc-Starvation Surges.

All mercury-arc rectifiers have a maximum current rating for any particular temperature, above which the ion supply to the arc fails and the current is chopped; when this occurs high-voltage surges are produced, owing to the inductance in the circuit. It is usual to operate well below these current values, but under certain operating conditions they may be exceeded. For example, when starting up after a week-end shut-down, a motor may require extra effort to move it, and if the rectifier is cold the grid control may be adversely affected, resulting in misfiring. This could easily result in an over-current sufficient to cause arc starvation.

Because of the risk of damage from such surges, it is standard practice to fit some form of surge protection on all mercury-arc rectifiers. This normally takes the form of non-linear resistance or spark-gap surge arresters connected between the anode and neutral or the anode and the earth across all secondary phases.

It should be noted that these surge arrestors are designed, not to eliminate surges, but to limit their value to within the surge strength of the equipment. Elimination of arc-starvation surges is possible only by direct adherence to the manufacturer's instructions regarding methods and conditions of operation.

(1.4.2) Over-voltages due to Switching and Regeneration.

With a drive of this nature (rectifier fed d.c.motor drive) there is also the possibility of over-voltages caused by sudden demand for regeneration facilities when motoring, or when when switching from motoring to generating or the reverse. For this a small fixed load in the form of a resistor is connected across the motor and this suffices to eliminate any sudden over-voltages due to regeneration.

(1.4.3) Over-Currents due to Backfires and Grid-Blocking.Failure.

Besides the normal insulation failure faults, mercury-arc rectifiers are liable under certain circumstances to backfires and failure of the grid blocking. For example, such faults could occur during surges caused by arc starvation or during over-loads. A backfire is an a.c. short-circuit inside the rectifier vessel itself from one anode to another. If at the time of backfire the rectifier is connected to a load which can feed back, there will also be a d.c. short-circuit via the rectifier cathode and the faulty anode.

Failure of grid-blocking when rectifying results in the voltage suddenly changing from its reduced controlled level to the full free-firing level, and, depending on the amount of firing delay may be equivalent to a short-circuit on the d.c. system. Such a failure during inversion could be more severe, in that the rectifier and machine would be in series, and the resulting short circuit would be at double the normal voltage.

As with all other electrical equipment, there is a fault level and a duration of fault which the equipment can withstand, and any protection has to be designed with this in mind. In this connection it should be appreciated that a backfire produces fault currents in the transformer windings and rectifier vessel of 30-50 times normal. On the d.c. side it is usual to fit a circuit breaker capable of interrupting any possible fault current due to short-circuit or failure of grid blocking in sufficient time to prevent the fault turning into a backfire. In case of backfires, both the a.c. and the d.c. protection must function rapidly enough to protect the transformer and to prevent any undue gassing in the rectifier, which would cause permanent damage.

On the a.c. side the a.c. breaker and the anode breaker are used. The a.c. breaker is used for clearing arc backs, for clearing over loads and for backup protection. The anode breaker can be used to clear an arc back by opening only the pole carrying the reverse current of the tube that has the arc back. It may be arranged to have all poles trip due to overload or forward fault current during an inverter arc through.

Sometimes the reactors are placed in various parts of the circuits to limit fault current and rate of rise of fault currents. It is undesirable to have too much reactance in the a.c. circuit as this makes it more difficult for the inverter to commutate. A d.c. reactor can be used to limit the rate of build-up of inverter fault current. Another requirement of the d.c. reactor is to limit the current ripple in the d.c. machine, particularly in single phase or in circuits having less than six phases. In circuits using reverse-connected convertors, reactors are required to limit instantaneous circulating currents if both convertors are always released.

(1.4.4) Temperature Control.

In order to minimise the incidence of arc-starvation surges it is desirable to accomodate mercury-arc rectifiers in an ambient temperature controlled chamber above a minimum value of 15 - 20°c; if this is not possible, temperature control of the rectifier has to be provided. In some makes of rectifiers both anode and cathode heaters are provided and controlled by a common switch. In addition, thermostatic control of the cathode heater is provided, operated from the rectifier cooling-air temperature, while the rectifier cooling fan is controlled independently according to the rectifier temperature by means of a thermostat situated on the anode plate.

Protection against the fan failure normally takes the form of single-phasing or thermal over current protection on the fan motor. Occasionally, depending on the rating of the equipment and the duty, it may be possible to put a thermostat on the rectifier tank, but this is normally not practicable owing to the slowness of response of available thermostates.

(1.4.5) Current Limiting[7]:

When only small control currents are required, it is possible to limit the output current of a rectifier to a pro-

-determined maximum. The control circuit used must be one that will remain quiescent until the preset load is reached and will then operate, retard the firing angle, and bring the current once again within a safe value. Such circuits may contain either thermionic values or static electromagnetic devices such as transductors. Where adjustments are not critical, metal rectifiers may sometimes be used in place of diode values.

A simplified limiting circuit is shown in Fig. 1.6. The input (e_i) is a voltage proportional to load, and (e_b) is a bias voltage. Whilst (e_i) is less than (e_b), V_1 can not conduct and no current flows in the resistor R. When (e_i) is greater than (e_b), V_1 conducts and the resistor now carries current. The voltage on the grid of V_2 changes in value from (e_b - e_r) to (e_i - e_r), V_2 conducts, and its anode current may be used to operate a phase-shifting circuit. It could be connected, for example, in the control circuit of the device outlined in Fig.4.5.

When armature and field control are used together, the limiter must first strengthen the field before reducing armature voltage.

(1.5) Reverse-Error Relay in Motor Control Loop.

When a change is required from rectification to inversion, it is necessary to detect when the actual speed exceeds the required speed. When this condition occurs, the polarity of the error voltage changes sign, and the amplifier input has to be switched to accept errors of this reverse sign. In order to initiate this change-over, a reverse-error relay is used, consisting of a two-stage magnetic amplifier whose output feeds a contactor. In order to prevent a hunting of the contactor, the amplifier bias is switched to give a dead zone between pick up and drop-off.

CHAPTER II

ANALYSIS AND PERFORMANCE OF HALF-WAVE RECTIFIER D-C SHUNT MOTOR SYSTEM

(2.1) Equivalent Circuit.

The rotating armature of a d-c motor represents, under steady conditions, a circuit consisting of a resistance R, an inductance L, and an electromotive force E_g generated in the armature winding and acting as a counter voltage, which tends to oppose the flow of current resulting from an external voltage applied to the armature terminals. This generated voltage is proportional to the speed of the motor, under the assumption of constant operating flux. An equivalent circuit of a half-wave rectifier motor-armature system is shown in Fig. 2.1(b). Where the generated electromotive force of the motor is represented by a battery, generating a voltage Eg, and the amature-winding resistance and inductance are represented by a resistor R_a and a reactor L respectively. The controlling resistance is represented by R_c, and the drop across the rectifier and armature - brush contact drop by batteries, generating voltages E_o and E_{br} respectively.

(2.2) Fundamental Equations.[8,9,10,11]

The principles and theory of controlled rectification are of fundamental importance in industrial control in general and the motor control in particular. The two cases of contro-

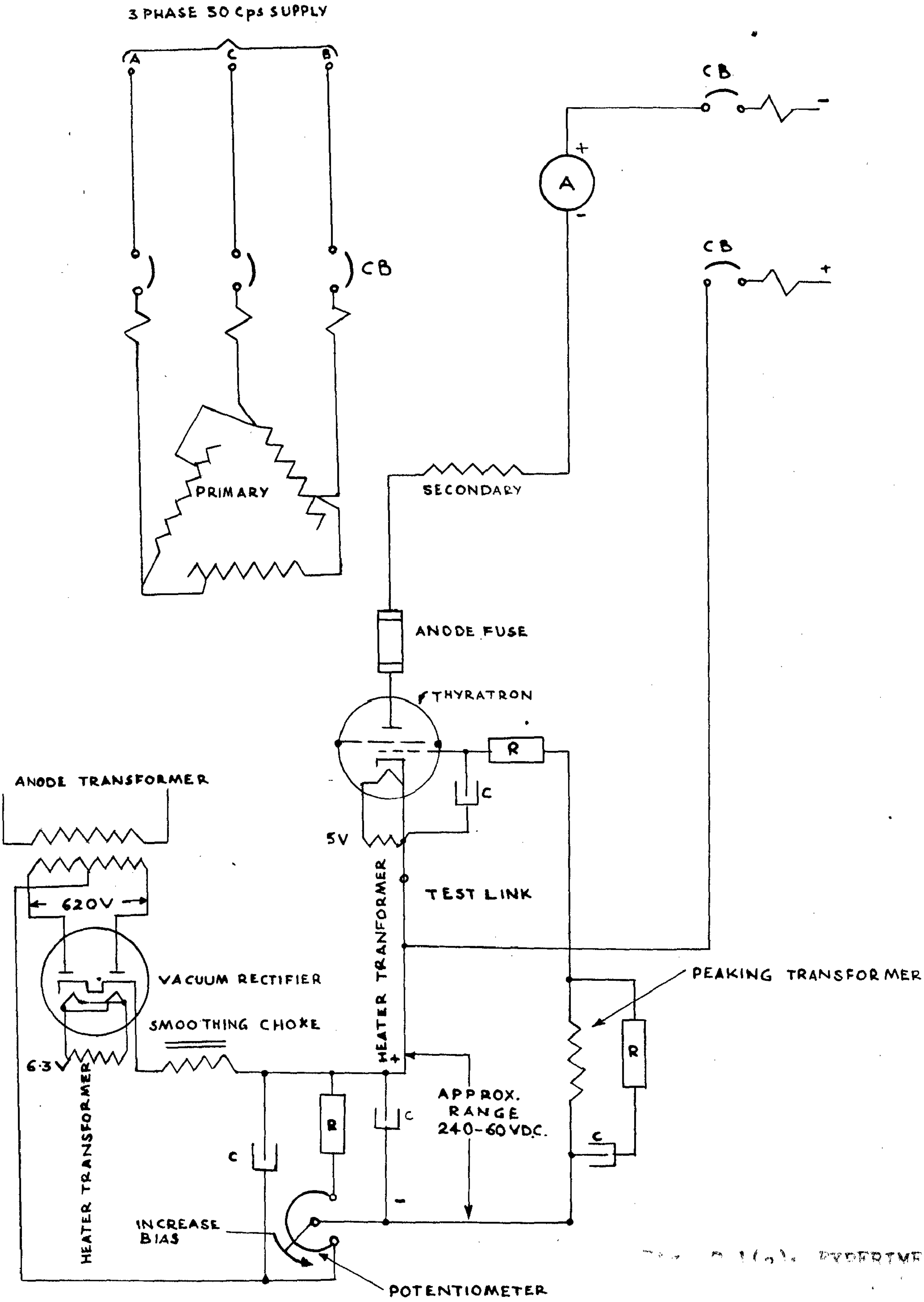
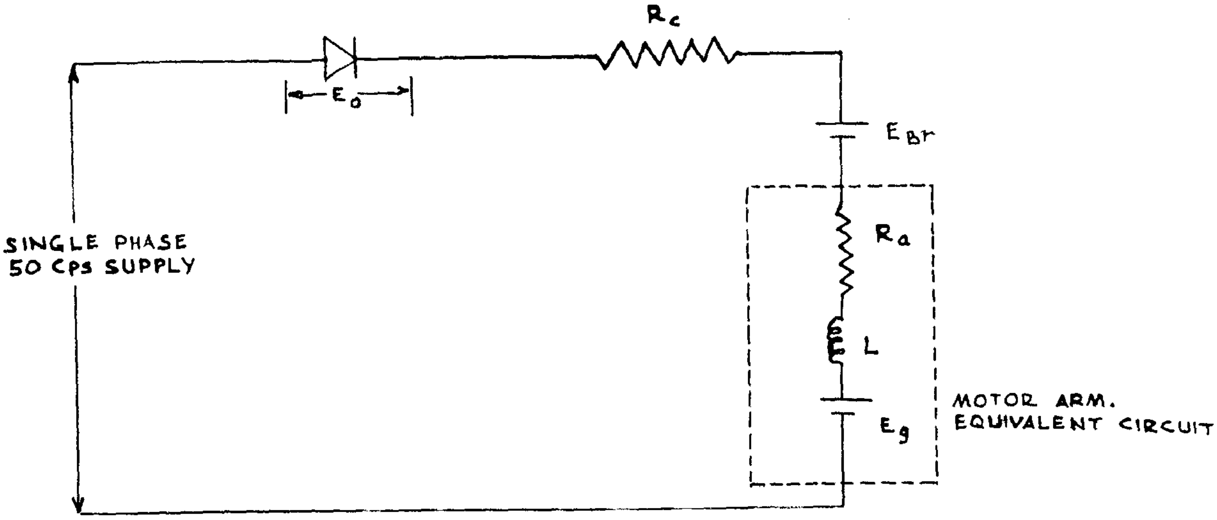
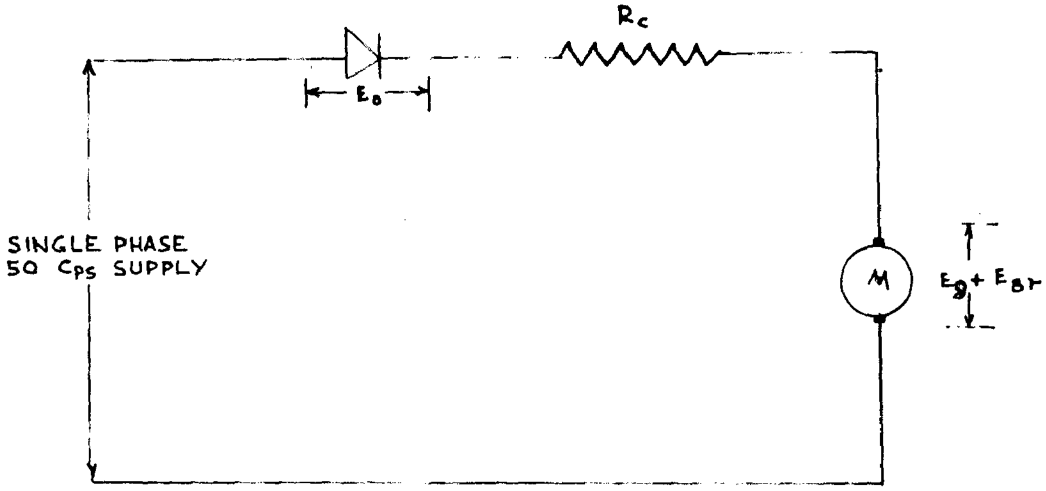


FIG. [illegible].1(a). EXPERIMENTAL


R_c
E_0
E_Br
SINGLE PHASE
50 Cps SUPPLY
R_a
L
E_g
MOTOR ARM.
EQUIVALENT CIRCUIT


R_c
E_0
SINGLE PHASE
50 Cps SUPPLY
M
E_g + E_Br

-lled rectification should be distinguished. The first one is the case of discontinuous load current where the current flowing in the load circuit, and supplied by a rectifier of a single-phase or a polyphase type, consists of discrete pulses with zero-current gaps between them. Discontinuous conduction can be obtained in any rectifier, regardless of the number of phases or in load circuit inductance, if the angle of ignition is sufficiently delayed. The case of discontinuous conduction is of prime importance in electronic motor-control systems in general because the typical feature of these systems is a wide range of control of the angle of ignition of rectifier tubes. Thus, the discontinuity of load current can always be encountered under certain operating conditions. From the theoretical point of view the case of discontinuous conduction is of fundamental importance since the relations and concepts involved in this case can be extended directly to the case of continuous conduction where the load current flows in a continuous manner and there are no zero-current gaps, although the a-c ripple of current may be considerable.

The Fig. 2.2 represents the time function of the anode supply voltage and the load current flowing in the armature of a d-c motor. The graphs are referred to a single rectifying element and, consequently, a single current pulse is shown without reference to neighbouring pulses. In fact, for the case of discontinuous conduction the shape of the current pulse does not depend upon the neighbouring phases, nor upon the number of phases of the rectifier In Fig.2.2, X represents the theoretical zero line of the sinusoidal anode-supply voltage. The voltage may be expressed as

$$e = E_m \text{Sin}\ (wt + \beta) \qquad (2.1)$$

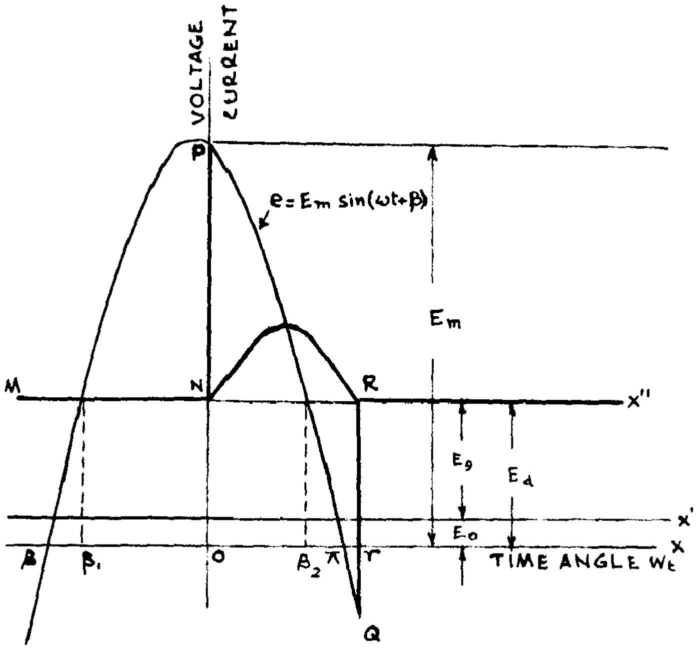


FIG. [illegible] VOLTAGE AND CURRENT TIME FUNCTIONS OF A R[illegible] CAPACITY LOAD [illegible] A SINGLE RECTIFYING ELEMENT.

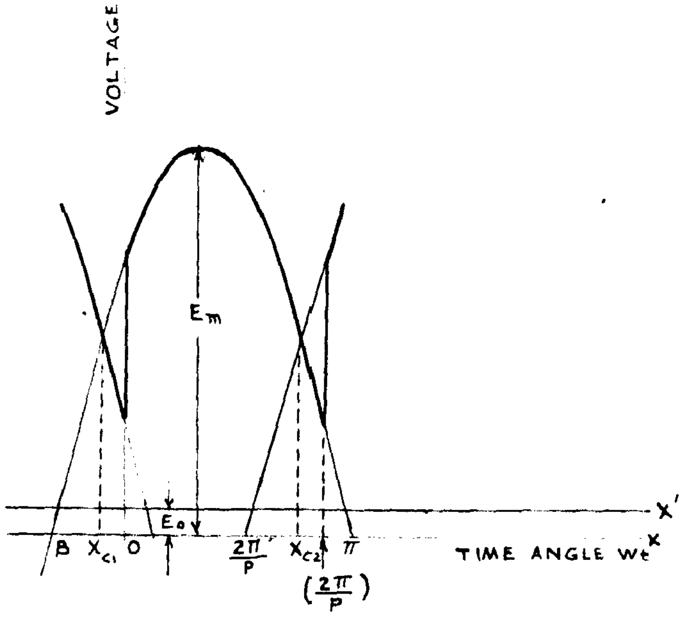


FIG. [illegible] VOLTAGE FOR CONTINUOUS CONDUCTION OF A POLYPHASE RECTIFIER (P = [illegible]).

where $E_m = \sqrt{2}\ E_s$ = peak value of anode voltage
ωt = variable time angle
β = angle of tube break down.

Again E_o is the arc-voltage drop of the rectifying element. This voltage drop may be assumed to be constant and equal to 15 to 20 volts. The brush contact drop may be assumed to be constant and equal to 1 volt at each brush, making two volts in total. The opposing electromagnetic force generated in the armature is represented by E_g. The control grid voltage and the critical grid voltage are not shown in Fig. 2.2. It is readily seen that a portion of the positive half cycle of the anode-supply voltage is used to overcome the sum of $E_o + E_g + E_{br} = E_d$, and that only the portion of the anode voltage rising above the line X'' can produce any current flow in the armature circuit. Thus, the controlled grid voltage and the critical grid voltage should be referred to the zero line X''.

Point N, corresponding to the time angle 0°, represents the point of ignition of the rectifying element, that is, the instant at which the rectifying element starts to conduct. The time angle r corresponding to point R, at which the rectifier stops conducting is called the " angle of extinction" of the rectifier. Thus the rectifying element is conducting over the period r and since the over-all cycle of the rectifying system is equal to $2\pi/p$ (in the most general case. However, for half wave rectifying system $p = 1$), where p is the number of phases, it is apparent that the non-conductive period of the rectifier is equal to $2\pi/p - r$.

If line X' is regarded as representing the potential of the negative terminal of the motor armature, the line MNPQR X'', consisting partially of the zero line X'' and partially of the portion of the a-c anode - supply voltage, will represent the potential of the armature positive terminal, that is, the cathode potential of the rectifier. In other words, the line MNPQR X'' represents the time function of the voltage across the armature with respect to zero line X'.

The equation of the current pulse in the load circuit during the conductive period of the rectifying element is a combination of a sinusoidal and an exponantial function of the time angle wt.

Applying the Kirchoff's second law in the loop consisting the rectifier-motor system (Fig. 2.1(b), the following equation can be written,

$$L \, di/dt + Ri + E_d = E_m \operatorname{Sin} (wt + \beta) \quad .. (2.2)$$

where $R = R_a + R_c$, and $E_d = E_g + E_o + E_{br}$ (2.3)

The complimentary function of Equation 2.2 is given by,

$$C.\ F. = A\, \epsilon^{-R/L\ t} \qquad (2.4)$$

The particular integral is,

$$P.\ I. = \frac{E_m\ R}{R^2 + L^2 w^2} \sin (wt + \beta) - \left[\frac{Lw\ \ E_m}{R^2 + L^2 w^2}\right] \left[\operatorname{Cos}(wt + \beta)\right] - E_d/R$$

$$= E_m/Z \sin (wt + \beta - \theta) - E_d/R \qquad (2.5)$$

where $Z = \sqrt{R^2 + L^2 w^2}$, and $\theta = \tan^{-1} wL/R$

Combining equations 2.4 and 2.5 and applying the conditic that when $t = 0$, $i = 0$, the complete solution of Equation 2.2

is,

$$i = -E_d/R + E_m/Z \sin(wt + \beta - \theta) + \left[E_d/R - E_m/Z \sin(\beta - \theta)\right] \epsilon^{-R/Lw\,(wt)} \qquad \ldots(2.6)$$

The variable time angle " wt" appearing as the independent variable in equation (2.6) is, of course, subject to limitation

$$0 \leq wt \leq r \qquad (2.7)$$

Since it follows from the definition of 0° (firing angle) and r that no current flows through the rectifying element for time angles outside the limits of expression 2.7.

The equation 2.6 can be modified to the form,

$$I = E_m/R \left[\cos\theta \sin(wt + \beta - \theta) - a + \left\{ a - \cos\theta \sin(\beta - \theta) \right\} \epsilon^{-R\,wt/Lw} \right] \qquad \ldots(2.8)$$

where a = voltage coefficient, which also may be called speed coefficient:

$$a = \frac{E_g + E_o + E_{br}}{E_m} \qquad (2.9)$$

The voltage coefficient 'a' has a particular significance. In the case of a rectifier-motor system, if the arc -voltage drop of the rectifier and the brush contact drop are neglected and a constant operating flux in the motor is assumed, coefficient 'a' will be directly proportional to the speed of the motor, as seen from the Equation 2.9. For that reason, 'a' may be called the speed coefficient of the rectifier-motor system.

The fundamental relationship that gives the value of r, for given values of speed coefficient 'a' and the impedance angle of the armature circuit θ, can be derived directly from Eq. (2.8), since for

$$\omega t = r$$

$$i = 0$$

Thus, the relationship for r is

$$\left[a - \cos\theta \sin(r + \beta - \theta) \right] e^{R/L\omega \; r} = a - \cos\theta \sin(\beta - \theta) \qquad \ldots(2.10)$$

Equation 2.10 represents the angle of extinction r and knowing other quantities, it can be found out.

Normally, for making approximate calculations, the inductance value can be assumed to be very small, and so the tube break down angle β is subject to a very definite limitation:

$$\beta_1 < \beta < \beta_2 \qquad (2.11)$$

where β_1 and β_2 denote particular border cases of the angle of tube breakdown, corresponding to the intersection of the zero line X'' with the graph of the anode-supply voltage (Fig. 2.2). The expression for β_1 and β_2 can be readily obtained from the equation of the anode-supply voltage referred to the zero line X''

$$e_a = E_m \operatorname{Sin}(\omega t + \beta) - E_d \qquad (2.12)$$

for the condition:

$$e_a = 0$$

$$\omega t = 0$$

$$\beta_1 = \sin^{-1} E_d/E_m$$

and $\beta_2 = \pi - \beta_1$

Thus we obtain

$$\beta_1 = \operatorname{Sin}^{-1} a \qquad (2.13)$$

$$\beta_2 = \pi - \sin^{-1} a \qquad (2.14)$$

The rectifier output voltage E_{dc} is defined as the average value of that portion of the transformer voltage which appears across the load during the conducting period of the rectifier. Obviously, the averaging is to be extended over the entire cycle of rectification, that is, over the period $2\pi/p$. It can be readily understood that, in the case of continuous conduction with a load consisting of R and L elements only, the rectifier output voltage can be identified with the voltage across the load terminals. However, this assumption is not true when one has to deal with discontinuous conduction of the rectifier, combined with a load circuit containing an electromotive force E_g such as in the case of an armature circuit of a d-c motor.

Fig. 2.2 shows that during the non-conductive period of the rectifier the voltage at the load terminals is equal to the electromotive force E_g generated in he load, whereas the rectifier output voltage during the same period is equal to zero. On the other hand, during the conductive period of the rectifier the load-terminal voltage is, of course equal to the rectifier output voltage. Thus, it is immediately apparent that here the load-terminal voltage E'_{d-c} is higher than the rectifier output voltage E_{d-c}.

In accordance with the previous definiton of the rectifier output voltage, the expression for its average value can be derived directly from Fig. 2.2, by integrating the anode voltage function with respect to zero line X' over the period of conduction 0° to r, and averaging the result over the entire phase cycle $2\pi/p$.

$$E_{d-c} = 1/2\pi/p \int_0^r \left\{ E_m \sin (wt + \beta) - E_o \right\} d\,(wt)$$

$$= p\, E_m/2\pi \left\{ \cos \beta - \cos (r + \beta) - a_o r \right\} \quad ..(2.15)$$

where $a_o = E_o/E_m$ —————— (2.16)

For a single phase half-wave rectifier Eq. 2.15 becomes

$$E_{d-c} = E_m/2\pi \left\{ \text{Cos}\, \beta - \text{Cos}\, (r + \beta) - a_o\, r \right\} \quad (2.17)$$

The average value of the armature voltage drop can be derived from Fig. 2.2 by integrating the voltage function with respect to zero line X'' over the conduction period of the rectifier, r, and averaging the result over the phase cycle $2\pi/p$;

$$I_{d-c}\, R = 1/\frac{2\pi}{p} \int_0^r \left\{ E_m\, \text{Sin}(wt + \beta) - E_d \right\} d(wt)$$

$$I_{d-c}\, R = \frac{p\, E_m}{2\pi} \left\{ \text{Cos}\, \beta - \text{Cos}\, (r + \beta) - a\, r \right\} \quad (2.18)$$

where $a = E_d/E_m = \dfrac{E_g + E_o + E_{br}}{E_m}$

For a single phase half-wave rectifier Equation 2.18 becomes

$$I_{d-c}\, R = E_m/2\pi \left\{ \text{Cos}\, \beta - \text{Cos}\, (r + \beta) - a\, r \right\} \quad (2.19)$$

The exact average value of the armature voltage drop can be obtained by integrating Equation (2.8), over the conduction period of the rectifier, r, and averaging the result over the phase cycle $2\pi/p$;

$$I_{d-c}\,R = \frac{p\,E_m}{2\pi}\left[\cos\theta\left\{\cos(\beta-\theta) - \cos(r+\beta-\theta)\right\} - a\,r + \left\{a - \cos\theta\,\sin(\beta-\theta)\right\}\left(1-\varepsilon^{-R/Lw\,r}\right)\tan\theta\right] \quad \ldots(2.20)$$

For a single phase half-wave rectifier,

$$I_{d-c}\,R = \frac{E_m}{2\pi}\left[\cos\theta\left\{\cos(\beta-\theta) - \cos(r+\beta-\theta)\right\} - a\,r + \left\{a - \cos\theta\,\sin(\beta-\theta)\right\}\left\{1-\varepsilon^{-R/Lw\,r}\right\}\tan\theta\right] \quad \ldots(2.21)$$

The average value of the direct voltage at the armature terminals E_{dc}' is, of course, equal to the sum of the counter electromotive force E_g and the armature voltage drop $I_{dc}\,R$:

$$E_{dc}' = E_g + I_{dc}\,R$$

Thus, from Equation (2.18)

$$E_{dc}' = \frac{p\,E_m}{2\pi}\left\{\cos\beta - \cos(\beta+r) - a\,r + a'\,2\pi/p\right\} \quad (2.22)$$

In case of single phase half-wave rectifier

$$E_{dc}' = \frac{E_m}{2\pi}\left\{\cos\beta - \cos(\beta+r) - a\,r + a'\,2\pi\right\} \quad (2.23)$$

where $a' = E_g/E_m$ (2.24)

The exact value of E_{dc}' can be obtained by adding E_g to the value of $I_{d-c}\,R$ obtained from Eq. 2.20 or Eq. 2.21 in the cases of p phase and single phase half-wave rectifiers respectively.

Equations 2.18 to 2.23 are general equations of controlled rectification, and considering equation (2.27), their validity extends to all the cases of continuous and discontinuous conduction of the rectifier, and to any combination of R, L, and E_g in the load circuit. Most of the conventional forms of expressions for average values of load voltages and currents can be derived directly from equations 2.18 to 2.23.

When the motor is stalled, $E_g = 0$ and, in that case,

$a' = 0$ (see equation 2.24)

Also, from equations 2.9 and 2.16 neglecting E_{br}.

$$a = a_o = E_o / E_m$$

Thus, if becomes apparent from equations 2.15, 2.18, and 2.22 that for a stalled motor.

$$E_{dc} = E'_{dc} = I_{dc} R = \frac{p E_m}{2\pi} \left[\text{Cos } \beta - \text{Cos } (\beta + r) - a_o r \right] \quad \text{...(2.25)}$$

For a single phase half-wave rectifier-motor system

$$E_{dc} = E'_{dc} = I_{dc} R = \frac{E_m}{2\pi} \left[\text{Cos } \beta - \text{Cos}(\beta + r) - a_o r \right] \quad (2.26)$$

In the case of " continuous conduction" of the rectifier (Fig. 2.9) the relationship between the angles of ignition and extinction (neglecting the rectifier-transformer leakage reactance) is

$$r = 2\pi/p \quad (2.27)$$

By substituting equation 2.27 in equations 2.15, 2.18, and 2.22, we obtain, for the case of continuous conduction,

$$E_{dc} = E'_{dc} = \frac{p E_m}{2 \pi} \left[\text{Cos } \beta - \text{Cos}(\beta + \frac{2\pi}{p}) - a_o \frac{2\pi}{p} \right] \quad (2.28)$$

$$\text{and} \quad I_{dc} R = \frac{p E_m}{2\pi} \left[\text{Cos}\ \beta - \text{Cos}(\beta + 2\pi/p) - a\ 2\pi/p \right] \qquad (2.29)$$

Further, neglecting the rectifier - arc drop ($a_o = 0$), and introducing the relationship between the angle of tube break down β and the angle ϕ of the delay of ignition beyond the natural commutating points X_{c1}

$$\phi = X_{c1} \qquad \text{(see Fig. 2.3)}$$

$$\phi = \frac{p\pi - 2\pi}{2p}$$

Equation 2.28 for the rectifier output voltage can be directly transformed into the conventional form, valid only for the continuous conduction.

$$E_{dc} = E_m\ p/\pi\ \text{Sin}\ \pi/p\ \text{Cos}\ \phi \qquad (2.30)$$

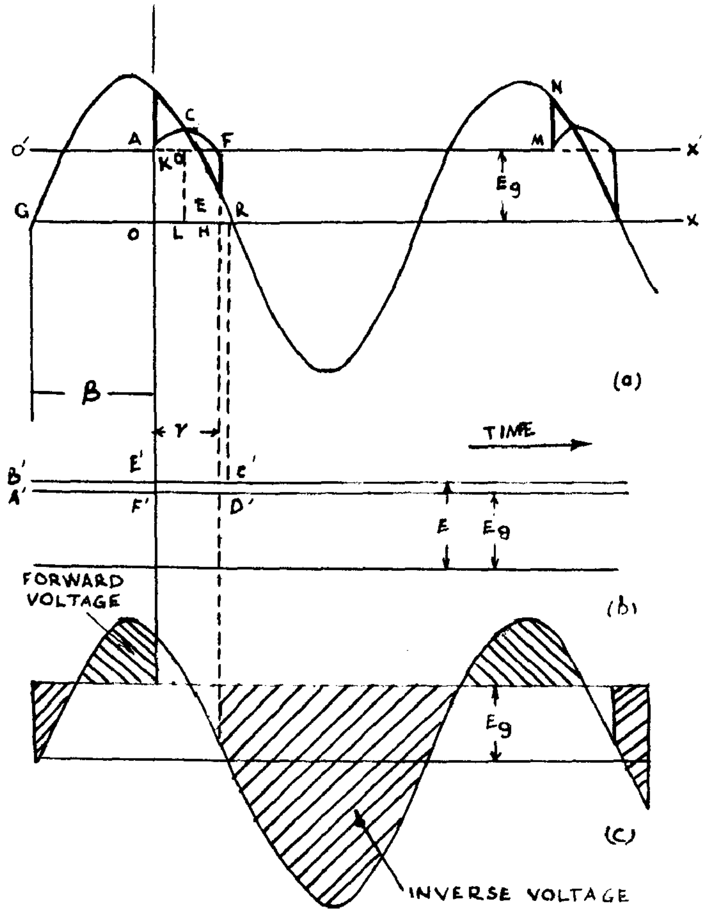
Thus, the special form of equation 2.30 can be derived directly from the general equation 2.22. It should be pointed out that, in contrast with equation 2.22, coefficients 'a' and 'a'', which depend upon motor speed, do not appear in equation 2.28, and equation 2.30. Thus, for continuous conduction the armature voltage is not affected by the speed of the motor.

(2.3) Load Characteristics of Half-Wave Rectifier D-C Shunt Motor System[8,10,15]

The graphical method of the qualitative analysis of characteristics will be used first, since it will help to clarify a number of concepts and explain the typical behaviour of the system.

In Fig. 2.4(a) are shown graphs of voltages and currents, represented as functions of the variable time angle ωt , for a

Fig. [illegible] TIME POSITIONS OF ARMATURE CURRENT, ARMATURE E.M.F. ARMATURE VOLTAGE DROP FOR SINGLE PHASE HALF WAVE RECTIFIED DRIVE.



Note: Shaded area represents the voltage across rectifier tube, Arc voltage drop neglected.

(a) Single phase half-wave rectifier drive
(b) D.C. Motor
(c) Time function of voltage across the rectifying element. Arc voltage drop is neglected.

motor whose armature is supplied by a single phase half-wave rectifier (p = 1) with a delayed angle of ignition. Fig. 2.4(b) shows analogous conditions for a conventional d-c drive, and in Fig. 2.4 (c) rectifier tube voltages (voltage appearing across the rectifying element) are specially emphasized. For the sake of simplification of the diagrams, the rectifier-tube arc-voltage drop and brush contact drop have been neglected in Fig. 2.4. In Fig. 2.4(a) and 2.4(c) is shown one sinusoidal anode - supply voltage for rectifier tube. It is assumed that the motor is running at constant speed; the counter electromotive force E_g generated in the armature winding is represented by line X'.

The tube starts to conduct at point A, Fig. 2.4(a), and at that instant the instantaneous voltage across the armature is represented by BO. At the instant when the rectifying elemement starts to conduct, the current is still zero, since the inductance of the armature winding prevents the current from rising immediately. If the instantaneous values of current are plotted in voltage scale as the iR drop with respect to zero line X', a pulse ACF will be obtained.

The iR -drop pulse will reach its peak at point C, where it intersects the anode-supply-voltage wave. At point D, where the a-c supply voltage intersects the line of E_g (line X'), there is no external voltage to cause the flow of current in the armature and, if the armature winding had a purely resistive character (Cos θ = 1), the current would stop flowing at that point. In other words, in the idealized case of a non-inductive armature winding the armature current plotted in scale of iR drop would follow the shape of the a-c anode-supply voltage ABD. The inductance of the armature circuit, which prevents the current from rising sharply at the point of ignition A, also prevents the current from dying out at point D, where the external voltage causing the current flow is equal to zero. The electromotive force of inductance keeps the current flowing up to point F.

The general circuit equation

$$e = iR + L\ di/dt + E_g \qquad (2.31)$$

can be interpreted graphically in the following manner [See fig. 2.4(a)].

At the point of ignition A the instantaneous supply voltage $e = BG$ consists of two components: component $AG = E_g$ balances the counter electromotive force E_g generated in the armature winding of the motor, component $BA = L\ di/dt$ constitutes the inductive voltage drop in the winding; that is, it balances the electromotive force of inductance ($-L\ di/dt$) opposing the flow of current. The resistance drop iR is equal to zero since $i = 0$. At point K, where he current reaches its maximum, $L\ di/dt = 0$, and the supply voltage $e = CL$ consists of two components $CK = iR$ and $KL = Eg$. Beyond point K, where the armature current starts to decrease the electromotive force of inductance changes its sign and acts in the direction to maintain the flow of current in the circuit, so that, when the external voltage ($e - E_g$) changes its sign at point D, the current is maintained by the electromotive force, $- L\ di/dt$. At point F, where the rectifying element stops to conduct, the electromotive force of inductance is just equal to FE, that is, to the difference of the counter electromotive force $FH = E_g$ and the supply voltage $e = EH$.

During the conductive period AF of the rectifying element, Fig. 2.4(a), the voltage at the armature teminals will, of course, follow the anode-supply voltage along the portion BDE of the sinusoidal voltage wave. During the non-conductive period of the rectifier the voltage at the armature terminals will be equal to the electromotive force generated in the armature winding. Although this electromotive force cannot produce any current in the load circuit because of the rectifier, it will appear across the armature terminals and will fully effect the reading of any voltage-measuring instrument. Thus, the actual voltage existing at the armature terminals will follow the line O'ABCEFMN with respect to the zero line X.

The average value of armature current, proportional to the average value of armature voltage drop (see Eq.2.18), is directly proportional to the difference of area ABD and area DFE, Fig. 2.4(a). The instantaneous torque, proportional to the instantaneous value of armature current will, of course, follow the graph of the current and will have a pulsating character. However, owing to the moment of inertia of the motor armature and of all the other rotating parts coupled to the motor shaft, the instantaneous speed will not vary appreciably, and E_g can be assumed as being constant for a given average speed.

If the load torque at the shaft of the motor is increased, the system must respond by an increased current in the armature. It is obvious from Fig.2.4(a) that the increase in current can be obtained either by advancing the angle of ignition (represented by OG) or by decreasing the value of the counter electromotive force E_g(decreasing speed). If it is assumed that the angle of tube breakdown (OG) remains unchanged, the increase in torque (or current) will result in a corresponding decrease in the counter electromotive force E_g. The same is, of course, true for a conventional d-c drive, whose armature voltage and counter electromotive force are shown in Fig. 2.4(b), but the extent to which E_g (that is, speed) will have to decrease for a given increase in torque is different in each case.

The speed of a shunt-wound motor can be expressed by

$$n = \frac{E - IR}{C_1 \phi} \qquad (2.32)$$

where n = speed of motor

E = armature voltage

I = armature current

R = resistance of armature circuit

ϕ = operating magnetic flux

C_1 = coefficient of proportionality

Assuming constant voltage E applied to the armature, and a constant operating flux ϕ, the speed of the motor will decrease with increasing current (torque) because of the armature voltage drop IR.

Equation 2.32 also can be applied in the case of a rectifier drive under the assumption that both E and I are average values of periodical functions shown graphically in Fig.2.4(a). Yet there is a basic difference between the two cases because for a d-c motor system the voltage at the armature terminals does not depend upon the electromotive force E_g, speed, or load (disregarding the possible line voltage drop), whereas in the case of a rectifier drive with constant angle of ignition and discontinuous current flow, the armature voltage E_{dc}' depends upon the electromotive force E_g, speed n, and load current I_{dc} of the motor.

Referring again to equation 2.32, it becomes apparent that the droop of the speed-torque characteristic must be considerably greater for the rectifier drive with discontinuous armature current because not only is the armature voltage drop IR increasing with load, but there also the armature voltage is decreasing at the same time.

The effect of E_g on the armature voltage is also apparent from equation 2.22 where both 'a' and 'a'' are functions of E_g.

The speed-torque characteristics of a rectifier drive, for a given angle of ignition and a given impedance angle of the armature circuit, can be calculated from equations 2.18 and 2.29. Equations 2.18 and 2.29 can be rewritten as follows. For discontinuous conduction

$$t_f = \frac{I_{dc}\, R}{E_m} = \frac{p}{2\pi} \left\{ \mathrm{Cos}\,\beta - \mathrm{Cos}(r + \beta) - a\, r \right\} \quad (2.33)$$

For continuos conduction

$$t_f = \frac{I_{dc}\, R}{E_m} = \frac{p}{2\pi} \left\{ \mathrm{Cos}\,\beta - \mathrm{Cos}\,(\beta + 2\pi/p) - a\, 2\pi/p \right\} \quad ..(2.34)$$

For half-wave rectifier d.c. motor system equation 2.33 becomes

$$t_f = 1/2\pi \left\{ \mathrm{Cos}\,\beta - \mathrm{Cos}\,(r + \beta) - a\, r \right\} \quad (2.35)$$

The expression $t_f = I_{dc}\, R/E_m$, representing the ratio of the armature voltage drop and the peak value of the rectifier-supply voltage, can be called the "torque factor" of the drive because it is directly proportional to the average armature current and to the average torque developed by the motor, if it is assumed that the operating field remains constant. This simplifying assumption is, of course, only approximately correct since the main flux will vary with load to certain extent because of the armature reaction. The torque factor as well as the speed factor 'a'' appearing in equations 2.33 and 2.34, is always less than unity

$$0 < t_f < 1$$

$$0 < a < 1$$

The equation for the motor armature voltage of a rectifier drive is equation 2.22. Now, a typical graph of the armature voltage as a function of current or torque may be calculated and plotted on the basis of values of speed coefficient 'a" and torque coefficient t_f.

Dividing both sides of equation

$$E_{dc}' = E_g + I_{dc}R \qquad (2.36)$$

by the peak value of the rectifier transformer voltage E_m,

$$E_{dc}' / E_m = E_g/E_m + I_{dc} R/E_m \qquad (2.37)$$

The ratio of the armature voltage E_{dc}' and the peak value of the rectifier-transformer phase voltage may be called the armature-voltage coefficient; it will be denoted by v_a. This coefficient of course, is directly proportional to the armature voltage:

$$v_a = \frac{E_{dc}'}{E_m} \qquad (2.38)$$

Considering equations 2.24 and 2.33, equation 2.37 can be represented as

$$v_a = a' + t_f \qquad (2.39)$$

Or

$$a' = v_a - t_f \qquad (2.40)$$

Analogous theoretical speed-torque characteristic for a conventional direct-voltage drive also can be represented in terms of speed and torque coefficients. Dividing both sides of equation

$$E_g = E - IR \qquad (2.41)$$

by the supply voltage which is equal to the armature voltage E,

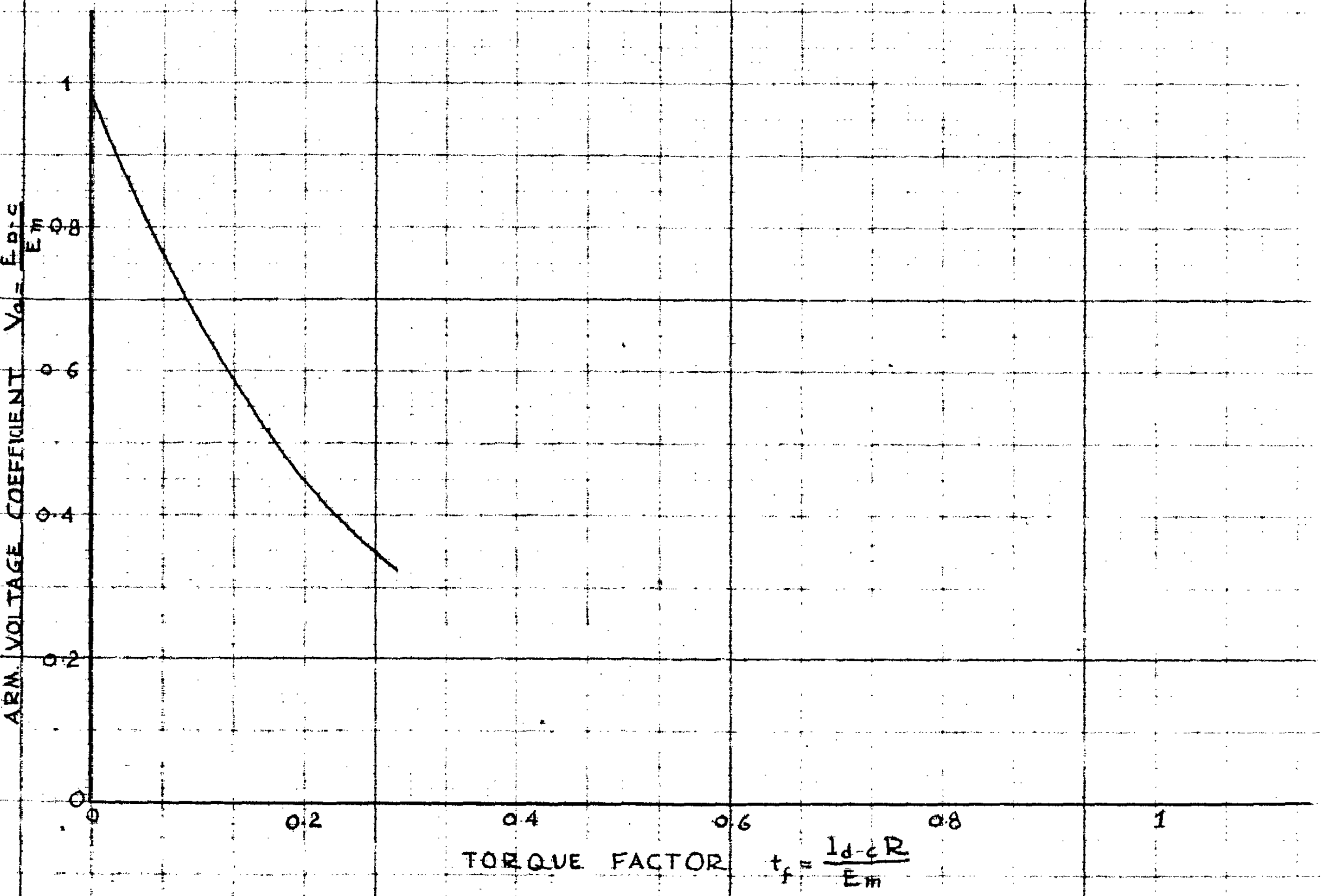


FIG. 2.5 (a) THEORETICAL VOLTAGE-TORQUE CHARACTERISTIC OF D.C. SHUNT MOTOR ON HALF WAVE RECTIFIED POWER

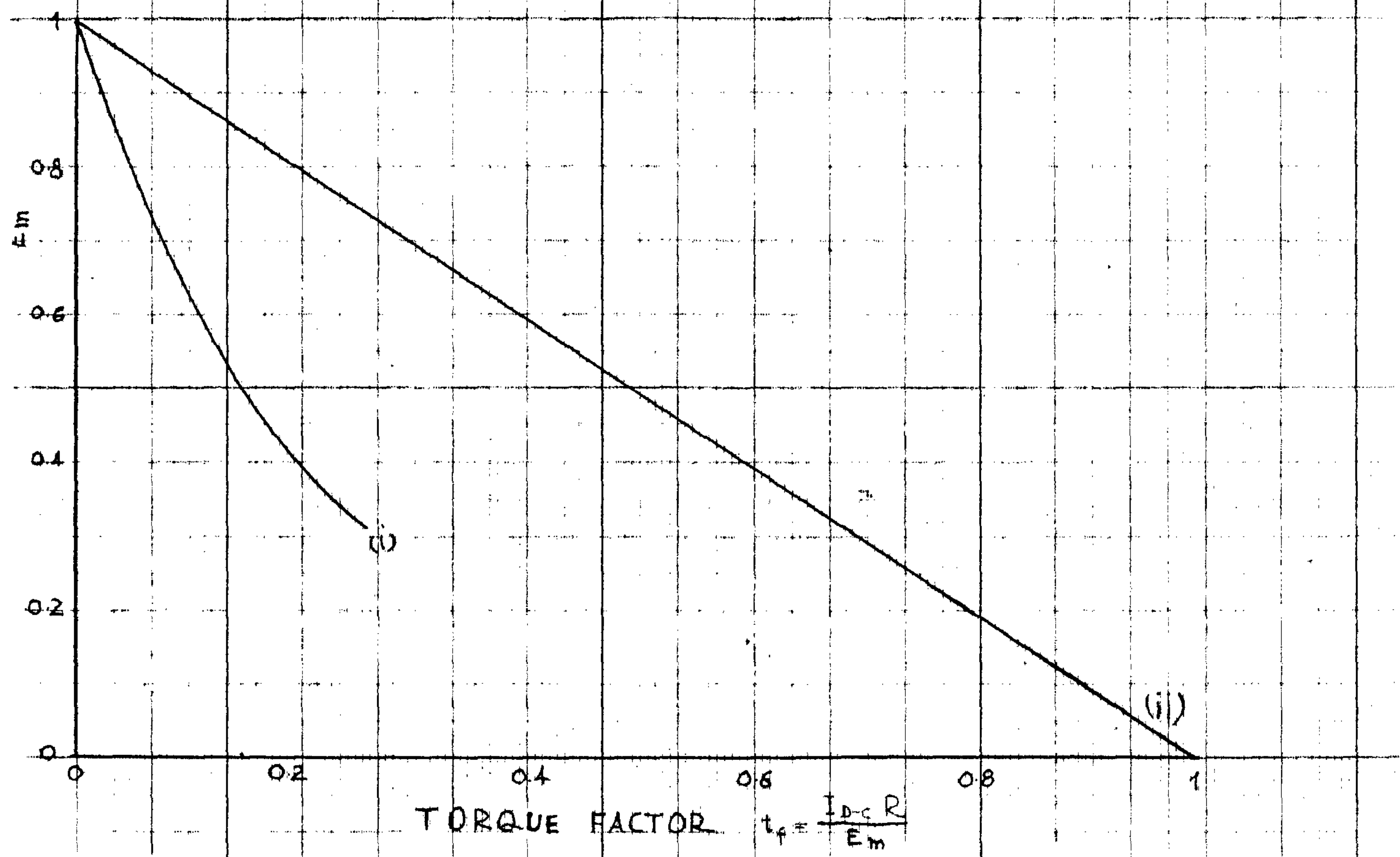
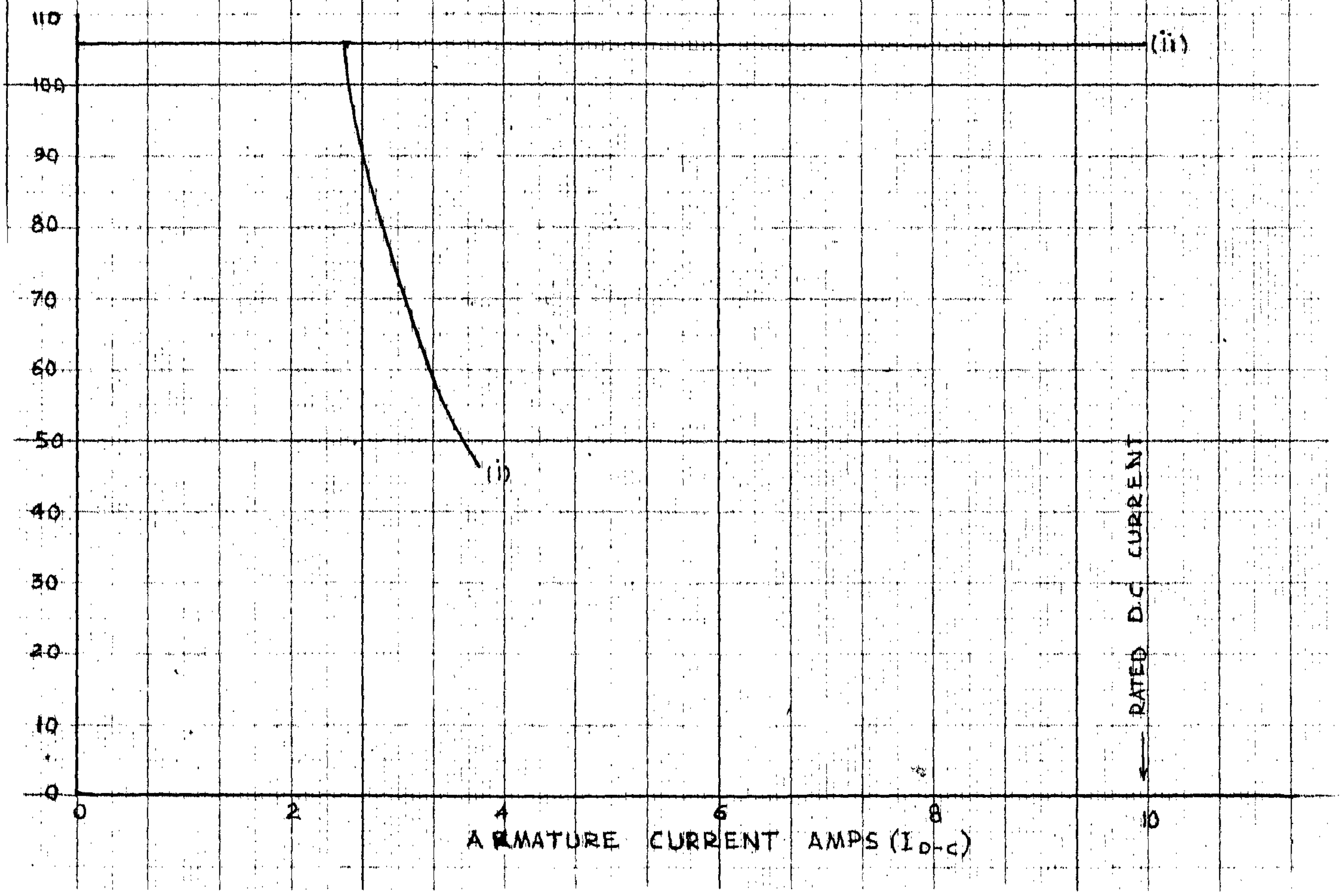


FIG 2.5 (b) THEORETICAL SPEED-TORQUE CHARACTERISTICS OF
(i) D.C. SHUNT MOTOR ON HALF-WAVE RECTIFIED POWER
(ii) D.C. SHUNT MOTOR ON D.C. SUPPLY

FIG 2.6(a) VOLTAGE-CURRENT CHARACTERISTICS OF
(i) D.C. SHUNT MOTOR ON HALF-WAVE RECTIFIED POWER
(ii) D.C. SHUNT MOTOR ON D-C SUPPLY



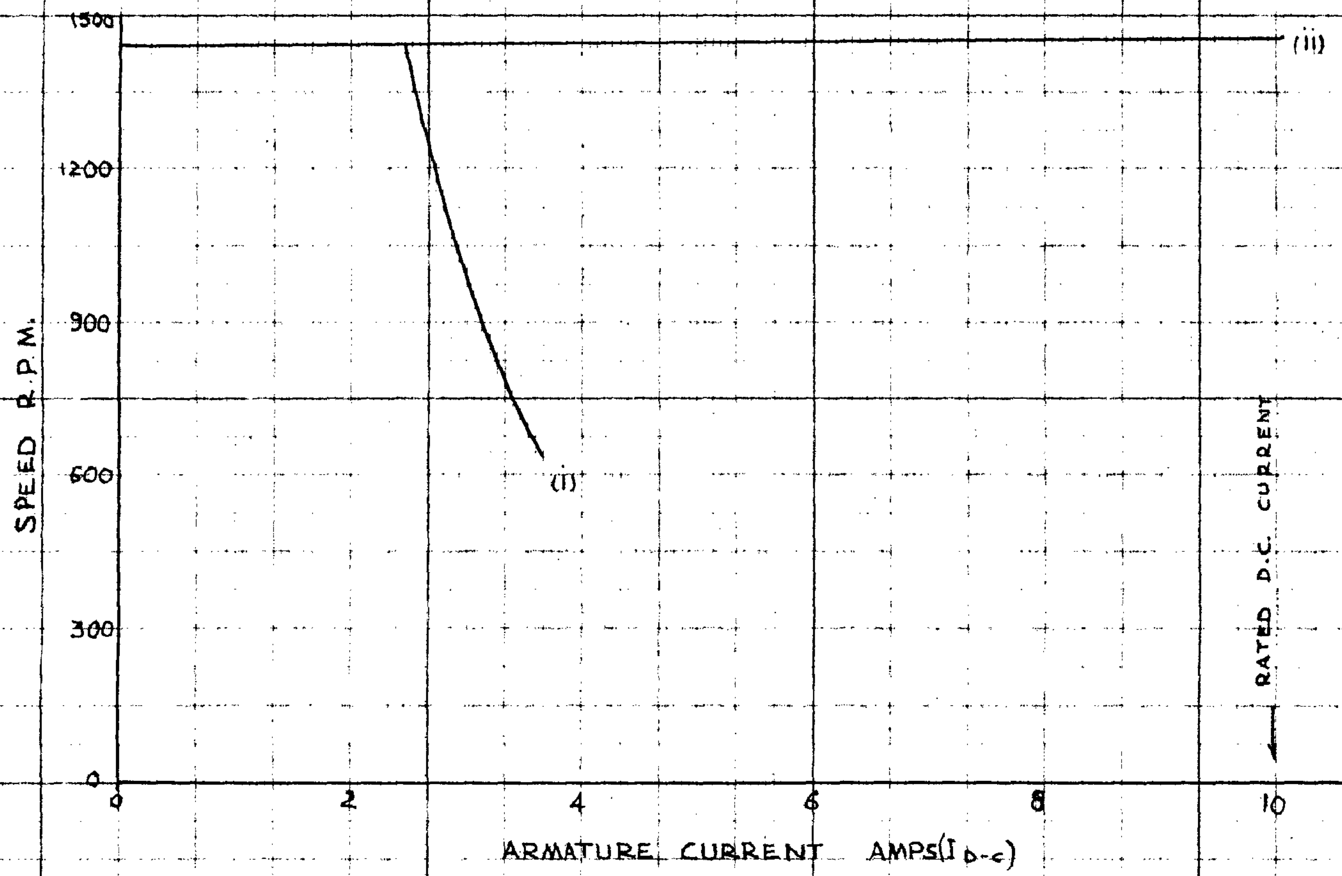


FIG 2.6 (b) SPEED-CURRENT CHARACTERISTICS OF

(i) D.C. SHUNT MOTOR ON HALF WAVE RECTIFIED POWER
(ii) D.C. SHUNT MOTOR ON D.C. SUPPLY. (THEORETICAL CHARACTERISTIC)

$$E_g/E = 1 - IR/E \qquad (2.42)$$

From Equation 2.42,

$$a_{dc} = 1 - t_{fdc} \qquad (2.43)$$

where $a_{dc} = E_g/E$ = speed coefficient

and $t_{fdc} = IR/E$ = torque coefficient.

It will be noted that Equation 2.43 is analogous to equation 2.40 . Since for a conventional d-c drive the armature voltage is equal to the supply voltage, the armature voltage coefficient v_{ad-c} is equal to unity.

Figures 2.5(a) and 2.5(b) show the theoretical speed-torque and voltage-torque characteristics both for d-c motor and the half-wave rectifier d-c motor system. Actually the curves obtained by experimental methods in the two cases were rather coincident with those calculated and it was not possible to show them very distinctly from each other. It can be seen that the half-wave rectifier d-c motor system has the drooping speed and armature voltage characteristics with the increase in torque.

Figures 2.6(a) and (2.6(b) show the speed-current and armature-voltage characteristics in case of both the systems. These experiments were performed on a 110 V, 10 amps, 1400 r.p.m.,1.25 h.p. d-c motor. For this E_m = 460 Volts, $\theta = 7^\circ$, $\beta = 14.7^\circ$, and the generated back emf in armature winding at rated speed and excitation was E_g = 100 volts. The tube drop E_c and brush contact drop E_{br} were taken 15 and 2 volts respectively.

(2.4) Instantaneous-Peak value and Form Factor of the Armature Current

It is important to note that the current in the armature of the motor always has a pulsating character so that the a-c component of the current wave is very considerable, even when there is continuous conduction.

There are three important concepts of the current and these are: the average value, the instantaneous-peak value, and the r.m.s. value of the armature current. The average value or the d.c. value of armature current determines the average torque and the horsepower developed by the motor, and appears in all conventional calculations. The instantaneous-peak value of armature current is of vital interest from the point of view of behaviour and proper selection of the main power-rectifier tubes. The controlled-rectifier tubes of the thyratron type are particularly sensitive to instantaneous peak currents, and if the peak currents exceed the rated value for a given type of tube, the tube may be permanently damaged.

In the half-wave polyphase rectifiers the peak value of current that is assigned to any tube is much less than the peak value of load current, because,

$$I_{tube} = \frac{I_{load}}{p} \qquad (2.44)$$

In order to determine analytically the instantaneous-peak value of the armature-current pulse, the time angle corresponding to the maximum of the current-time function should be found first. By differenciating the equation of the current pulse (equation 2.8) with respect to time angle wt, and further equating the result to zero, the equation for the time angle x_m corresponding to the maximum value of the current pulse is obtained:

$$\text{Cos}(x_m + \beta - \theta)\, \epsilon^{R\, x_m /Lw} = a/\text{Sin}\ \theta - \frac{\text{Sin}(\beta - \theta)}{\tan\ \theta} \quad ..(2.45)$$

Equation 2.45 represents the relationship between the peak-current angle x_m and the angle of tube breakdown β, that is, it represents x_m as an implicit function of β for different values of parameters 'a' and 'θ'.

Considering the peak-current angle x_m as represented by equation 2.45, the expression for the peak value of the armature-current pulse can be obtained directly from equation 2.8:

$$I_m = E_m/R \left[\text{Cos}\ \theta\ \text{Sin}(x_m + \beta - \theta) - a + \left\langle \left\{ a - \text{Cos}\ \theta\ \text{Sin}(\beta - \theta) \right\} \right\rangle (\epsilon^{-R/Lw\ x_m}) \right] \quad ..(2.46)$$

where $x_m = f(\beta)$ may be calculated from equation 2.45

Whereas equations 2.45 and 2.46 represent rigorous analytical relationship, in some cases a simpler approximate formula for instantaneous-peak value of the load current for discontinuous conduction may prove more useful[10.]:

$$I_m = \frac{\pi^2\ I_{dc}}{\sqrt{2\pi p\ r}} \qquad (2.47)$$

In case of single phase half-wave rectifier equation 2.47 modifies to:

$$I_m = \frac{\pi^2\ I_{dc}}{\sqrt{2\pi\ r}} \qquad (2.48)$$

In equations 2.47 and 2.48

I_{dc} = average value of the load current

p = number of phases of rectifier

r = angle of extinction in radians.

It will be recalled that the angle of extinction r can be calculated from equation 2.10.

The approximate formula for I_m, equation 2.47 or 2.48, can be derived under the simplifying assumption of a purely sinusoidal wave shape of each current pulse and a symmetrical location of its instantaneous peak. Although the above assumption, strictly speaking, is incorrect, the approximate formula 2.47 is useful for estimating purposes, particularly in the vicinity of the critical angle of ignition.

From the approximate formula for the instantaneous-peak current, equation. 2.47, one can obtain directly the approximate expression for the so-called " peak-coefficient" which is defined as the ratio of peak and average currents, and represents a convenient way of describing the peak-current conditions in the load circuit of a rectifier[10.]:

$$f_m = I_m / I_{dc} = \frac{\pi^2}{\sqrt{2 \pi p r}} \qquad (2.49)$$

and for a single phase half-wave rectifier

$$f_m = \frac{\pi^2}{\sqrt{2 \pi r}} \qquad (2.50)$$

The third significant value of the armature current is the rms value. The rms value of current is responsible for the losses in the armature winding of the motor and must be used in the well-known formula I^2R, which determines these losses. Thus, the rms value of current has a direct effect on the frame size and efficiency of the motor. In a conventional d-c drive, where a pure d-c current flows through the brushes of the motor, the average current is equal to the rms value of current. In a rectifier drive, however, the presence of a considerable a-c component in the unidirectional armature current is responsible for the increase in the rms value, which is always higher here than the average value. Consequently, the efficiency of the motor is decreased so that very often the motor-frame size must be increased to dissipate additional losses, without an excessive size of temperature. Moreover, the rms value of current is closely related to the instantaneous-peak value and, for the same average current, both increase or decrease simultaneously.

The exact rms value of current for a single phase half wave system can be found by the help of equation 2.8. The rms value is given by

$$I_{rms} = \sqrt{\frac{1}{2\pi} \int_0^r i^2 \, d(wt)} \qquad (2.51)$$

where

$$R^2/E_m^2 \int_0^r i^2 \, d(wt) = a^2 r + \left[r - 1/2 \left\{ \mathrm{Sin}\, 2(r+\beta-\theta) - \mathrm{Sin}\, 2(\beta-\theta) \right\} \right] \mathrm{Cos}^2\, \theta$$

$$- \frac{A^2 \frac{Lw}{2R}}{} \left\{ e^{-2R/Lw\, r} - 1 \right\}$$

$$+ 2\, a\, \mathrm{Cos}\, \theta \left\{ \mathrm{Cos}\, (r + \beta - \theta) - \mathrm{Cos}\, (\beta - \theta) \right\}$$

$$+ \frac{2A\, aLw}{R} \left[e^{-R/Lw\, r} - 1 \right]$$

$$+ 2A \frac{L^2 w^2}{R^2} \mathrm{Cos}\, \theta \left[\mathrm{Cos}\, (\beta - \theta) + R/Lw\, \mathrm{Sin}\, (\beta - \theta) - e^{-R/Lw\, r} \left\{ \mathrm{Cos}(r+\beta-\theta) + \frac{R}{Lw} \mathrm{Sin}(r+\beta-\theta) \right\} \right]$$

here

$$A = \left\{ a - \mathrm{Cos}\, \theta\, \mathrm{Sin}\, (\beta - \theta) \right\}$$

In rectifier-motor systems it is customary to deal with the " form factor" of the armature current, defined as the ratio of the rms value to the average value:

$$f_f = \frac{I_{rms}}{I_{d-c}} \qquad (2.52)$$

Thus, the form factor is indicative of additional motor losses, as well as of the character of commutation for a given load current of the motor. An approximate simplified formula for the form factor of the armature current for discontinuous and continuous conduction of the rectifier, based on the assumption of a purely sinusoidal symmetrical pulse, is given below, and may be used for estimating purposes.[9.]

$$f_f = \frac{\pi^2}{2\sqrt{\pi p r}} \qquad (2.53)$$

for a single phase half-wave system,

$$f_f = \frac{\pi^2}{2\sqrt{\pi r}} \qquad (2.54)$$

The exact value of the form factor for single phase half-wave system can be obtained by the help of equations 2.21 and 2.52.

For the border case, dividing discontinuous and continuous conduction of the rectifier each rectifying element conducts over the entire phase cycle equal to $2\pi/p$; hence

$$r = 2\pi/p \qquad (2.55)$$

when equation 2.55 is substituted in equation 2.53, the form factor for the border case, becomes

$$f_{fb} = \frac{\pi}{2\sqrt{2}} = 1.11 \qquad (2.56)$$

For the case of discontinuous conduction, the form factor is always greater than 1.11, and for the case of continuous conduction the form factor of the load current is always less than 1.11:

$$f_{f\ disc} > 1.11$$

$$1 < f_{f\ cont} < 1.11 \qquad (2.57)$$

Obviously, for the theoretical border case of a pure direct load current, the form factor is equal to unity.

(2.5) Results of Waveform Analysis

The different important quantities of the current waveform were calculated by means of different formulae given in the above sections and they were compared with those obtained by experimental results. Throughout the test the d.c. excitation of the motor was kept constant. The various parameters of the system were:

E_m = 400 volts, E_g (at rated speed and excitation) = 100 V.,
E_{br} = 1 volt at each brush, E_0=15 Volts, $\theta = 7^\circ$, $\beta = 14.7^\circ$

For the sake of only comparing the results obtained by the two methods, only the results at no load were compared. The waveforms of current obtained by theoretical methods and experimental observation are shown in fig.2.7(a) and 2.7(b). It can be seen that they are quite similar to each other. However, the initial rate of rise of current is slower in the actual case due to added inductance of transformer etc. which has not been taken into account in the theoretical result.

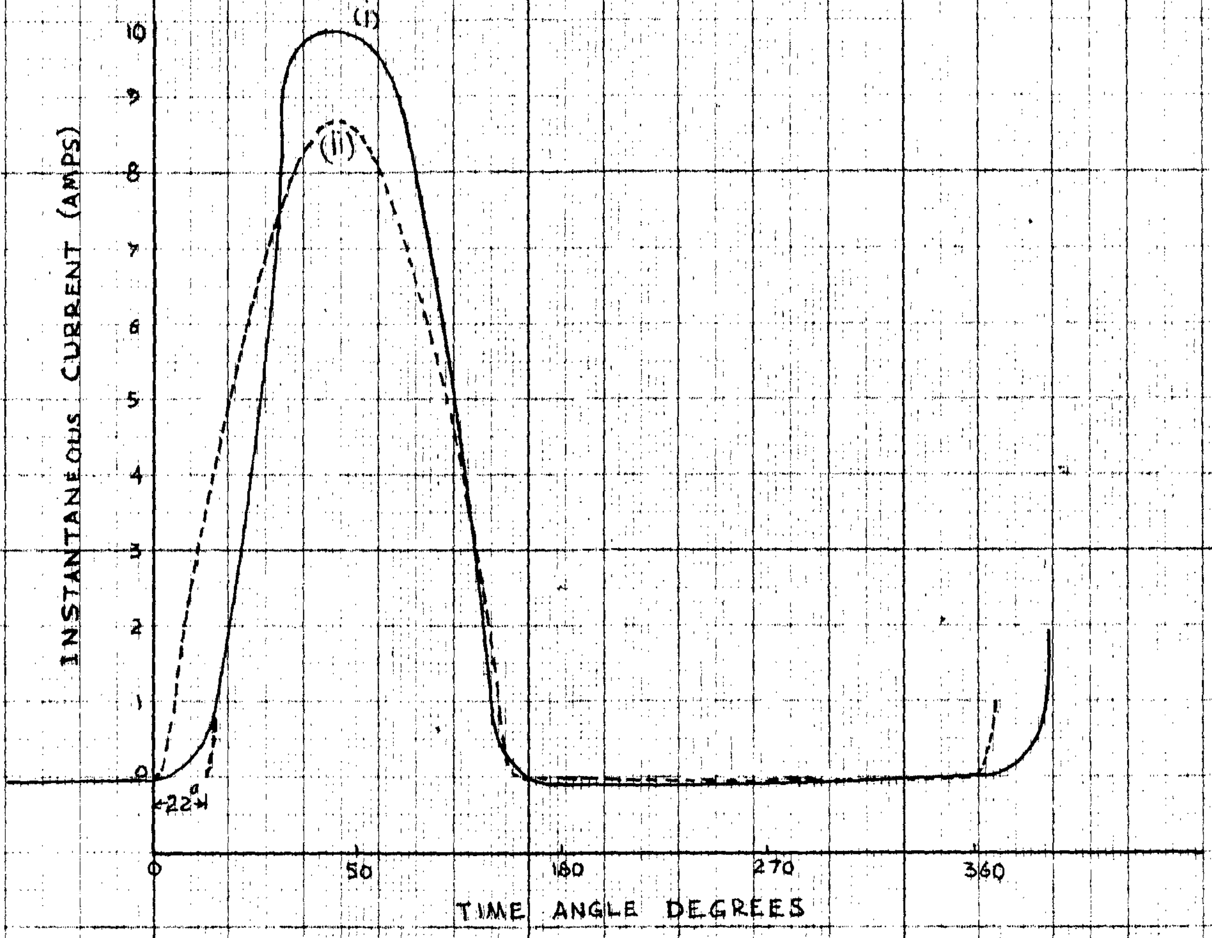


FIG 2.7(d) CURRENT WAVE FORMS

(i) OBSERVED BY C.R.O

(ii) CALCULATED BY EQUATION 2.8.

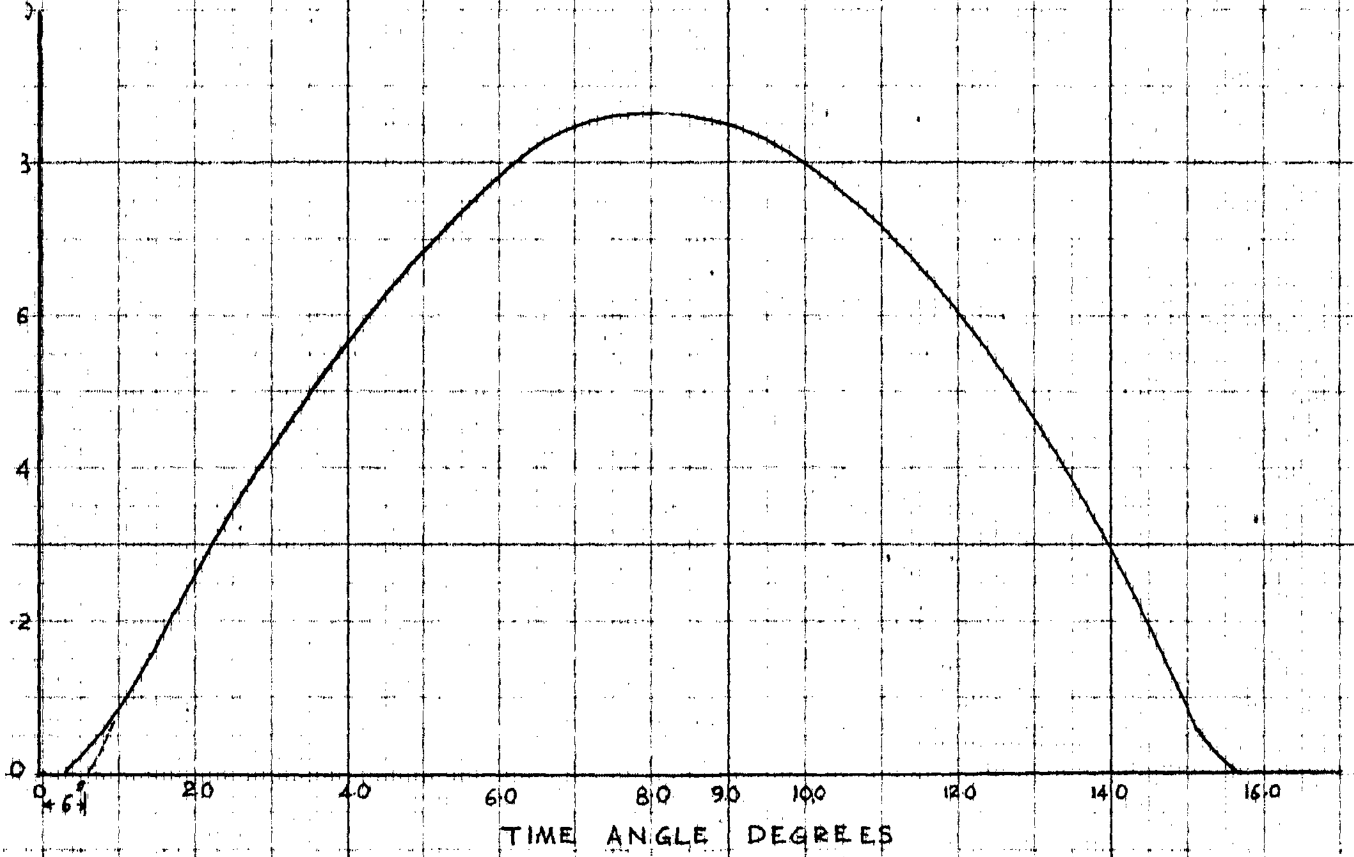


FIG 2.7(b) CURRENT WAVE FORM CALCULATED BY EQUATION 2.8

The following is the table showing various results for a single phase half-wave rectifier-d.c shunt motor system:

Average value of current (I_{dc})	Using formula 2.21	Using formula 2.19	Observed value
	2.4 amps.	2.38 amps.	2.5 amps.
Instantaneous peak value of current I_m	Using formula 2.46	Using formula 2.48	9.9 amps.
	8.78 amps.	5.7 amps	
R. M. S. value of current I_{rms}	Using formula 2.51	Using formula 2.52 and 2.54	4.2 amps.
	4.1 amps.	4.55	
Peak coefficient of current f_m	Using formula 2.46 and 2.21	Using formula 2.50	3.92
	3.66	2.37	
Form factor of current	Using formula 2.21 and 2.51	Using formula 2.54	1.68
	1.71	1.68	

Calculated period of conduction = 157.5°

Observed period of conduction = 165°

From the above table it can be observed that the results, calculated by using rigorous formulae, and by the observations taken are quite similar. However the difference can be due to the fact that there can always be some error in the observations and also the inductance of the transformer, overlap angle etc. These results show that the theoretical analysis done for the half-wave rectifier d-c motor system gives results which are quite in line with the actual results. So the rigorous analysis can be safely used for estimating the performance of the system, before actually performing the tests on the system.

(2.6) Effect of Armature-Reaction On Wave Shape of Flux Density.[12.]

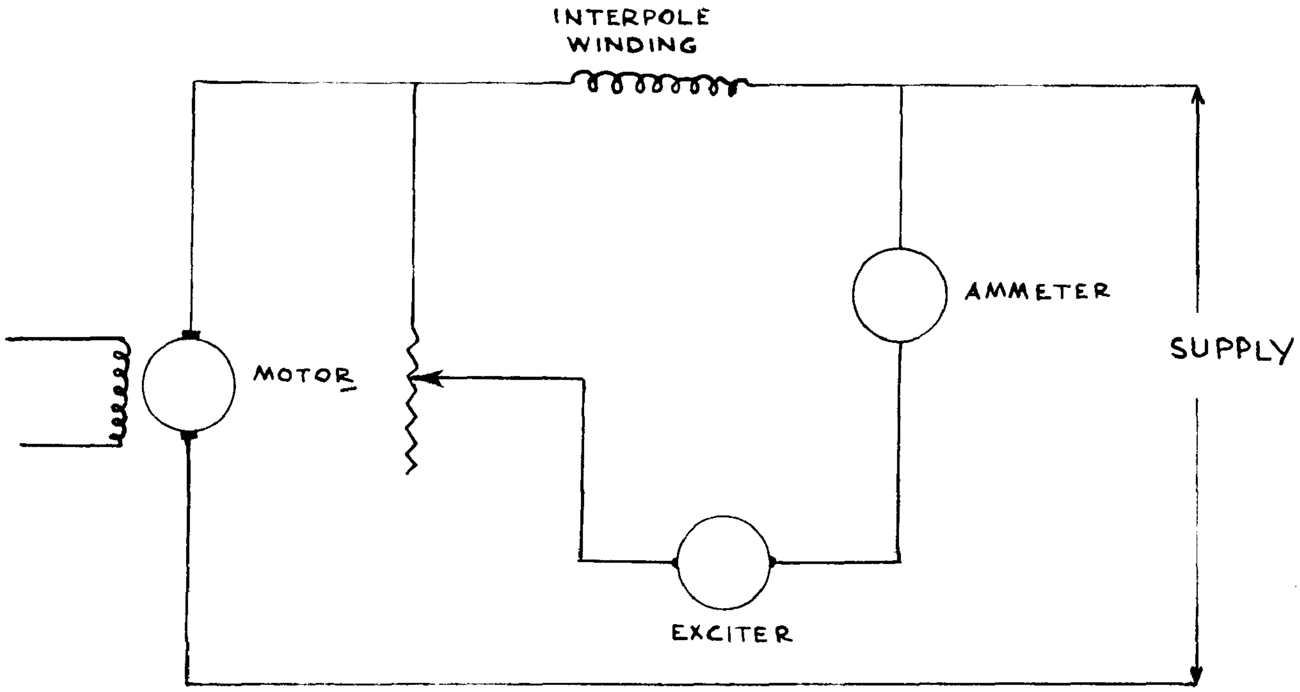
The fig. 2.9(a) and 2.9(b) show the field flux distribution in case of a d.c. motor and half-wave rectifier fed d-c motor. Both the wave-shapes were taken on the same machine.

The wave shape in case of half wave rectifier fed d-c motor, contains additional ripples as compared the case of ordinary d-c motor. These ripples are there due to the presence of harmonics in the armature current. For the practical purposes it is sufficient to consider only the 50 cps component of ripple current. Now there can be two cases. In the first case the alternating current and so the a.c. cross flux are zero. In the other case the alternating current has the peak value and so also the a.c. cross flux. Such alternations in the cross flux tend to increase the stray energy losses in the pole shoe. In order to limit the a.c. component of cross flux, it is necessary to limit the a.c. component of current in the armature current. For this there is no need of redesigning the motor for increasing the armature inductance but sometimes it may be necessary to add a choke in the armature circuit.

(2.7) Commutation Test.[12,13.]

In the half-wave rectifier fed d-c motors or the rectifier fed d-c motors in general, the commutation is very poor. The commutation performance is judged by taking the "black band" commutation characteristic of the machine. This method of judging commutation performance derives its name from the zone of variable commutating field strength at any load in which commutation will be sparkless or black. This zone is obtained by first opposing (bucking) then aiding (boosting) the load current flowing through the commutating field coils at any value of load on the machine, and plotting curves against load of amperes boost and buck at which light general sparking just begins. The resulting curves represent a band between the limits of which commutation is black, hence the name " black band".

In order to take a " black band" on a machine, it is necessary to vary both the load and the commutating field strength. For variations in load, the motor may be loaded by means of a belt pulley arrangement or by means of loading a generator if the motor-generator set is there. For varying the commutating field strength a variable-voltage power supply of sufficient capacity is connected across the commutating field winding (and compensating or pole face winding if one is present and it is interconnected with the commutating field winding) of the machine under observation. The most convenient type of variable voltage supply is an exciter, the armature of which is connected through a variable resistance to the commutating field terminals as shown in Fig.2.8(a). The buck-and-boost current can then be varied both by the resistance in the armature circuit of the exciter and by field control of the exciter.


INTERPOLE WINDING
AMMETER
SUPPLY
MOTOR
EXCITER

[illegible]

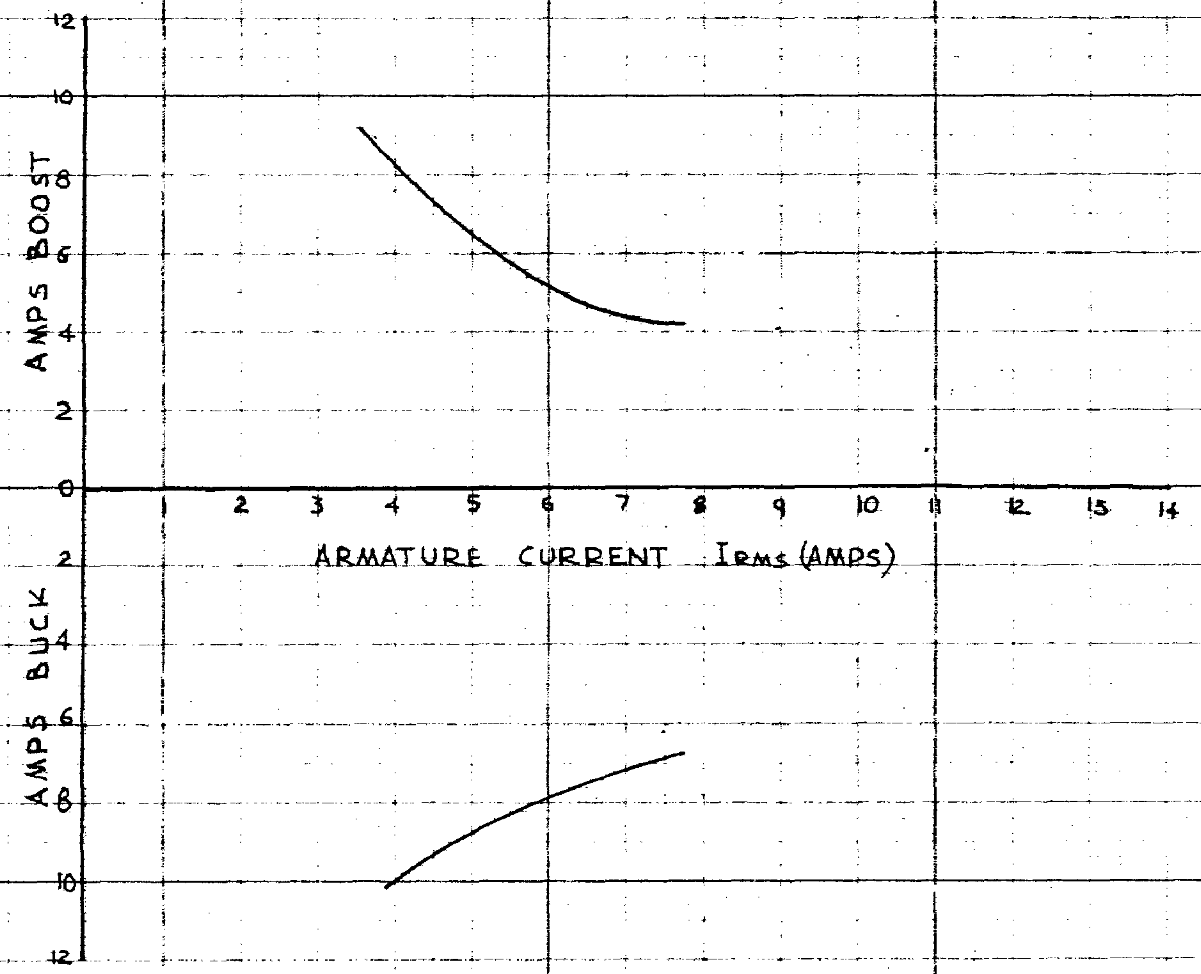


FIG. 2.8(b) 'BLACK BAND' COMMUTATION CHARACTERISTIC OF D.C. SHUNT MOTOR ON HALF WAVE RECTIFIED POWER

A convenient method of determining whether the ammeter is connected to read 'buck' or 'boost' is to disconnect the exciter lines and, with a low value load on the machine, short the lines from the commutating field together, thus shunting some current around the commutating field. If the ammeter reads up scale, it is connected to read 'buck' current.

Load should never be quickly removed from a machine which has buck or boost on it, as this may result in severe sparking and damage to the brushes and commutator.

It was not possible to determine the 'black band' in the case of operation of d-c motor under test on d-c supply as there was no impairment in commutation (sparking etc.) even with heavy 'buck' or 'boost' current in commutating field winding. So the test was abandoned in this case due to the fear of damage to the commutating pole winding.

However, it was easy to determine the 'black band' in case of operation of d-c motor on half-wave rectified power. The percentage bucking is given by[12],

$$\text{Bucking percentage} = x = \frac{C-1}{2C} \times \frac{m}{m+1} \times 100 \text{ percent} \qquad (2.58)$$

The percentage 'boost' is given by[12]

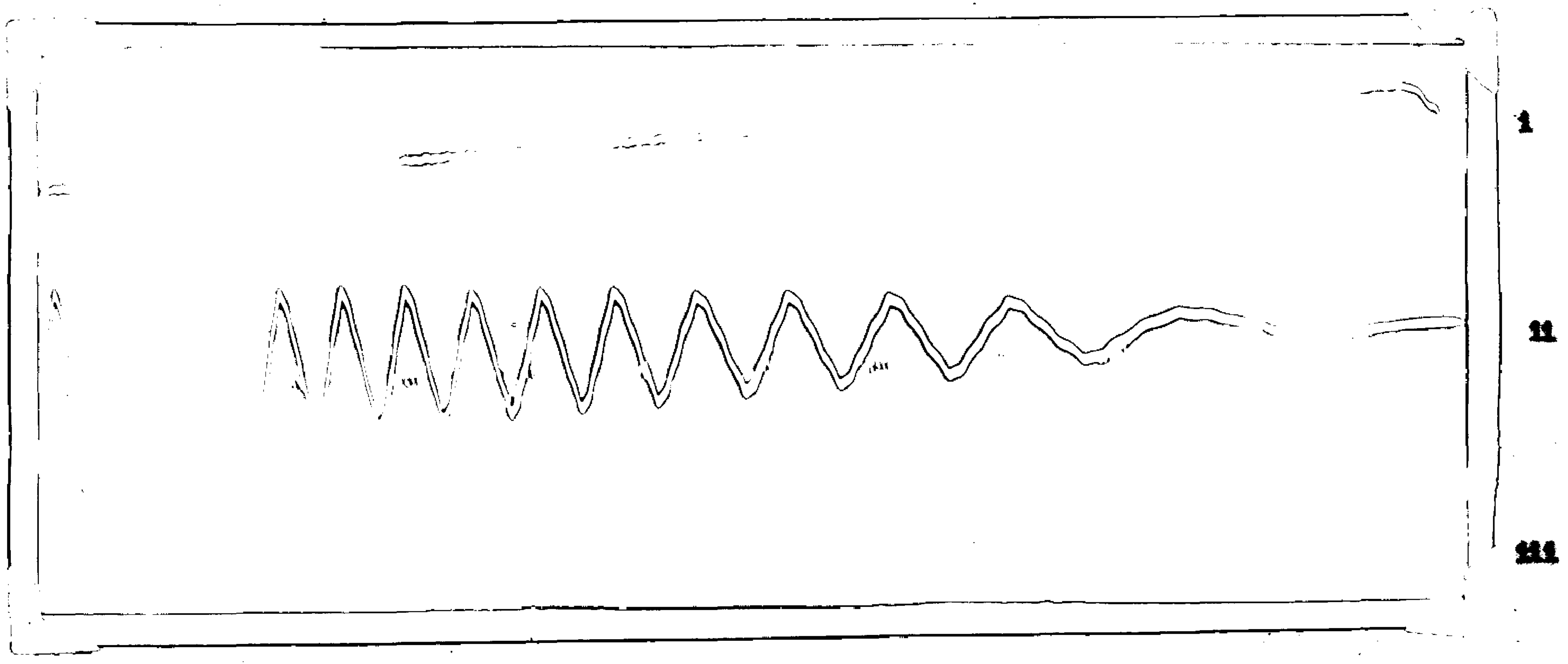
$$\text{Percentage boost} = y = \{(C-1)/2C\} \times \{m/(1-m)\} \times 100 \text{ percent} \qquad (2.59)$$

where C = ratio of compole to armature turns

$m = I_{50}/I_{d-c}$ = Ratio of peak 50 cps ripple to d-c current.

(2.8) Starting Inrush current and Acceleration.[14]

The figs. 2.9(a) and 2.9(b) show the oscillograms of the starting inrush current and acceleration in the case of a

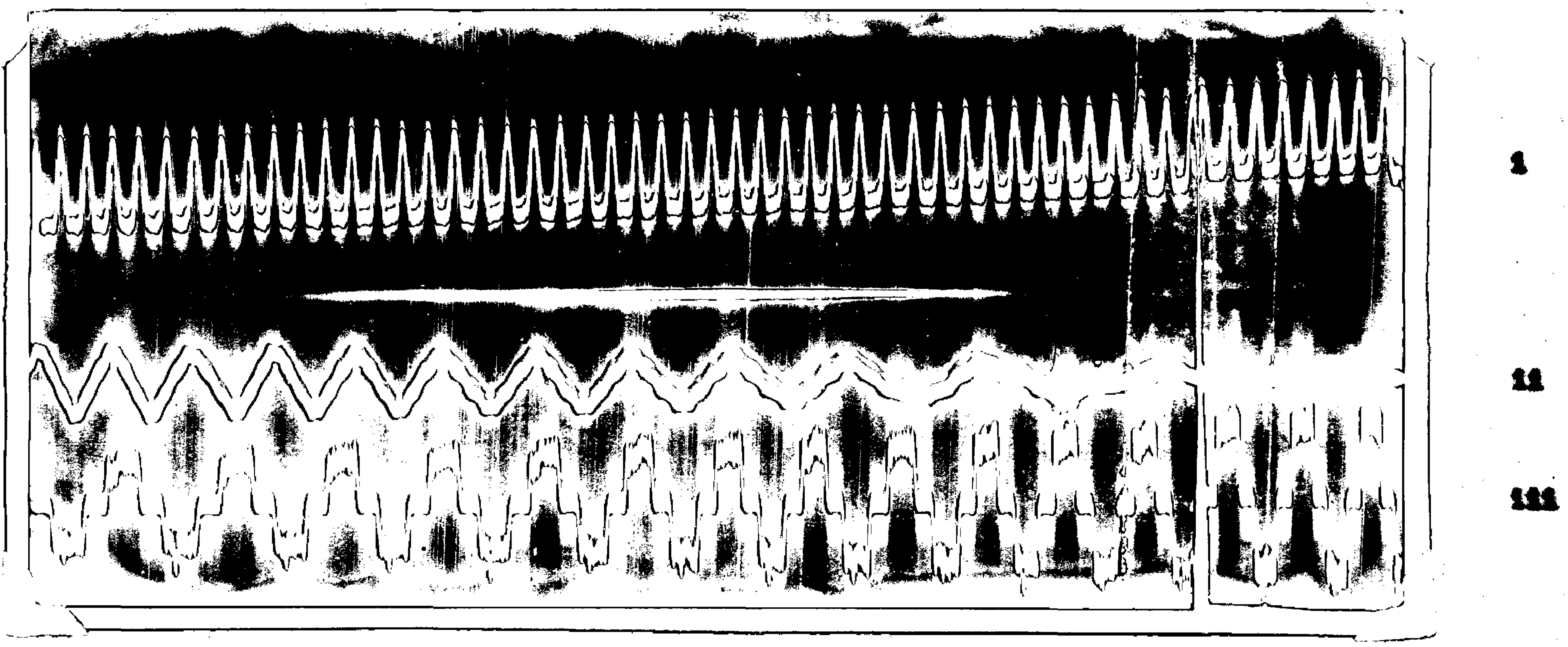


i. inrush current- time characteristic at starting

ii. speed-time characteristic at starting

iii. field-flux distribution wave-form

Fig. 2.9(a) Starting characteristics and field flux distribution wave form of d-c shunt motor on d-c supply.



i. inrush current-time characteristic at starting

ii. speed-time characteristic at starting

iii. field-flux distribution wave-form.

Fig. 2.9(b) Starting characteristics and field-flux distribution wave form of d-c shunt motor on half-wave rectified power.

purely d-c motor and in case of d-c motor on half-wave rectified power.

The starting inrush current in the case of d-c motor on half-wave rectified power was much less than in case of pure d-c motor. It is not very clear from the oscillograms as in the first case the sensitivity of the oscilloscope was much increased as the original value of current fed into the vibrator of the oscilloscope was too small to initiate it. However, it would be seen by the 'kick' method of the ammeter pointer. The reason of the lesser value of the starting inrush current in the case of half-wave rectifier fed d-c motor was the poor regulation of the rectifier equipmentand the increased drop across the regulating resistance. It is clear that, as the inrush current is low, the starting torque is less and so it is not desirable that the load may have a high moment of inertia and thus requiring a higher starting torque. In this respect the pure d-c motor was found to be much better and had a large starting torque. However, on the other hand the rating of the starter resistances can be smaller in the case of half-wave rectifier d-c motor system.

Figs. 2.9(a) and 2.9(b) show the initial accelleration of the two types of motors. These curves were taken by recording the tachogenerator output which was sinusoidal and so a line joining the peaks of the waves shows the velocity at any instant. It is clear that the acceleration of the pure d-c motor is much faster than that of the half-wave rectified power fed d-c motor. This, again, is due to the poor regulation of the rectifier system. So it can be said that a simple half-wave rectifier d-c motor system will not have a good or quick response to changes in load as desired in many systems. The speed will drop to a great extent in the first instance as the load is increased and then it will rise slowly to the value determined by the rectifier output voltage which corresponds to the new value of load current. So the correcting means, which will be discussed in the chapter, on 'control', should be eimployed, to such a system.

(2.9) Rating of Motors, Efficiency, and Power Factor.[10,15]

Although d-c motors of standard design are normally used in electronic drives, and no special design modifications are required, the horsepower rating of the motor generally is affected by the wave shape of the armature load current. It will be recalled that the form factor of rectified armature current always is greater than unity, whereas standard d-c- motors are ratedon the basis of pure d-c supplied, which give the current form factor equal to unity. The copper losses in the armature winding are increased, with respect to normal d-c losses, in direct proportion to the square of the form factor. Magnetic losses in the armature, frame, and pole faces are normally increased too, but to a much lesser extent. Generally, an assumption of a total increase in losses of the motor of 50 to 60 percent is satisfactory for a rough estimation of the motor frame size. The fig. gives a comparitive idea of copper losses in the case of a pure d-c motor and a d-c motor on half-wave rectified power.

Some times, various means are used to reduce the armature current form factor to such a low value (1.01 to 1.05) that no change in motor horsepower rating with respect to the conventional d-c case is required. Furthermore, the reduction of the form factor has a beneficial effect on the commutation of the motor, particularly at higher speeds. The reduction of the form factor can be accomplished by reducing the rectifier transformer voltage to a bare minimum, and by increasing the impedance angle of the load circuit by the addition of a reactor in series with

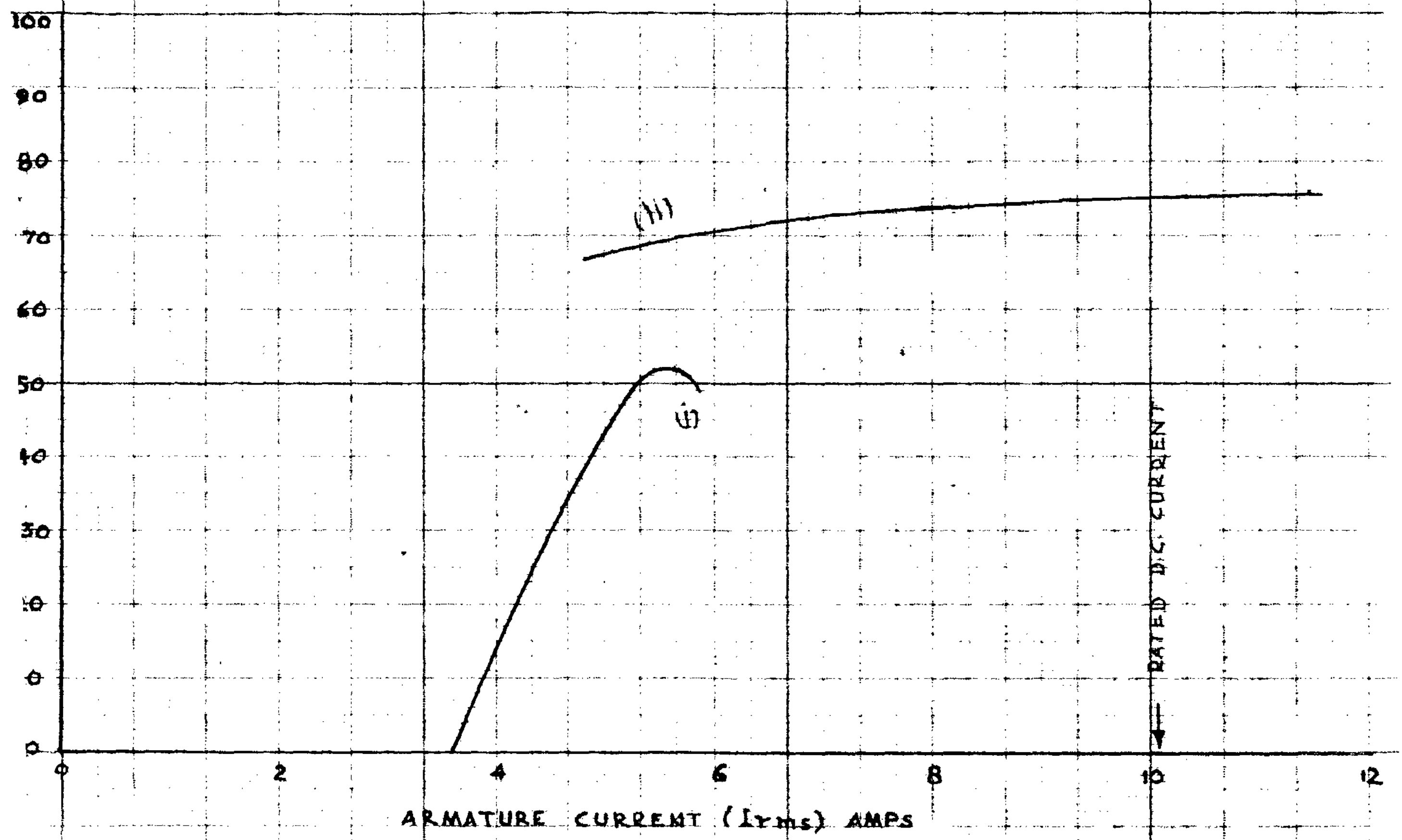


FIG 2.10 (d) EFFICIENCY-ARMATURE CURRENT (IRMS)
CHRACTERISTICS AT 1100 R.P.M OF
(i) D.C. SHUNT MOTOR ON HALF WAVE RECTIFIED POWER
(ii) D.C. SHUNT MOTOR ON D.C. SUPPLY

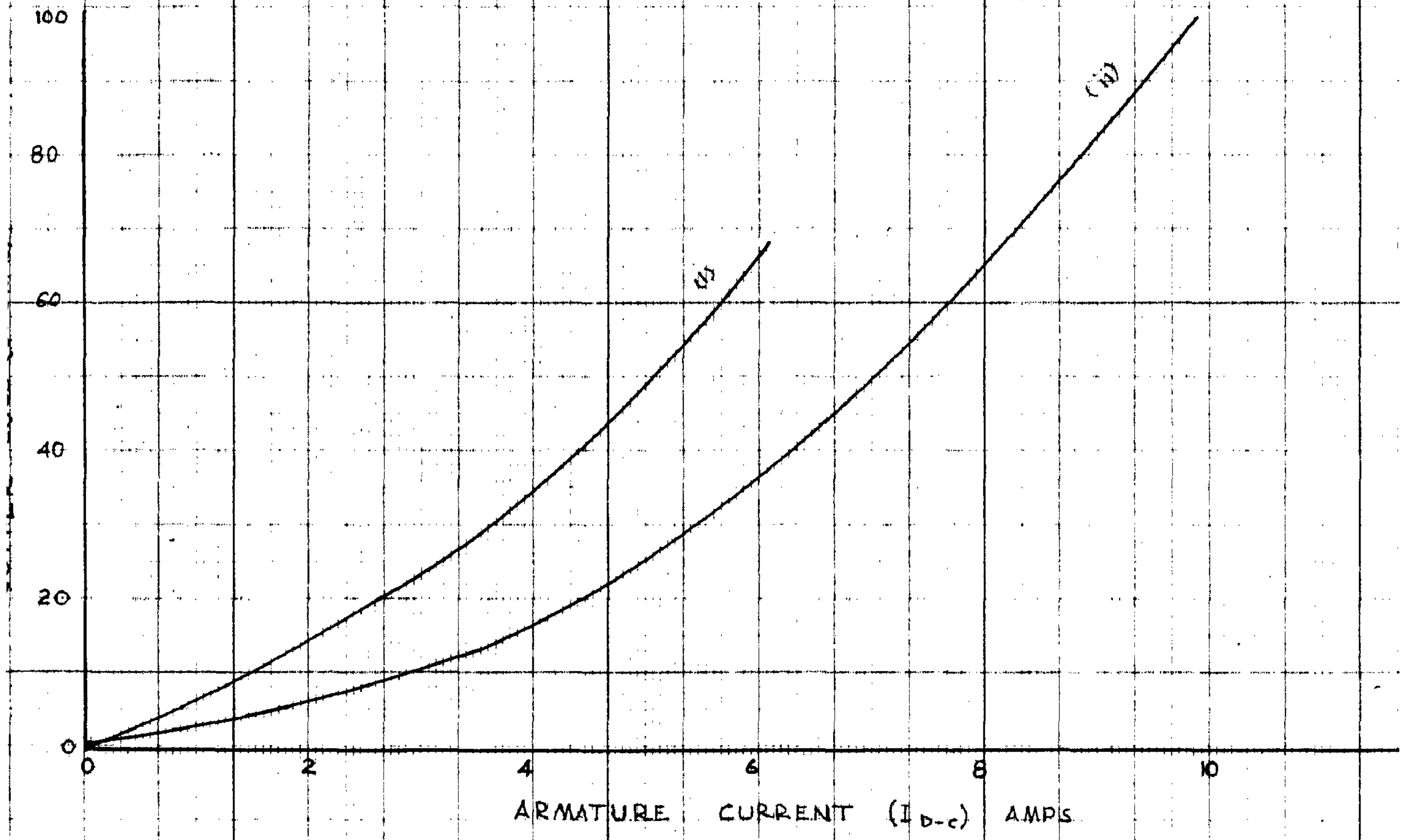


FIG 2.10 (b) COPPER LOSS-ARMATURE CURRENT (I_{D-C}) CHARACTERISTICS OF

(i) D.C. SHUNT MOTOR ON HALF-WAVE RECTIFIED POWER

(ii) D.C. SHUNT MOTOR ON D.C. SUPPLY

the armature. However, the addition of a heavy and rather expensive reactor may offset the advantage of improved motor rating.

The efficiency of an electronic drive can be expressed as

$$\eta = \frac{746 \quad P_M}{\sqrt{p_L} \quad I_L \quad E_L \quad p\,f.} \qquad (2.60)$$

where P_M = horsepower developed at the motor shaft

p_L = number of phases of the a-c supply line

I_L = line current

E_L = line voltage

$p.f.$ = power factor at the line terminals.

In fig. 2.10(a) is shown the experimental graph of the efficiency of the electronic drive (on half wave rectified power) as a function of motor armature current. Full rated excitation was maintained throughout the test. It will be noted that the efficiency is increasing with the increase in armature current. The efficiency becomes zero for no-load current of the motor since for this current no torque or power is developed at the shaft of the motor. The no-load current is a function of speed and it increases with the increase in speed.

As should be expected, the efficiency at rated excitation is about 53 percent. The maximum efficiency of the same motor on d-c supply is about 77 percent. Although at the first glance such an efficiency may be seen rather low, it should be borne in mind that it should be compared with the overall efficiency of a conventional ward-leonard drive. Then it would be clear that the efficiency of an electronic drive is comparable to that of a conventional Ward-leonard drive.

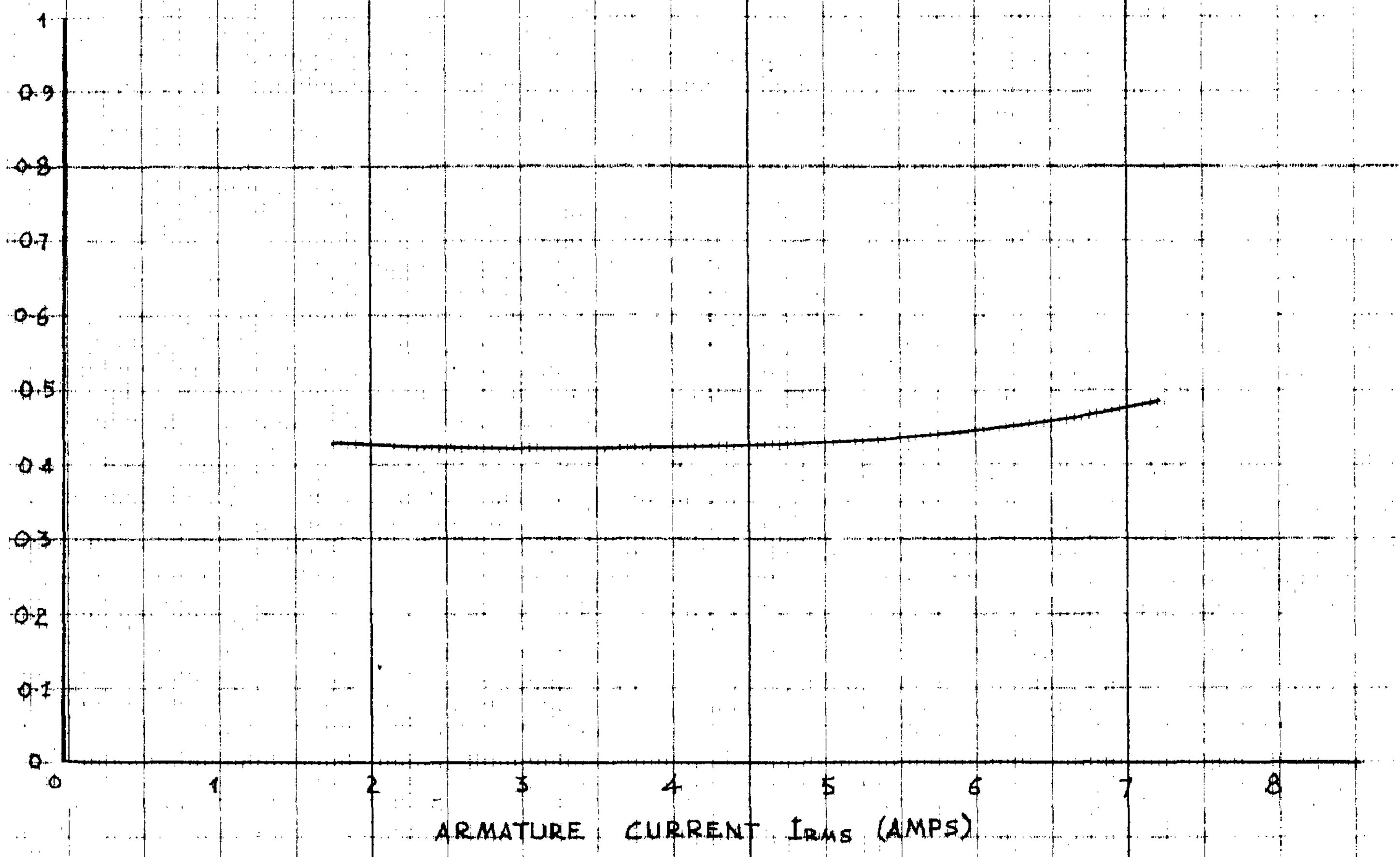


FIG. 2.11 POWER FACTOR (AT LINE TERMINALS)-ARMATURE CURRENT (I_{RMS}) CHARACTERISTIC OF D.C. SHUNT MOTOR- HALF WAVE RECTIFIER SYSTEM AT 1100 R.P.M.

The power factor at the a-c supply terminals of an electronic rectifier drive is of some interest, particularly wherever large powers are involved. In general, the power factor is relatively low and, for higher powers power-factor correcting means may be advisable in order to reduce the reactive power absorbed by the system. The main reason for a low p.f. is the principle of control of output voltage of the rectifier by delayed ignition of rectifier tubes.

Experimental graph of the power factor plotted as a function of armature current is shown in Fig. 2.11. Generally speaking, the power factor does not change very appreciably with the load current.

(2.10) Servomechanism Analysis[8,9,16.]

The d-c motor and controlled rectifier combination is used as the prime mover in some of the automatic, closed loop, speed control systems. Here the servo analysis of the constant speed system will be presented.

Let the operating point be fixed by the combination of β_o, n_o, and T_o, where the control angle or angle of tube break down β_o, produces a steady state torque T_o, at a steady state speed, n_o. The effect of a small change of the control angle $\Delta\beta$, upon the change of speed Δn, is now considered.

The torque required by the load over and above that required to accelerate the moment of inertia, J, is represented by T_L and is given by equation 2.61:

$$T_L = T_o + \frac{\partial T_L}{\partial n} \Delta n \qquad (2.61)$$

It is assumed, of course, that the change of speed is small enough such that T_L as a function of speed in the region of the operating point may be considered as a straight line. The developed torque, T, is a function of both β and n. This leads to equation 2.62:

$$T = T_o + \partial T/\partial n \ \Delta n + \partial T/\partial \beta \ \Delta \beta \qquad (2.62)$$

By equating the total torque required by the load (including that required for acceleration) to the developed torque equation 2.63 results:

$$\frac{d(\Delta n)}{dt} + \left[\frac{\partial T_L}{\partial n} - \frac{\partial T}{\partial n}\right]\Delta n = \frac{\partial T}{\partial \beta}\Delta\beta \qquad (2.63)$$

The partial, $\frac{\partial T_L}{\partial n}$, is fixed exclusively by the nature of the load and other true partials are fixed by the characteristics of the rectifier motor combination.

The partials, $\partial T/\partial n$ and $\partial T/\partial \beta$, could be determined directly by graphical methods. It is more direct to determine these partials through the use of some explicit expressions for them.

From equation 2.10, the expression for speed coefficient is

$$a = \cos\theta \left[\frac{\sin(r+\beta-\theta) - \epsilon^{-R/L\omega^{r}} \sin(\beta-\theta)}{1 - \epsilon^{-\frac{R\,r}{L\omega}}}\right] \qquad (2.64)$$

Equations 2.64 and 2.35 are true in the transient case also, because there is no delay in armature current response to a change in β. We can find the partial of torque factor in respect to speed coefficient by the use of equation 2.35:

$$\frac{\partial t_f}{\partial a} = \frac{1}{2\pi}\left[\frac{\partial r}{\partial a}\left\{\mathrm{Sin}\,(\beta + r) - a\right\} - r\right] \qquad (2.65)$$

where β is constant. In order to evaluate the partial of r in respect to 'a', the equation 2.64 is used:

$$\frac{\partial r}{\partial a} = \frac{1 - e^{-\frac{R}{Lw}r}}{\mathrm{Cos}\,\theta\left[\mathrm{Cos}(r+\beta-\theta) + \frac{R e^{-R/Lw\ r}}{Lw}\left\{\mathrm{Sin}(\beta-\theta) - \frac{a}{\mathrm{Cos}\theta}\right\}\right]} \qquad (2.66)$$

where β is a constant.

The combination of equations 2.65 and 2.66 can be used to determine the factor, $\partial t_f/\partial a$, after choosing the angles β, r, and 'a' corresponding to the desired operating point.

The partial of torque factor in respect to the control angle can be determined by taking the partial of t_f in respect to β from equation 2.35 and the partial of r in respect to β from equation 2.64.

$$\frac{\partial t_f}{\partial \beta} = \frac{1}{2\pi}\left[-\mathrm{Sin}\,\beta + \mathrm{Sin}\,(\beta + r) + \left\{\mathrm{Sin}\,(\beta + r) - a\right\}\frac{\partial r}{\partial \beta}\right] \qquad (2.67)$$

where 'a' is a constant

$$\frac{\partial r}{\partial \beta} = \frac{e^{-R/LW\ r}\,\mathrm{Cos}\,(\beta - \theta) - \mathrm{Cos}\,(r + \beta - \theta)}{\mathrm{Cos}(r+\beta-\theta) + \frac{R e^{-R/Lw\ r}}{Lw}\left\{\mathrm{Sin}(\beta-\theta) - a/\mathrm{Cos}\ \theta\right\}} \qquad (2.68)$$

where 'a' is a constant

The combination of equations 2.67 and 2.68 can be used to determine the factor $\partial t_f/\partial \beta$. In order to convert the partials of t_f in respect to 'a' and β, to the corresponding partials of T in respect to 'a' and β, the following equation is used:

$$T = K_t \; I_{d-c} \qquad (2.69)$$

where K_t is an excitation constant equal to pound-feet of torque per ampere of armature current.

Since $t_f = \dfrac{I_{d-c} \; R}{E_m}$, it can be seen that

$$\frac{\partial T}{\partial n} = \frac{K_t \; K_n}{R} \quad \frac{\partial \; t_f}{\partial \; a} \qquad (2.70)$$

because $a = E_d / E_m \quad E_g / E_m = K_n{}^n / E_m$

where K_n is a speed constant and is equal to volts generated in armature per rpm.

and $$\frac{\partial T}{\partial \beta} = \frac{K_t \; E_m}{R} \quad \frac{\partial \; t_f}{\partial \; \beta} \qquad (2.71)$$

Equation 2.63 is rewritten in terms of n and β as shown in equation 2.72. It is assumed that each of these variables n and β, represent a small variation above or below the corresponding operating point value.

$$J \frac{\partial \; n}{\partial \; t} + \left[\frac{\partial T_L}{\partial \; n} - \frac{\partial T}{\partial n} \right] n = \frac{\partial T}{\partial \beta} \beta \qquad (2.72)$$

By substituting jw for the operator d/dt in equation 2.72, equation 2.73 gives the transfer function.

$$\frac{n}{\beta} = + \frac{\partial T / \partial \beta}{\frac{\partial T_L}{\partial n} - \frac{\partial T}{\partial n} + jw^J} \qquad (2.73)$$

In equation 2.73, n and β are the complex sinusoidal values of speed and control angle respectively, and w is the angular velocity of the sinusoidal variation in both n and β. Equation 2.73 gives the complex ratio of the response of the system, n to the complex driving force, β. This ratio is useful in predicting the performance of any closed loop control system that uses the rectifier motor as the prime mover.

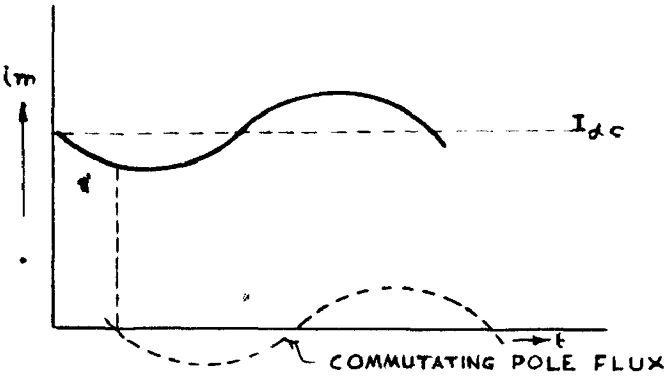
CHAPTER III

OPERATIONAL PROBLEMS IN HALF-WAVE RECTIFIER D.C. SHUNT MOTOR SYSTEM.

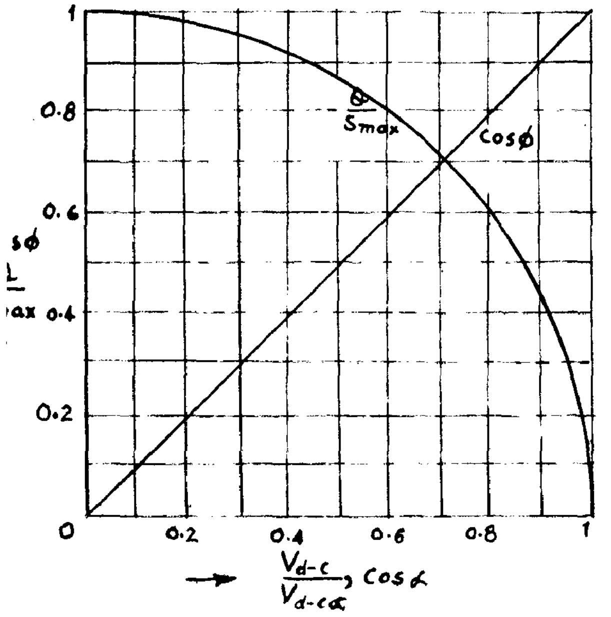
(3.1) Commutation.[17,18.]

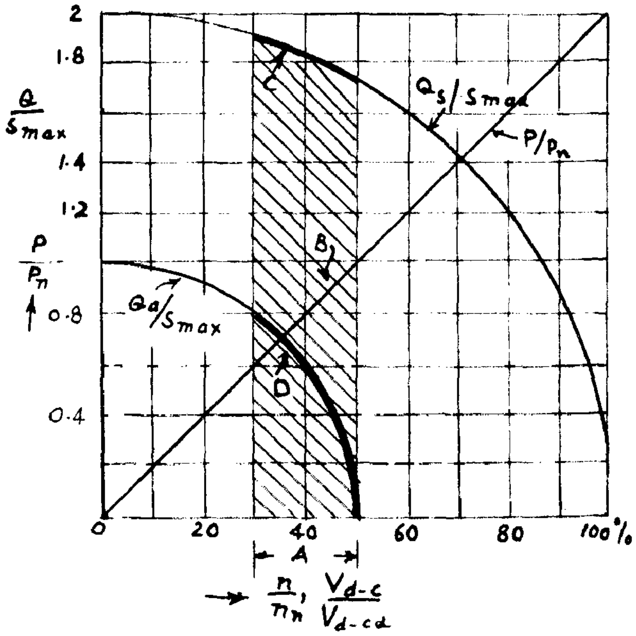
There is a degradation of commutation performance when a rectified power supply is used with a motor. This impairment of the commutation occurs for several reasons. The ripple current produced of the rectifier is of sufficiently high frequency (50 cycles) to increase the reactance voltage of the coils undergoing commutation, thus tending to collapse the width of the black band more as the magnitude of the ripple current increases. Eddy currents in the magnetic circuit of the quadrature axis will cause the commutating pole flux to lag behind the harmonic current vibrations. A higher degree of saturation, and the associated increase in leakage flux,will also increase the phase shift between the current and the flux in the quadrature axis. Because the commutating pole flux does not precisely follow the current, the lag in flux will be maximum when the current is at the minimum value or weak. Conversely the commutating flux will be most in step when the current is at the peak of the ripple. This effect when integrated over a complete cycle, will result in a greater net flux or an apparent strengthening of the commutating field when ripple current is present.

Phase correction of the commutating pole flux can either be achieved by constructional modifications of those stator parts which carry the commutating pole flux, or by adding



[illegible] OF COMMUTATING [illegible]





[illegible]

[illegible]

Q_s [illegible]

Q_a [illegible] control.

a reactance in the shunt circuit to bring the resultant flux of the commutating poles into the appropriate position with respect to armature field.

However, the amount of phase displacement depends on the actual motor load, so one impedance value of the shunt can satisfy only one particular load; in order to have a wide operating range the rectifier-motor installations can be equipped with means for variation of the shunt constants by selective contactors.

(3.2) Heating.[16,17,18]

There is a slight increase in temperature due to ripple current above that observed with a generator power source. The temperature differences are higher during higher ripple heat runs. Normally, the minor variations in obtaining repetitive data of a self ventilating machine tends to shroud any temperature changes due to harmonic influence on copper or iron losses. For instance, with say 6 percent ripple current, there is no perceptible increase in temperature. An explanation of this heat run result lies in an examination of the anticipated increase in losses At 6 percent rms ripple, the increase in copper losses would be less than 4 percent even if the effective resistance of the armature circuit was ten times greater at 600 cycles per second than the d.c. resistance. Similarly, the increase in hysteresis and eddy losses in the armature and stator laminations can be shown to be very low under light current ripple operation of a compensated machine. The effect of ripple current on temperature rise of d.c. motors can be categorically classified as inconsequential. A continuous ripple current of significant magnitude to produce heating cannot be obtained due to the limit imposed for acceptable commutation performance.

(3.3) Vibration.[18,19]

There is generally no perceptible change in vibration for various magnitudes of current ripple. A change in the air borne noise level can be there, however. The change in audio noise level observed suggests that greater care is required to secure the laminations and other internal parts which would conceivably become loose and drop into the air gap of the machine. Rotor slot skewing may be employed if the increased noise level is objectionable.

When a gearing has to be employed, then with solid gears the 50 cycle torque pulsation is about the twice (±) than with resilient gears. Although the resilient gear effectively reduce the magnitude of pulsating torque, the value with standard solid gears is not generally great enough to cause mechanical failure. Hence an expensive resilient gear is not justified.

(3.4) Shaft Potential.[17]

The shaft potential gets much increased when the motor is supplied by a rectifier. In one experiment, which was performed in one electrical manufacturing company, on a 1250 k.w., 8 poles 720 rpm, 750 volts, d.c. machine, the shaft potential increased from 3 to 33 volts.

This indicates that greater care must be taken to insure adequate pedestal insulation for motors powered by a rectifier. There exists not only the problem of conductive shaft currents through the bearing insulation, but also the possibility of capacitive discharges through the oil film caused by the high frequencies induced by a rectifier.

to 1). At constant excitation current the speed of a d.c motor increases in proportion to the armature voltage, so that the d.c voltage V_{dc} and speed n can be plotted as abscissa ; with Q/S_{max} and cos Ø as ordinate (Q is the reactive power and S_{max} is maximum apparent power at rated load).

It is well known that active load surges influence mainly the frequency; and when the rectifier is fed from a supply system the latter determines the frequency, whereby the kinetic energy of the alternator sets is usually adequate to ensure that this is hardly affected. Even in cases of private power plants the frequency variation remains mostly within permissible limits.

Much more disturbing are the reactive load surges occurring with rectifier plants. From the power-factor curve of a rectifier having voltage regulation via grid control, a reactive load curve is obtained which is represented by the arc of a circle. The highest reactive load surges of a rectifier unit are therefore to be expected in particular at low speeds. However, just within this speed range the motor is subjected to the severest conditions with regard to acceleration and load surges.

Reactive current peaks result in voltage drops along the network reactances, which increase inversely with respect to the short circuit power P_c of the network at the point of connection of the rectifier plant and in proportion to the reactive load peak Q of the rectifier. The following approximation applies:[5]

$$\frac{\Delta V}{V} = \frac{Q}{P_c} 100 \quad \text{(in percent)}$$

Admitting a voltage drop of 3 percent, Q is equal to $P_c/33$.

From this results the first and most important counter measure, namely, the connection of the reversing drive to the

(3.5) Deterioration of cables.[20]

It has been noticed tha the incidences of failures are more in cables carrying rectified power than in ordinary cables. The reason for this are the harmonics generated by the rectifier equipment. The various effects of rectifier harmonics on the dielectrics of cables are:

(1) Dielectric Losses:- The dielectric losses are considerably increased in the presence of harmonics but in high voltages cables they are only a secondary factor in determining the thermal stability of the dielectric. (The phenomena is the same as for hysterisis loops in magnetic materials).

(2) Increased crest Voltage:- The generation of harmonics increases the crest value of the voltage and so some shortening of cable life can be expected in case of operation over prolonged periods.

(3) Internal Discharges:- It is well known that some residual voids are inevitable in cables of the solid type. The stresses in these voids are very much greater than the dielectric strength of gases under atmospheric pressure. It can be shown that if voltage wave contains 12th harmonic of about 20 percent amplitude, the number of discharges-and thus the total energy released in the void- is doubled and the life of the dielectric can get reduced by about half.

(3.6) Network Reprecussions from Rectifier-Fed Installations.[5]

At the full rectifier voltage, i.e. at the basic (or higher) speed of the connected d.c. motor, the load peaks produce practically pure active power surges, as shown in Fig. 3.2(a) (at full voltage the power factor of a rectifier is equal strongest point of the network; this is of great importance in the case of private networks. Unless special measures are taken there are therefore certain limitations in the applications of rectifiers. So some steps should be taken to extend their field of application of appropriate means. One step in this direction is to connect capacitor banks in parallel; but these only serve to improve the average power factor of the plant without having any influence on the reactive surges proper. Another possibility is to adapt the system of connection and control. Several solutions have been proposed; but for technical reasons and reasons of economy, many electrical manufacturers prefer phase-sequence or asymmetrical grid control. The principle involves increasing the d.c. voltage by first varying the phase control of some of the anodes so that at half the d.c. voltage these anodes are fully controlled (i.e. are working at full voltage), the power factor being equal to 1. Thereupon the rest of the anodes are brought up to the full voltage. The remarkable phenomenon is that at half the d.c. voltage the reactive power again becomes zero, and even when the d.c. voltage is zero, its value is only half as much as with symmetrical grid control. The reason is that within the range from zero to half the rated voltage, the primary current reaches only half of the value which corresponds to the current at full voltage.

Within the critical speed range, i.e. between 30 and 50 percent of the basic speed, the reactive load surges, with asymmetrical grid control, are only a fraction of those occuring with normal gird control. It has enabled the field of application of rectifiers to be extended.

CHAPTER IV

CONTROL OF HALF- WAVE RECTIFIER FED D-C SHUNT MOTORS

(4.1) Methods of Controlling Speed.

The speed of a d-c motor, fed by the rectified power, can be controlled by varying the applied armature voltage, by controlling the excitation or by varying the number of conductors in series. The last method is not common. The methods, that are generally used, are the variation of armature voltage and the variation of the excitation. Various methods can be there to achieve these and any method must meet the following requirements:-

(i) It must be capable of responding to the various requirements of changes in conditions of speed and load.

(ii) It must include the means of holding currents to limits determined by ratings of the equipment. This is particularly important during acceleration and deceleration when ignitron equipment is operated with high ignition delay. It is necessary that the load should not be allowed to exceed the maximum limit during inversion.

(iii) The reversal time of the motor should not be made unnecessarily short, as it is probable that an extremely short reversal time will require additional and more expensive equipment, which may make the overall application uneconomical.

However, the field is generally separately excited by direct current. So the methods that are common to ordinary d-c motors by controlling the field, are applicable in the rectifier d-c motor systems also and so they need not be discussed here.

Many methods are there which can possibly be applied for varying the armature voltages. Some of these methods are as follows[7]:

(4.1.1) Using a Rotary Booster in the D.C. Circuit.

A rotary booster in the d-c circuit is not of any importance now and is of theoretical interest only.

(4.1.2) Using a Regulator in the Primary Circuit of the Transforme

The use of regulator in the primary circuit of the transformer is common where the motor has to make long runs at reduced speeds and with heavy torques. The normal power factor of the rectifier is maintained at its high value throughout the speed rang First cost is higher, however, as not only the regulator itself is involved, but the auxiliary circuits requiring a constant voltage must be fed separately from the input side to the regulator necessitating an auxiliary transformer. The weight of the unit and the space required for a given output is thus increased by an amount depending upon the speed range required, and further if the speed range is small and the output is not to be reduced to zero volts for starting purposes, a motor starter will be an additional requirement. The sliding-contact type of regulator is generally used, induction and moving-coil types being alternations.

(4.1.3) Using Transformer Tappings.

If speed changes are rarely needed and only one or two fixed speeds are required, the secondary winding of the transformer may be tapped, and links with off-circuit switches used to connect the anodes to the windings.

Simple as this method appears at first sight, it is not greatly used owing to the added complications in transformer design, especially when the number of phases used in rectification exceeds three there.

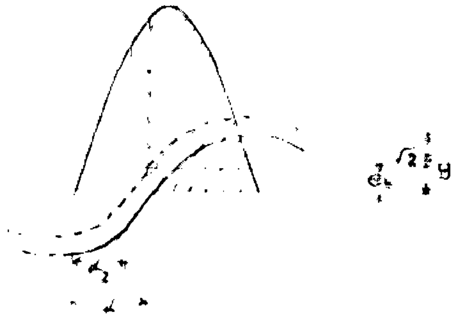
(4.1.4) Using Grid Control.

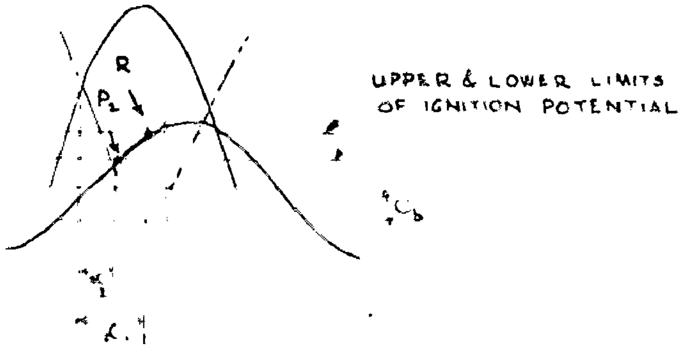
Grid control is the commonest method. The interpositioning of control grids betwwen each anode and the cathode enables the firing instant of anode to be delayed beyond its natural firing point in the cycle, and thus the mean d.c. output voltage can be varied. A few examples of grid control are being given here:-

(4.1.4.1) Phase-Shift Control

For sinusoidal working (known as " soft control"), phase-shift control is generally used. Since, provided the output current is continuous, the voltage reduction factor for a grid-controlled rectifier is cos α, the output voltage of the rectifier as a function of angular rotation of the rotor of the phase-shifting induction regulator obeys a cosine law. This is quite satisfactory for manual control, but may lead to difficulties when the regulator is motorized, owing to the large differences in movement required to obtain equal increments of output voltage at different parts of the control range.

The method of feeding the phase-shifter needs careful arra gement. For example, when a simple induction regulator is used for phase-shifting, the supply to the regulator is liable to distortion by the rectifier it is controlling. This is particularly so if out-




R
P2
UPPER & LOWER LIMITS
OF IGNITION POTENTIAL

-put current becomes discontinuous and when the rectifier forms the major part of the load on the a.c circuit when severe distortion occurs, hunting results, with a period of the order of .5 - 10 seconds, depending on the inertia of the load. The distoriton caused by the motor load current results in a change in firing instant and tends to give a lower output voltage; the machine thus decelerates and draws less current. The waveshape consequently resumes its original form, and the motor then accelerates as the firing instant is corrected, the distortion thus appearing again. This cycle will repeat itself indefinitely.

(4.1.4.2) Bias Shift Control.

Bias shift control is less frequently used owing to the unsatisfactory nature of the control obtained when firing angles are large. The decrease in slope of the wave front of the control voltage causes a variation in firing instant, and fluctuations in output voltage result.

Further, for any set phase relationship between anodes and grids, the phase shift illustrated in Fig. 4.1, is given by

$$\alpha_1 - \alpha_2 = \text{arc Sin} \frac{e_b}{\sqrt{2}\, E_g} \qquad (4.1)$$

The output voltage of the rectifier is consequently

$$V_\alpha = V_d \text{ Cos} \left[\alpha_1 - \text{arc Sin} \frac{e_b}{\sqrt{2}\, E_g} \right] \qquad (4.2)$$

giving an even less satisfactory relationship between angular rotation of the controlling device and shaft speed.

Equation 4.1 indicates that, to avoid the use of large bias voltages, E_g should be low in value. E_g should also be kept low as possible, since during the portion of the cycle when the grids are negative with respect to the cathode, excessive grid voltage will cause grid sputtering, with a consequent decrease in bulb life. Conflicting with these considerations is the fact that a slope of about 20 volts per electrical degree is required for good control. The result is a compromise, r.m.s. voltages of between 300 and 400 volts being used.

(4.1.4.3) Impulse Control.

If automatic speed control is employed, soft control is generally satisfactory, provided that the total output required can be obtained from a single bulb, as small variations in output voltage will be corrected by the automatic regulator.

These variations may arise from changes in the firing instants of the anodes following changes in the ignition potentials as a result of load or bulb temperature. For glass bulbs, ignition potentials are normally 20-30 volts, and Fig. 4.2 shows the effect of changes in this value. Ignition may occur either at P_1 or P_2, the corresponding firing delay angle being α_1 and α_2. These erro cause disproportionately large changes in output voltage and the error worsens as firing delay increases.

If impulse control is used, the whole range of possible ignition potential is covered simultaneously, so that a constant firing delay angle results.

Whenever several grid-controlled bulbs are to work in parallel, impulse control (known as hard control) is essential. If current is to be shared equally between the bulbs; it is imperative that all the grids associated with the same phase are " triggered", i.e. released together. If one grid is released after the other, the associated anode may either fire late or block together, depend-

-ing largely on the grid control system used. If this happens, the remaining anodes must carry the additional load between them.

When only one bulb is used, there is little point in using hard control to maintain precise speed unless the input to the rectifier is stable and compensation is made for the effects of armature I R drop and armature reaction.

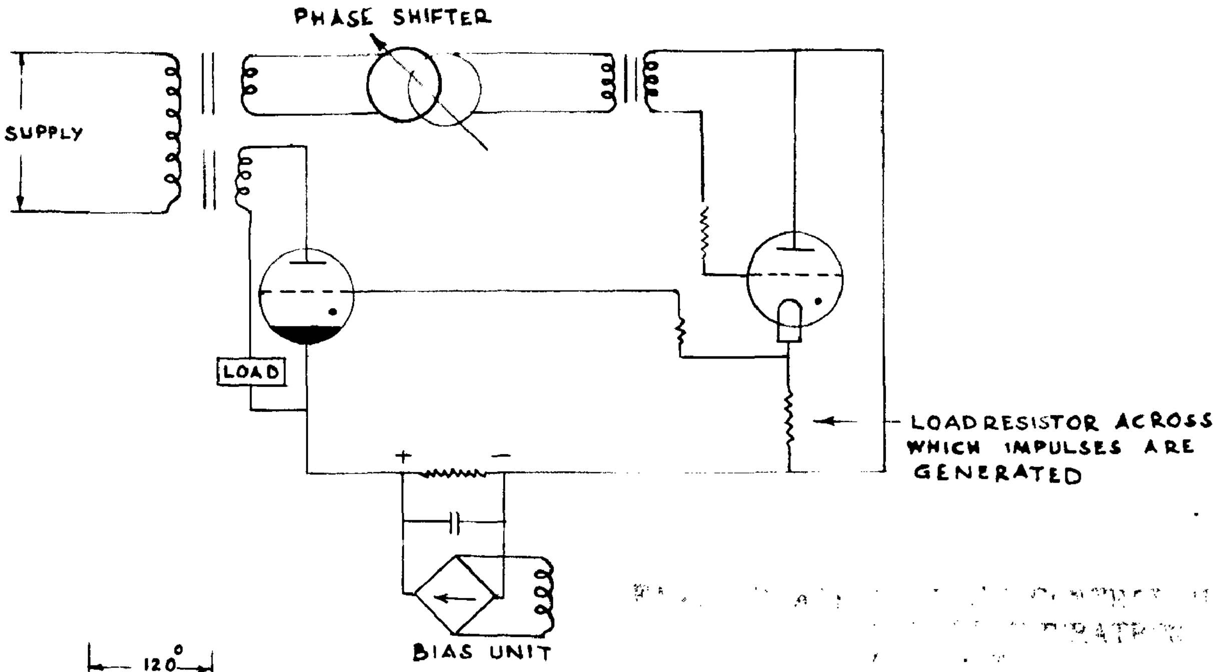
It can be used, however, with advantage when the rectifier is fed from supply having high reactance or when the rectifier forms the major part of the system load.

(4.1.4.4) Generation of Impulses for Grid Control.

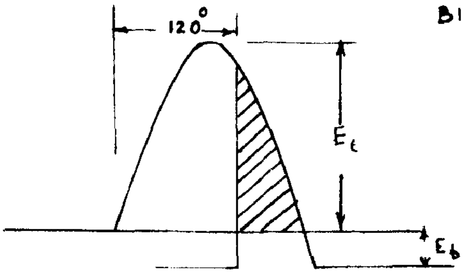
The impulses may be generated in many different ways, mechanically using a synchronously driven commutator; statically using electronic techniques, or statically using electromagnetic techniques.

The synchronous commutator is less often used, it being generally preferable to avoid auxiliary rotating machines if at all possible.

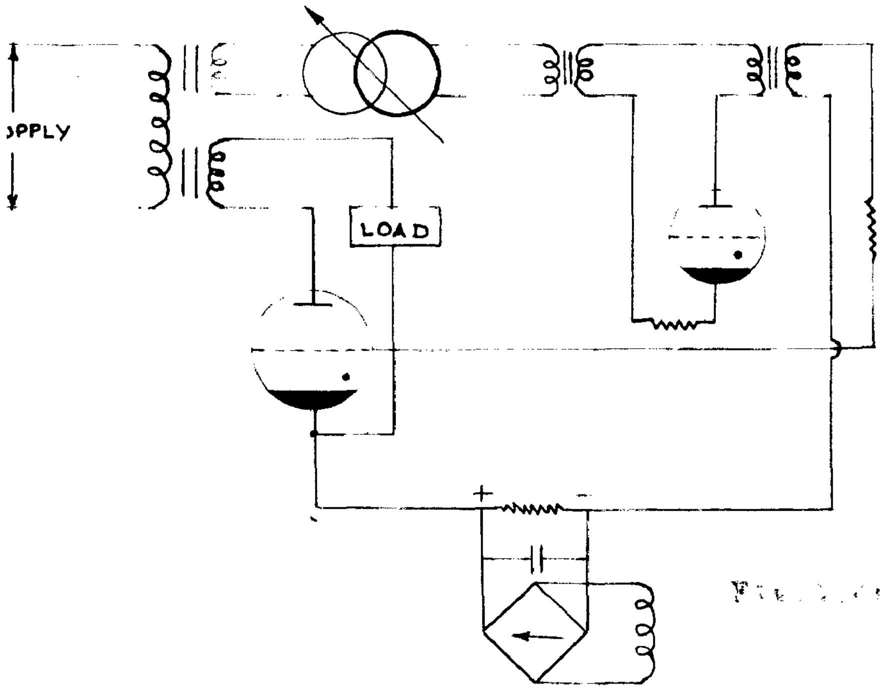
The simple circuit shown in Fig. 4.3, illustrates, one way in which thyratrons may be used to generate steep-fronted impulses, but it has the disadvantage that the control unit and the main bulb are directly interconnected. Using a variation shown in Fig. 4.4, however, it is possible to separate the two. When this system is used, it then becomes possible to replace the thyratron with a small grid-controlled rectifier bulb and to eliminate the disadvantages of possible value failure and heating-time delays when starting up. The first cost of such a unit and its size is, however, three or four times greater than the thyratron equivalents.


PHASE SHIFTER
SUPPLY
LOAD
+
−
BIAS UNIT
LOAD RESISTOR ACROSS WHICH IMPULSES ARE GENERATED

[illegible]


120°
E_t
E_b

[illegible]


SUPPLY
LOAD
+
−

[illegible]

In some circuits using thyratrons, the anodes of the thyratrons are fed with direct current via an oscillatory circuit. In this manner the value can be made to stop conducting once it has started, as the anode current consists of a series of pulses. Phase shift of the impulses generated is achieved by using bias shift technique. With this system the use of a phase-shifting induction regulator is eliminated, and an impulse having constant amplitude over the whole control range is generated.

When electromagnetic equipment is used, the principal alternatives are the use of special peaking transformers having Mumetal shunts, or small shell-type transformers having more or less normal core construction, generating peaks rather by virtue of the circuits in which they are connected. The use of filaments is avoideed, but size and weight of equipment is slightly increased. In many cases this is hardly disadvantage worth noting since above about 20 h.p. the grid-control apparatus will be very small in comparison with other items of equipment.

The simplified circuit of such a control system is shown in fig. 4.5, operation being as follows:

The reactor is arranged so that the current in the transformer primary has a nearly triangular wave form. The core of the transformer saturates once per cycle, and generates two short-duration impulses, one positive and one negative. The latter is suppressed with a suitable metal rectifier. The instant at which the saturation occurs can be predetermined by the amount of current flowing in the control winding. While the triangular current waveform is maintained, the impulse may be shifted in phase with respect to supply without loss of peak height. In practice a shift of about 180° is possible using both positive and negative control currents. With correct design, the impulses have a satisfactory form and main-

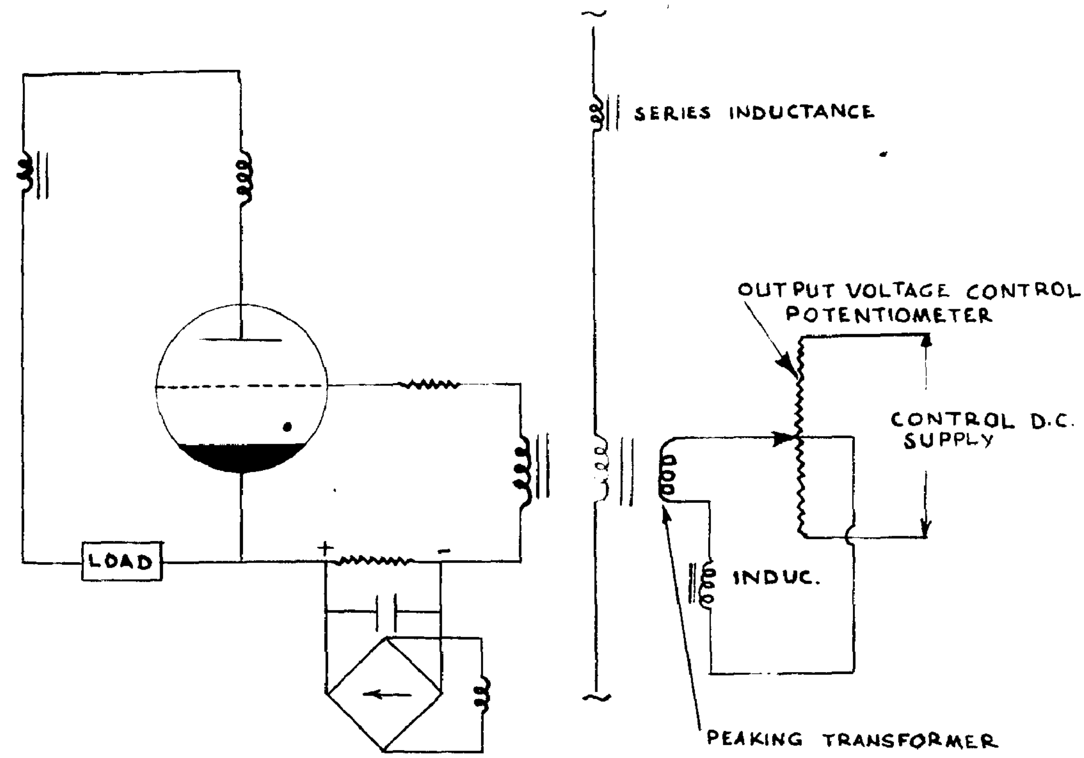


Fig. 4.7. IMPULSE CONTROL WITH [illegible]

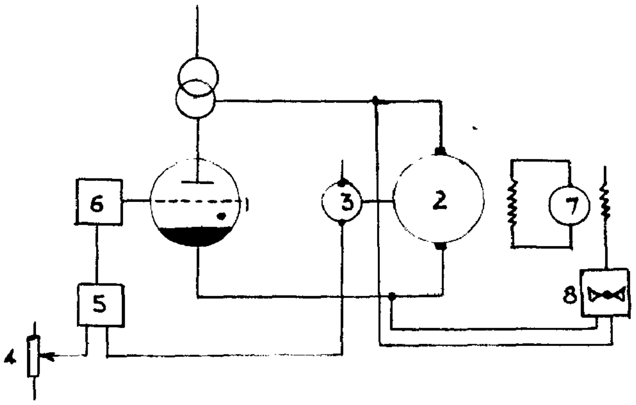


Fig. 4.8. CIRCUIT DIAGRAM OF A [illegible] SYSTEM, WITH HIGH QUALITY [illegible]

1. Rectifier
2. D. C. motor
3. [illegible]
4. [illegible] potentio-meter
5. [illegible]
6. [illegible]
7. [illegible]
8. [illegible]

tains a suitable constant amplitude in operation. Considerable care in design is needed, however to ensure that the wave front remains sensibly vertical - an essential point if bulbs are to be operated in parallel.

With such systems, it is possible to control the motors by using comparatively small power in the regulator circuits, a point which is especially advantageous where motor speed has to be a function of more than one variable, as signal mixingis then possible.

(4.2) Methods of Maintaining Constant Speed.[21,22.]

The aperiodic, vibrationless corrective control of the speed following load surges is extremely important for preventing the motors from fluttering between stands. The desired control speed depends largely on the mechanical data of the operating system. Thus for high speed motors (20 - 30 m/s speed) a considerably faster and more accurate speed control is necessary than for slow speed motors.

(4.2.1) Unit Connected Rectifiers.

For the most exacting control-response requirements with respect to the corrective control of load surges, the unit system offers the best solution. With this arrangement it is possible to exert a direct inertia-free influence on the main circuit of the rectifier by way of control grids.

The motor in Fig. 4.6, is connected direct with the neutral point of the rectifier transformer. For the sake of simplicity the d.c. breaker incorporated in the main circuit is not shown in the diagram. Control with respect to constant speed is based on a comparison of a voltage (at the tachogenerator 3) which is proportio-

-nal to speed with a constant, desired voltage set at the master rheostat on the control desk. Provided the speed does not deviate the difference between these two voltages is practically zero. As soon as the motor is loaded, however, the initial drop in speed brings about a drop in the tachogenerator voltage; the difference compared with the desired value is considerable. This tachogenerator voltage is fed to a control amplifier (5) which then gives the command to the grid control set (6) for the displacement of grid impulse, whereby the voltage at the rectifier is increased. The speed continues to increase until the difference between the tachogenerator and desired voltage is extremely small and the motor has again attained its original speed. In order to eliminate any trace of inertia from the control circuit, the control amplifier(5) and the grid control set are electronically operated. Thus every variation in the speed of the motor initiates, by way of the control grids, an immediate correction in the armature voltage, conducing to a rapid return to the desired speed.

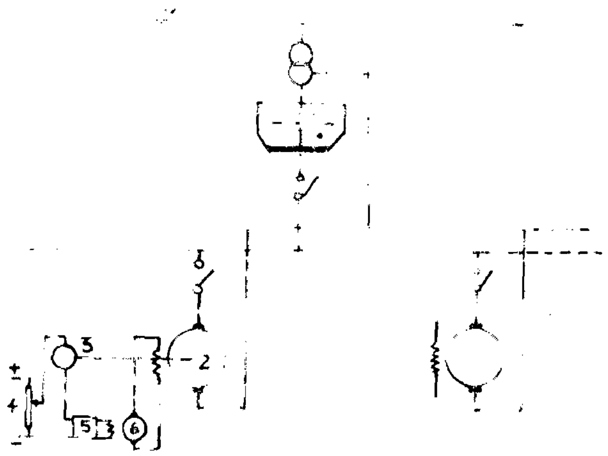
For rapid response to the speed control it is important to have a voltage reserve at the rectifier, for which reason the latter must be designed for a somewhat higher voltage than the moto The same voltage reserve which is available for rapid control is also enlisted indirectly for controlling the automatic field weakening of the motor. If the desired speed is raised by altering the setting, when the motor is rotating at the basic speed, i.e. with full field current and full armature voltage, the rectifier voltage first rises to its maximum value. Since now no speed-control reserve is available, the voltage must be reduced again. A rolling sector regulator measures the voltage and weakens the motor field unti the preset speed at rated motor voltage is attained. This automatic field control corrects slowly. When once the preset speed attained, the field correction regulator retains its position and does not take part when load change occur; the rapid regulation is left exclusively to the grid control.

With such arrangement the constancy of speed is far superior to the conventional speed constancy of a synchronous motor; the rotor angle of the latter is considerably greater than the angle of lag of the controlled d.c. drive.

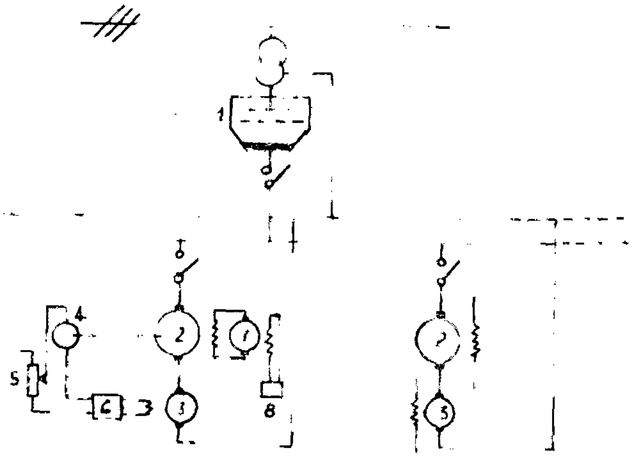
(4.2.2) Busbar Circuit with Field-Regulated Motors.

In view of the fact that in some drives, it is permissible to allow longer control times than those achieved with unit circuits, it is an advantage to select the simpler and cheaper busbar arrangement with field regulation of the motors. A group of motors are connected in parallel by means of busbars which, as a rule, are fed from grid-controlled rectifiers; control with respect to constant voltage is customary.

In this case, too, the speed control of the motors is based on a comparison of the tachogenerator, voltage, which is proportional to speed, with the desired value preset at the control penel.The difference between the two, which corresponds to the amount the speed deviates from the prescribed value, exerts an influence on the motor field by way of an amplifying arrangement (control amplifier 5 and exciter 6) as shown in Fig.4.7. If the speed tends to drop as a result of a load imposed on the motor, a small, additional weakening of the field, introduced via the control circuit, brings it back again to its original value. According to the accuracy and rapidity of the response required of the control, rolling -sector regulators, magnetic amplifiers or electronic amplifiers are employed as control amplifiers. The exciters are built as rapid exciters with



3
2
+
4
−
5
3
6



1
4
2
1
2
5
6
3
3
8
5

fully laminated stators, so that dynamically good control characteristics are assured; for simple cases normal exciters are quite suitable.

The dynamic control quality of this economic solution can be somewhat improved by the addition of a purely electronic excitation. In this case a small rectifier or thyratrons supply the entire excitation output. Finally, reference is made to the arrangement employing a multi-stage magnetic amplifier which supplies its output direct to the field without an intermediate exciter. This system is more suitable for small excitation outputs.

Field control is ideally suitable for all thoseccases where extremely short dynamic control times for the unit or booster systems are not essential. The available control elements enable the control device to be adapted economically to the requirements of operation for all the driving powers required.

(4.2.3) Busbar Connection with Armature Control of the Motors by Rapid Boosters.

If equally rapid control is required with busbar connection as with the unit system, it is necessary to revert to the principle of direct influence on the armature voltage. With this objective in view it is necessary to visualize between the busbars and each motor a rapid booster, i.e. a supplementary generator (Fig.4.8), whose duty is to supply the small additional voltage to the armature circuit for rapidly correcting the load impulses. The speed, however, is adjusted over a wide range by a slow-acting field correcting control which brings the exciting current of the motor automatically up to such a value that the booster has only to supply that additional voltage necessary for correctively controlling the load impulses. The booster can thus be designed for a small rated output. Such boosters, ~~a~~ built as single-stage amplifiers and therefore posses the sturdiness needed for various applications. Special means enable the time constant to be brought to the extremely low value of 20 ms.

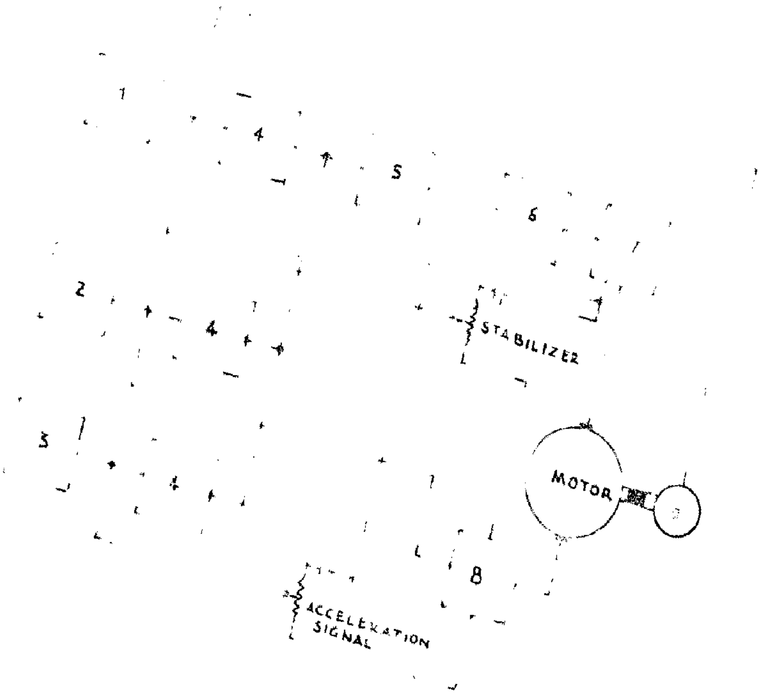
Having regard to the shortest control times, the booster is excited by thyratrons which are controlled by the electronic controller. An effective electronic-circuit ensures great reliability and a long expectation of tube life. The rolling sector regulator is intended for adjusting automatically the field weakening with respect to the speed. The results obtained by this method are comparable with those obtained from a plant operating on the unit system. The decision as to whether to install this or that form of control is not governed by technical considerations, and should rather be considered from case to case by comparing first costs.

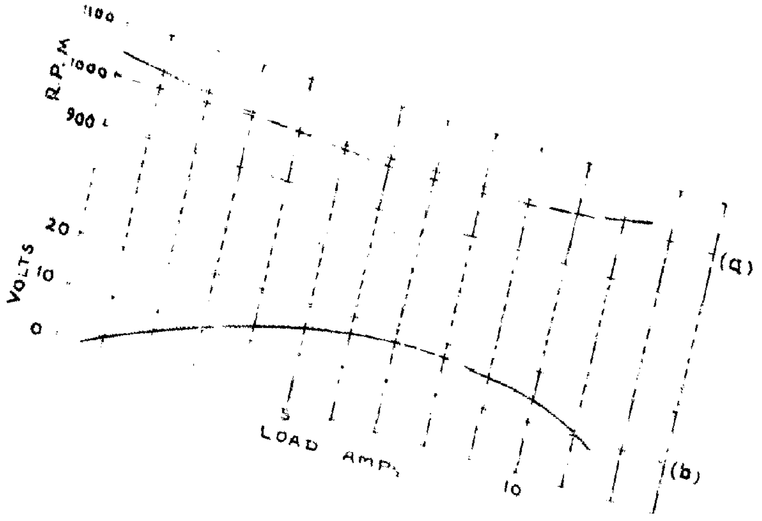
(4.2.4) Sensitivity of Tachogenerator Speed Control Systems.

If an error voltage V_c is required to produce maximum speed, i.e. the reference exceeds the tachogenerator voltage by V_c volts when rectifying, and an error V_c' is required for full speed on inversion, i.e. the tachometer voltage exceeds the reference by V_e' or inversion, the speed for the same reference in the two conditions will differ by an amount corresponding to $V_e + V_e'$. This is an inherent feature of any one-sided system and can be eliminated only by reducing the reference voltage when the control changes from power to inversion. Any such effect is not present in the Ward-Leonard system which is a rival to rectifier-fed systems.

(4.2.5) Loop Control System.[7,23.]

The control scheme is shown in Fig. 4.9. It consists of three main control loops, namely speed control, current limit, and


1
4
5
6
2
4
3
STABILIZER
MOTOR
8
ACCELERATION SIGNAL


1100
1000
900
R.P.M.
20
10
0
VOLTS
5
LOAD AMPS
10
(a)
(b)

acceleration or retardation limit. In the speed-control loop, a reference voltage selected by the operatór's lever is compared with a current signal derived from a d.c. current-transformer and the error voltage is fed into a second pre-amplifier. Similarly, in the acceleration loop, a preset reference is compared with an acceleration signal obtained by measuring the rate of change of the armature voltage and the error is fed to a third pre-amplifier. The combined pre-amplifier output is amplified and used to control the static phase-shifter, producing an armature voltage proportional to the error. In each of the three main loops, subsididary loops are connected for stabilizing the controls.

(4.2.6) Stability of Loop Control-System.[22,23.]

Experience in many applications has indicated that a signal corresponding to the rate of change of armature voltage connected as a negative feedback would stabilize the speed control, and in practice this proved to be correct. The current and acceleration limits can be stabilized by feeding back the rate of change of amplifier output.

(4.2.7) Compensating for I R drop in Motor Armature.[3,7.]

A device known as "I R drop compensator" is sometimes used. A current transformer connected in either the rectifier transformer primary or secondary circuit is used, and the secondary terminals are led to a small metal rectifier whose output provides a bias which is approximately proportional to load. This bias can be used to alter the phasing of the grid control, and thereby adjust the armature terminal volts.

There are several drawbacks to the wide use of this device. First, it is unaffected by the supply fluctuations; Secondly, it constitutes positive feedback and, unless the speed/torque characteristics of the motor concerned are level or drooping, it may cause instability; thirdly, for the same reason, it may cause trouble at starting unless it is slow-acting (whereupon some of its advantages are reduced). Lastly, it does not necessarily provide the same degree of compensation at any speed, as reference to Fig. 4.10, will show. The upper curve shows the speed for constant armature-terminal volts over the load range, whilst the lower curve shows the additional volts required to give contant speed. Despite these drawbacks the circuits have been widely applied.

(4.3.) Methods of Speed Reversal.[6,18,[illegible]]

In some applications, for example in rolling mills, lathes etc., it is required that the drive should be such that its direction of rotation can be reversed. The same principles are applicable to the dynamic braking of motors.

The direction of energy flow in an electronic power converter is determined by the polarity of the voltage, which in turn can be adjusted by control of the ignition angles. Current cannot be reversed in a given converter because of the blocking action of the electronic tubes; therefore, power reversal can be accomplished only by reversing the voltage. Hence the operation of the electronic power converter differs from that of a d-c machine, in which the current reverses to accomplish reversal of power, or regeneration. In applying electronic power converters in applications which require regeneration, it is necessary to make provision in the circuits so that the con-

-verter tubes will carry positive current and will have the circuit voltages impressed in the proper polarity upon the converter when it is desired to regenerate. Many methods are used and those which are common are discussed in the following paragraphs:

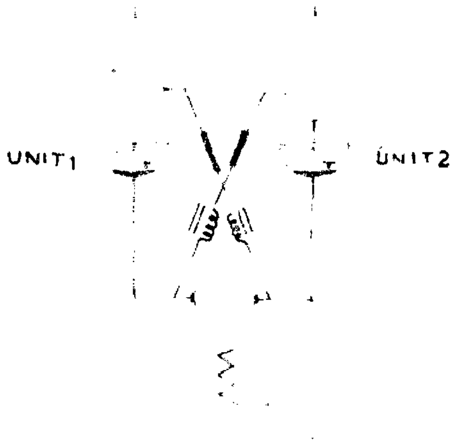
(4.3.1) Dual Mercury-Arc Rectifiers for Motor Armature

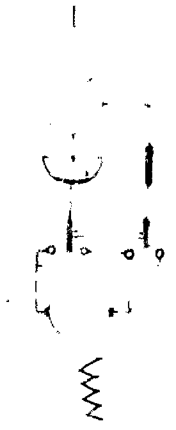
In this method two mercury-arc rectifiers are used with one reverse-connected. Such an arrangement provides a circuit for current in either direction for the drive motor. This method has been applied extensively in Europe using continuously excited tubes. Fig. 4.11(a) shows typical circuits and operation of the reversing drive using dual mercury arc rectifiers to feed the motor armature. In this method reactors are to be used to withstand the instantaneous voltage between the rectifier units and to limit the resulting circulating current. The reactors are also required to limit the ripple in the motor current, especially at the conditions of high rectifier delay and with inverter operation.

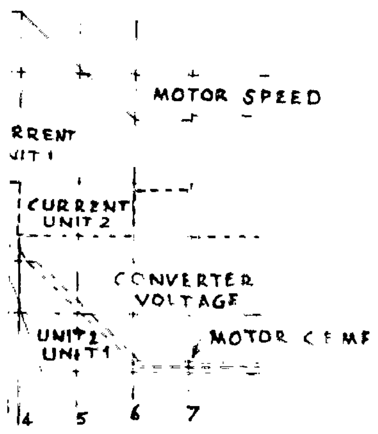
This electronic converter circuit must be completely symmetrical with respect to voltages and number of tubes for each direction of drive-motor rotation, as the same amount of rectification and inversion is required for each direction of rotation. No dissymmetry is possible in many applications where there can be fewer inverter units than rectifier units and in which the inverter units can be operated with a higher d-c winding voltage.

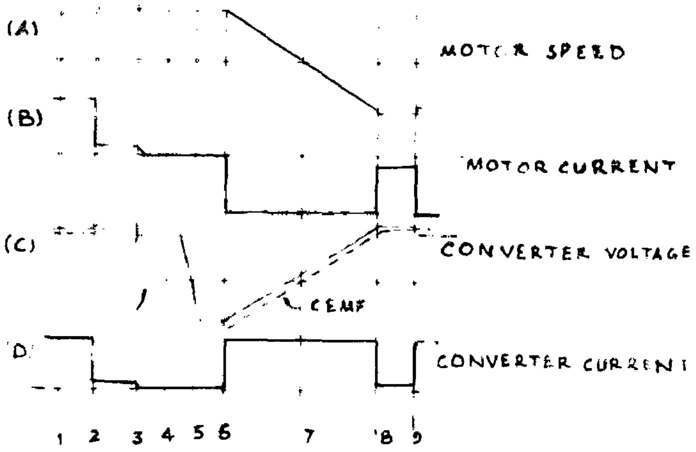
A typical operation sequence during motor reversal using the arrangement is as follows:

(1) At instant 1 the motor is loaded in the forward direc-


UNIT1
UNIT2




MOTOR SPEED
RRENT
NIT 1
CURRENT
UNIT 2
CONVERTER
VOLTAGE
UNIT2
UNIT1
MOTOR CEMF
4
5
6
7


(A)
MOTOR SPEED
(B)
MOTOR CURRENT
(C)
CONVERTER VOLTAGE
CEMF
(D)
CONVERTER CURRENT
1
2
3
4
5
6
7
8
9

-tion. The ignitron converter unit 1 is operated at a small rectifier delay so that its average output voltage is lower in magnitude than the inverter counter voltage of unit 2.

(2) At instant 2 the motor load is removed and the motor is now operating at a constant speed without load.

(3) At instant 3 ignitron converter 1 is delayed to an inverter operating condition and its current is blocked when its voltage is less than the motor counter emf.

(4) At instant 4 unit 2 is advanced slightly so that its counter-voltage is less in magnitude than the motor counter emf. Current 0 now is carried in converter 2 during the interval 4 to 6. The motor decelerates during the interval 4 to 5. The ignition angles of unit 2 must be advanced so as to provide approximately constant current at about rated current as the motor decelerates.

(5) At instant 5 the motor speed is zero and converter unit 2 is operating as a rectifier to supply the motor armature resistance drop. Further advance in the firing of ignitron converter 2 will cause it to continue to operate as a rectifier and to accelerate the motor in the reverse direction during interval 5 to 6.

(6) At instant 6 the motor is running in the reverse direction and is supplied by ignitron unit 2 operating as a rectifier.

(7) At instant 7 the load is applied in the reverse direction

This arrangement has the disadvantage of requring some duplicate converter equipment. Each ignitron converter unit operates at an average duty cycle of one half that of the drive motor.

Since the peak motor loading contributes in determining the required number and size of ignitrons, this arrangement will in many applications require a greater number of ignitrons than that of other method which use a single ignitron converter.

An alternate circuit arrangement and operation of this system is to omit the reactor in each converter and to release only one converter at a time so as to eliminate circulating currents between the ignitron converter units. The reactor to limit ripplecon then be a single reactor in the motor branch. The operation sequence of this arrangement is similar to that of Fig.4.11(b). except that when it is desired to decelerate in the forward direction, rectifier unit 1 is blocked completely and unit 2, which was previously blocked, is now released to fire as an inverter. Thus, only one ignitron unit is released at a given instant and no circuit is released between the two ignitron converter units for circulating current to flow.

(4.3.2) Single Electronic Converter with Reversing Switch in Armature Circuit.

To eliminate the disadvantage of having two reverse connected mercury-arc rectifiers, it is necessary to provide a means to reverse the voltage on a single converter when it is desired to have regeneration. This method has been employed extensively in Europe using continuously excited tubes.

A typical operation of sequence during motor reversal for the arrangement shown in Fig.4.12(a) is as below:

(1) First of all initially the motor is loaded in the forward direction. Current is conducted from the rectifiers to the motor through the armature contacts.

(2) At instant 2, the load is removed. The motor is now operating at constant speed with friction load.

(3) At instant 3, the reversal cycle is begun by lowering the the rectifier voltage by phase delay so that it is a small amount below the motor counter emf. This results in blocking of the motor current. The contacts can open at this time with no current to interrupt and with a minimum of voltage across them.

(4) At instant 4, armature contacts are opened to disconnect the circuit between the rectifier and the motor. During the interval from instants 4 to 6, the motor is coasting with its armature open circuited.

(5) Between instants 4 and 5, the rectifier firing angles are changed from rectification to maximum voltage inversion. This change is completed at instant 5.

(6) At instant 6 the motor contacts are closed in reversed fashion for reverse rotation which connected the circuit so that the motor can regenerate into the rectifier convenier.

(7) During interval 6 to 7 the rectifier angles are advanced as the motor decelerates, so that the motor current is nearly constant and is at about rated current. When the motor speed becomes zero at instant 7, the converter is operating as a rectifier to supply the armature resistance drop.

(8) During interval 7 to 8 further advance in firing will cause the ignitrons to continue to operate as rectifiers, and the motor will accelerate in the reverse direction.

(9) At instant 8 the motor is up to full speed in the reverse direction and is running with friction load.

(10) At instant 9 load is applied in the reverse direction.

This arrangement has the advantage that only one mercury arc rectifier is required and its duty cycle is the same as that of the main motor. The disadvantage of this arrangement is the requirement of the reversing contactor and the large number of operations which result in considerable maintenance.

(4.3.3) Single Electronic-Converter for Armature and means to reverse Field.

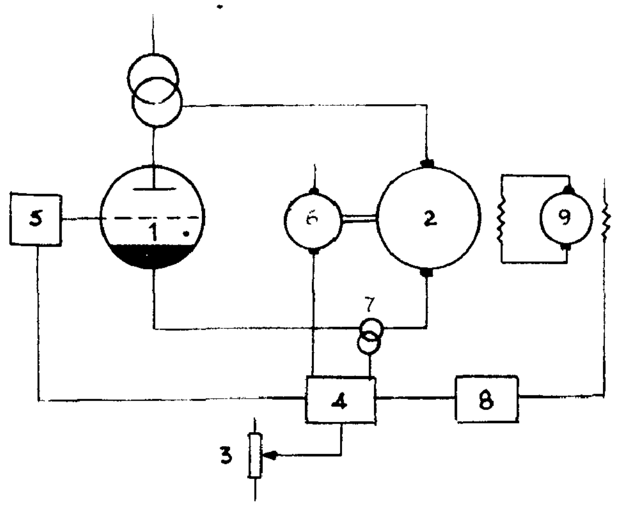
Another method using a single electronic converter is to obtain reversal of motor voltage by means of reversing the field. To reverse the motor as rapidly as possible it is necessary to over-excite the field in order to cause it to reverse in a minimum of time. This can be accomplished by supplying the field from a rotating exciter or by feeding it from an electronic rectifier system using two reverse connected converters. Provision must be included to de-energize the armature current by reducing or blocking the rectifier voltage before de-energizing the field or in event of loss of field. This method has been studied and applied in Europe but not as extensively as the previous two methods.

A typical operating sequence during motor reversal of an arrangement using the single electronic converter circuit of Fig. 4.13(a) is as follows:-

(1) At instant 1 in Fig. 4.13(b) the motor is carrying load at rated speed in the forward direction.

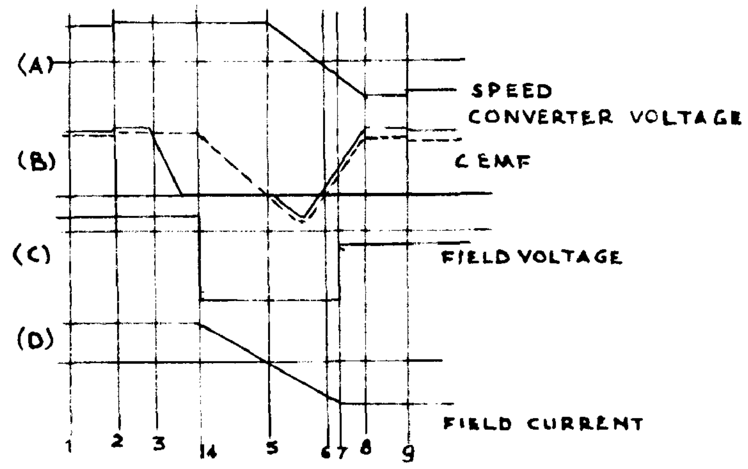
(2) At instant 2 the work load ends and the motor is running at rated speed and no load.

(3) At instant 3 the reversing cycle is begun by reducing the armature voltage by phase control of the electronic converter. The armature current is blocked when the converter voltage becomes less than the counter emf.


5
1
6
2
9
7
4
8
3

[illegible]

[illegible]


(A)
(B)
(C)
(D)
SPEED
CONVERTER VOLTAGE
C EMF
FIELD VOLTAGE
FIELD CURRENT
1
2
3
14
5
6
7
8
9

[illegible]

(4) During interval 4 to 5 the field voltage is reversed and is several timesthe rated value. The field current is forced to zero by regenerative action of the rotating exciter. If a dual ignition convertor system is used on the field circuit, one of the units will operate as an inverter during the interval.

(5) During interval 5 to 7 the field is built up in the opposite polarity. During interval 5 to 6 the main convertor is inverting to provide the required current and torque to cause the motor to decelerate. At instant 7 the field current is at rated value in the opposite polarity and the field voltage reduced to the normal magnitude.

(6) At instant the motor speed is zero and the converter is operating as a rectifier to supply the armature resistance drop.

(7) During interval 6 to 8 the converter operates as a rectifier to accelerate the motor in the reverse direction.

(8) At instant 8 the motor is at rated speed in the reverse direction and is without load. The field is at its normal value and the armature current is low.

(9) At instant 9 the load is applied with the motor running in the reverse direction.

This arrangement has the advantage of using a single electronic converter for the armature circuit and thus obtaining the best possible utilization of the tubes. The greatest disadvantage of this arrangement is that this method inherently requires a greater time for motor reversal with a conventional motor than the method using dual converters for the armature circuit. This additional time is required to obtain decay and reversal of field, which has a time constant of the order of several seconds. One or more of the following methods may be used to shorten the motor reversal time:-

(1) *Overexcite the Field*:- By applying over voltage of 5 to 10 times normal field voltage, the time required to reverse the field can be minimized.

(2) *Laminate the Motor frame*:- The use of a laminated motor frame will reduce the circuits for eddy currents and thereby allow the field flux to be changed faster. The motor construction is more expensive but will result in a much lower field time constant.

(3) *Use higher armature current*:- Operation with higher armature current during deceleration can be used to obtain the required torque while the field current is being built up to the opposite polarity.

CONCLUSION

The various results obtained by the application of theoretical formulae are comparable to those obtained by experimental observations. So the theoretical analysis can be of great help where the new equipment is to be installed. In such cases it is always desirable to find out the rating of the equipment at the first instance and this can easily be done by using theoretical formulae.

As already seen, the simple half-wave rectifier d-c. shunt motor combination is not a very good practical proposition. It has drooping speed-torque characteristic and so, as such, will not be suitable for constant speed drives. For constant speed at any load, the various methods, already discussed, are to be applied. The starting torque, acceleration etc. are also poorer, as compared to a pure d-c shunt motor. However, the overall efficiency of the half-wave rectifier d-c shunt motor system is comparable to that of the Ward-Leonard system, and so it can be prescribed in place of conventional Ward-Leonard system.

Now-a-days, various types of rectifier d-c motor combinations are available and modern trend is to replace the conventional motor-generator sets for d-c supply. However, the half-wave rectifier d-c shunt motor system is a new-comer and many improvements are necessary before this system is practicable in industry. However, the improvements can be done on the lines already suggested in the dissertation.

The author believes that the above system will get impetus in industry in the automatic, closed loop, speed control systems. As already seen, the half-wave rectifier d-c shunt motor system is not a practical proposition, at present, in the industrial drive schemes and for that purpose many refinements are desirable. However, this system can be satisfactory in the control applications where the load is low and a flexible controlled prime mover is required.

BIBLIOGRAPHY

1. Calverley, H. B, Jarvis, E.A.K., and Williams, E.: " Electrical Equipment For Rectifier Locomotives", Journal I.E.E., 1957, Vol. 104, Part A, page 341.
2. Wittaker, G. C., and Hatchinson, W. M.: " The Pennsylvania Railroad Ignitron- Rectifier Locomotive", Transactions of the A.I.E.E., 1952, Vol.71, Part II, page 37.
3. Humphrey, A. J., and Shrider, K. L.: " D-C Motor Drive Employing the xatron, a grid-controlled mercury arc rectifier, a variable-speed", Transactions of the A.I.E.E., 1957, Vol.76, Part III, page 1245.
4. Mulhern, M. J., and Crawford, S. N.: " Rectifier equipment for electronic d-c motor drives", Transactions of the A.I.E.E., 1950, Vol. 69, page 211
5. Matta, U.: " The utilization of mutators in hot-rolling mills"', Brown-Boveri Review, 1956, Vol.43, page 452.
6. Hagensick, C. G., and Cham, E. J.:" Analysis of ignitron rectifiers for reversing - mill drives", Transactions of the A.I.E.E., 1958, Vol.77, Part II, Page 259.
7. Bingley, P.: " The characteristics and control of rectifier-motor variable - speed drives", Journal I.E.E., 1952, Vol.67, Part I, Page 189.
8. Vedder , E. H., and Puchlowski, K. P.: " Theory of rectifier - d.c. motor drive", Transactions of the A.I.E.E., 1943, Vol.62, Page 863.

9. Puchlowski} K. P.: " Voltage and current relations for controlled rectification with inductive and generative loads", Transactions of the A.I.E.E., 1945, Vol.64,Pp.225.

10. Puchlowski, K. P.: " Electronic Motor Control", Electronic Motor Control", Industrial Electronics Reference Book(book) by Electronics Engineers of the Westinghouse Electric Corporation, page 533.

11. Pfaff, R. W.: " Characteristics of phase-controlled bridge rectifiers with d-c shunt motor load", Transactions of the A.I.E.E., 1958, Vol. 77, Part II, page 49.

12. Mandl, A.: " Single phase 50 c/s a.c. traction using a rectifier", Journal I.E.E., 1955, Vol.102, Part A,Pp.339.

13. Schroeder, T. W., and John, C. A.; " The black band method of commutation observation", Journal of the A.I.E.E.,1941, Vol.60, page 446.

14. Shapiro, I.L.: " Automatic electric rectifier drives for lathes", Direct current, 1959, Vol.4, page 212.

15. Reiter, C. R., and Ammerman, C. R.:" Increased losses in a d-c motor when operated from grid controlled rectifiers", Transactions of the A.I.E.E., 1952, Vol.71, Part II,page 77.

16. Harris, L. D.: " Servomechanism Characteristics of d-c motor driven by controlled rectifiers", Transactions of the A.I.E.E., 1951, Vol. 70, part II, page 1582.

17. Schmidt, A.(Jr), and Smith, W.P.:" Transactions of the A.I.E.E., 1948, Vol.67, page 679.

18. Dunaiski, R. M.: " The effect of rectifier power supply on large d-c motors", Journal of the A.I.E.E.,1960,Vol.79, Part III, page 253.