SPEED CONTROL OF A D.C. MOTOR WITH THE HELP OF SERIES SATURABLE REACTOR

by

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C E R T I F I C A T E

CERTIFIED that the dissertation entitled " SPEED CONTROL OF A D.C. MOTOR WITH THE HELP OF SERIES SATURABLE REACTOR" which is being submitted by A.D. Shangarpawar in partial fulfilment for the award of the Degree of MASTER OF ENGINEERING in ADVANCED ELECTRICAL MACHINES of the 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 8 months from January 1967 to August 1967 for preparation of this dissertation at this University.

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CONTENTS

N O M E N C L A T U R E

N_{c1}	Number of turns on control winding 1(which is connected in series with d.c. motor).
N_{c2}	Number of turns on control winding 2, to which error voltage is applied.
N_{c3}	Number of turns in control winding 3 , to which constant D.C. voltage is applied.
I_{c1}	Current in control winding 1.
I_{c2}	Current in control winding 2
I_{c3}	Current in control winding 3.
N_L	Number of turns in load winding.
R_o	Output resistance of load circuit.
L_o	Inductance of load circuit.
$T_o = L_o/R_o$	Time constant of load circuit
$N_c I_c$	Total control ampere turns.
$E_{d.c}$	D.C. output volts at the rectifier bridge d.c. terminals
Ω_m	Speed in radians / second of d.c. motor.
Ra	Motor armature resistance.
La	Motor armature inductance.
Ta	Motor armature time constant.
Tm	Mechanical time constant
Jm	Moment of inertia of the motor.
f_m	Viscous friction coefficient.
K_b	Back voltage constant

K_1	Torque constant
$I_L = I_a =$	Motor armature current.
R_{c1} and L_{c1}	Resistance and inductance of control winding 1
T_{c1}	Time constant of the control winding 1
R_{c2}, L_{c2} and T_{c2}	represents resistance, inductance and time constant of control winding 2.
$E_{(n)}$	Voltage at generator armature, terminals which is proportional to Motor speed.
V_r	Reference voltage
E_{error}	Error Voltage
I'_{c2}	Current in control winding 2 due to $E(n)$
I''_{c2}	Current in control winding 2 due to V_r

SYNOPSIS

D.C. motors are used for special purpose drives, where it is necessary to control speed, torque, power rate of acceleration and retardation etc. "Ward Leonard Principal' of speed control is in great use today in very many forms. Now-a-days generally a.c. supply is available. To supply the d.c. motor converting units are required.

A scheme based on armature voltage control method of speed is built. The controlling unit being series saturable reactor and the converting unit being rectifier bridge. The principle underlying the system is explained in the following lines. As the load increases the current through compensating winding increases. Hence the ampere turns on saturable reactor core increases. This results into higher saturation and consequent reduction in reactanse of saturable reactor. So the drop across it reduces. Thus the voltage at motor armature terminals can adjust itself, with load changed in a desired manner, resulting into constant speed.

The saturable reactor has been constructed and used in the scheme. An attempt has been made to analyse the scheme. A methodology has also proposed for different speed settings.

CHAPTER I

1.1. INTRODUCTION

1.2. NORMAL METHODS OF SPEED CONTROL OF D.C. SHUNT MOTOR

1.3. MAIN METHODS OF SUPPLYING ADJUSTABLE VOLTAGE TO ARMATURE OF D.C. MOTOR FROM A.C. SUPPLY

1.4. SCOPE OF WORK

1.1. INTRODUCTION

Expansion of industrial activities, mechanisation of manufacturing process and automation of industrial processes have greatly increased the use of motors and their control in industry. When electric motors were first introduced manual control was used. Many industrial processes require automatic control of motors according to the process requirements.

'Magnetic Control' is one of the ways to achieve automatic control. An important advantage of magnetic control is the ease with which the performance of motor can be adjusted and maintained.

Three phase a.c. power is available, today, in all industrial areas. So generally a.c. motors are used where drive requirements can be satisfied by comparatively simple characteristics of a.c. motors. As d.c. power distribution for industrial use is uneconomical, the use of d.c. motors for drive applications is decreasing. Their principal use is for special purpose drives, where it is necessary to control speed, torque, power, rate of acceleration and retardation dynamic braking and so forth.

For these drives which needs the superior speed control characteristics of d.c. motors, individual conversion units are provided to convert a.c. power from the distribution system to d.c. power for supplying individual d.c. motor.

1.2. NORMAL METHODS OF SPEED CONTROL OF D.C. SHUNT MOTOR

The outstanding characteristic of d.c. motor is its adaptability to control of its torque and speed. The steady state output characteristics are given by

$$T_m = K_a \phi I_a$$

and $$v_m = \frac{V_t - I_a R_a}{K_a' \phi}$$

Where I_a and V_t are the steady state values of the armature current and terminal voltage and K_a is a constant fixed by design of the armature winding. Control of torque and speed can be obtained by variation of any of the quantities ϕ, I_a and V_t. So the normal methods of speed control of d.c. motors are,

1.2.1. Armature Resistance Control

The speed can be reduced for a given torque by insertion of an adjustable resistance in series with armature. This method is used for starting or for short time slowdowns. The disadvantage is powerloss in resistor.

1.2.2. Constant Armature Voltage controlled filed Excitation

This method is simple and satisfactory for speed control of shunt or compound motor over a speed range of about 4 or 5 to 1. This field excitation is controlled by variation of voltage applied to field circuit or by an adjustable resistor in series with it. The power loss is comparatively small.

1.2.3. Constant Armature Current, Controlled Field Excitation.

The chief obstacle to more wide spread use of this method seems to be constant armature current source.

1.2.4. Constant Field Current Controlled Armature Voltage

This system is the most commonly used when manual or automatic control of speed is required over a wide range in both directions of rotation. The controlled armature voltage may be obtained from controlled rectifiers receiving power from a.c. source or it may be from a seperately excited d.c. generator.

This adjustable armature voltage system of motor speed control was invented by 'Ward - Leonard' This is now a days used for wide variety of feedback control systems. In their original scheme, a seperately excited generator was used as power source and voltage adjustment was obtained by adjusting the generator field. Initially, the adjustable voltage system was used on drives requiring close speed control over a wide range. Examples of applications are steel rolling mills, mine hoists, paper making machines and machine tools. The most important characteristics of 'Ward-Leonard' controls may be summarised as :

1. Considerable power amplification in rotating machine enabling drives of larger ratings to be constructed using relatively low power control electronic technique.
2. Ability to provide stepless speed control of d.c. motor.
3. Ability to provide +ve or -ve torque at motor output shaft.
4. Easy adaptibility for either manual or automatic control systems.

The 'Ward-Leonard' principle of armature voltage control of D.C. motor for speed control is used widely with different a.c. to d.c. conversion units for either open loop or automatic control of motor speed.

1.3. THE MAIN METHODS OF SUPPLYING ADJUSTABLE VOLTAGE TO ARMATURE OF D.C. MOTOR FROM A.C. SUPPLY .

i. Shunt Generator for Supplying motor armature power.

ii. Semiconductor rectifier with induction regulator.

iii. Thyratron rectifier.

iv. Ignitron rectifiers.

v. Magnetic amplifiers.

The use of d.c. motor at a given spot in the plant with 'spot conversion' equipment is the most economical method of providing a high performance, adjustable speed drive. Once the conversion equipment has been provided, speed control of motor can be accomplished by control of armature voltage with little additional investment. Hence adjustable voltage control is used universally, Whenever 'spot conversion' is indicated. The characteristics of above mentioned conversion apparatus are given below :

1.3.1. Shunt Generator for Supply of Motor Armature

1. Voltage and current can be easily reversed by manipulating reversible generator and motor field.
2. Overload capacity of motor and generator are high.
3. A.C. and D.C. circuits are independent.
4. Reflection of D.C. load peaks in a.c. system is low.
5. Use of synchronous motors for driving d.c. generator will improve power factor of a.c. system.
6. Maintenance is high due to mechanical wear but easily available.
7. Noise and vibration more.
8. Conversion efficiency is comparatively low.
9. Excitation requirements are high and time constant long.

1.3.2. Semiconductor Rectifiers with Induction Regulator

1. Voltage regulation is inherently low, power factor and conversion efficiency are high.
2. These are no problems in regard to d.c. voltage wave shape.
3. A.C. and D.C. power circuits are connected electrically.
4. Response time is slow.
5. Moving parts of induction regulators require maintenance.

1.3.3. Thyratron Rectifiers

1. Economical in lower h.p. sizes, high efficiency and low idealing losses.
2. Very low control power requirements, fast response, easily regulated to a high degree of accuracy.
3. Weight and space requirements are low can be well mounted in the lower h.p. ratings.
4. No mechanical maintenance.
5. Tubes require warm up time.
6. Tube life is limited because of hot cathode

1.3.4. Ignitron Rectifiers

1. Completely static, no mechanical maintenance is required.

2. Efficiency and power factor are high, idealing losses are low.
3. Time constant is extremely short, control power requirements are low, regulators of high accuracy are practicable.
4. Conversion equipment is compact, space requirements and weight are low.
5. Cooling water is needed.
6. Poor utilization at 230 volts.
7. A.C. and D.C. circuits are connected electrically.
8. Because of chopped up D.C. current waves, these may be telephone interference problems.

1.3.5. Magnetic Amplifiers

1. Conversion equipment is completely static, components inherently possesses long life.
2. There is no warm up time, so that conversion equipment is immediately available.
3. Floor space required and weight are low. There are no foundation problems and the convertor is shock and vibration resistant.
4. Response time is short.
5. Efficiency of conversion is high and idealing. losses are low.
6. Power factor is low at low speeds.
7. Over load capacity is low.

8. A.C. and D.C. circuits are interconnected electrically.

9. Fan cooling is needed for efficient utilisation of active materials.

Thus it is seen that a d.c. motor control scheme can be built utilising basic A.C. supply and any one of above mentioned converting and armature voltage controlling equipments.

1.4. SCOPE OF THE WORK

In this work it was proposed to assemble a scheme for speed control of seperately excited d.c. motor. The scheme is based on basic Ward Leonard Principal. Series saturable reactor is to be used to control the voltage at motor terminals when supplied from A.C Single phase supply through reactor and rectifier conversion unit. The saturable reactor and other units of scheme are to be constructed and the circuit is to be sett up.

It is also desired to analyse the scheme and check for stability of scheme. In short the work comprises of :

1. Construction of components.
2. Study of components and setting of scheme.
3. Testing of the scheme.
4. Analysis of the scheme.
5. And to propose general methodology.

CHAPTER II

2.1. SATURABLE REACTOR OR MAGNETIC AMPLIFIER CONTROL OF D.C. MOTOR

Control of current in A.C. circuit by using auxiliary d.c. excitation to vary the impedanse of saturable reactor with the load has been known for many years. One application has been the control of lighting loads. The early use of saturable reactors for motor control was handicaped by unsufficient development in rectifiers. In recent years dry disk rectifiers of selenium, or copper oxide have proved a convenient means for rectification of load current in order to obtain d.c. output. Rectifiers for armature control of d.c. motors were first used about 20 years ago, but until 1954-55 that kind of drive has not been of major importance, primarily because of excessively dropping speed torque curve. Recent engineering developments, however has improved the performance of the rectifier motor system so that it has become one of the most perfected drives.

With the development in rectifier technique, the use of magnetic amplifier or saturable reactors in d.c. motor speed control systems increased rapidly. Presently one of the most important and useful application of saturable reactor or magnetic amplifier has been in the control of the d.c. motors, particularly speed. It is generally suitable for powers of the order of a few kilowatts, for higher powers of the motor it is economical to use a rotary amplifier. Saturable core devices offered a robust alternative to electronic equipments for control of d.c. motors.

There are two main reasons for an extremely poor speed regulation of the elementary rectifier drive for d.c. motors.

1. Armature I R drop.
2. Consequent decrease in armature voltage with increasing torque.

The later reason is of prime importance and has a predominant effect on the behaviour of a rectifier drive. A closed loop compensation for this decrease in armature voltage effects the speed regulation considerably. Closed loop regulators have been constructed using "Ward-Leonard" systems using either thyratrons or magnetic amplifiers to control generator field excitation. The recent advent of silicon controlled rectifiers has enabled significant improvements to be made in this type of equipment in the following ways :

i. Efficiency
ii. Realiability
iii. Performance

Nowadays a good number of closed loop control systems have been developed using magnetic amplifiers.

2.2 REVIEW OF LITERATURE

From the study of literature it seems that the development of magnetic amplifier controlled motor is very recent, not more than two decades.

2.2.1

W. Walter[1] has given a circuit for voltage control using magnetic amplifier which is further used in speed control of d.c. motors. A patent was obtained by D. W. Fath and F. S. Horner on "Saturable reactor Ward Leonard control system in June 1954. An illustrated description of a combination of saturable reactor and selenium rectifiers for controlling lift motors by means of a Ward Leonard set was given by G. Sichling and H. Watzinger. Magnetic amplifier control of d.c. generator driving a group of d.c. motors for accurate control of relative speed and cut in a continuous process' is described by E. G. Ager and D. C. Pettit.[2]

2.2.2

A Kusko and J. G. Nelson[3] dealt in detail about magnetic amplifier control of d.c. motors. They made an analytical and experimental study of the steady state operation of d.c. motor with armature power supplied through metalic rectifiers and controlled by saturable reactors. They have described the following cases.

i. Operation of a d.c. motor with armature voltage control by magnetic amplifier.

ii. Saturable reactor control of armature current and

iii. Magnetic amplifier control of armature voltage with compensation proportional to armature current.

To describe more specifically, the speed torque characteristics of the motor were determined for above mentioned cases. The effectiveness of simple feedback connections and the use of external armature circuit inductance was ascertained in improving the speed regulation. An expression for speed of the motor, in terms of torque and firing angle was derived. The firing angle is assumed to be a function of control current only. The circuits for all above mentioned cases along with experimental curves are given.

2.2.3.

W. Leonhard (4) presented a paper on 'Speed control of D.C. Motor using a 'Magnetic Amplifier' It deals with simplified analysis of the open loop characteristics of a system using a magnetic amplifiers for speed control of separately excited motor with two cases i.e., rectifier which supplies to the armature of d.c. motor. Velocity feedback in which a voltage proportional to the speed of the motor is applied to control winding of magnetic amplifier is described. The motor is driving a lathe. Experimental results of the system are given.

2.3. THE SYSTEM ASSEMBLED

2.3.1.

A simple closed loop , speed control system for the seperately excited d.c. motor with constant field excitation, using a series saturable reactor is assembled. The Schematic diagram representation of it is shown in Fig. 1 .

The system consists of the following components

i. Seperately excited d.c. motor.
ii. A series saturable reactor.
iii. A rectifier bridge.
iv. A d.c. generator coupled to the motor

The detailed description of components follows in the next Chapter.

2.3.2. Description of the System

The load windings of saturable reactor are supplied from the 230 volts a.c. terminals. The load winding is further connected to the a.c. terminals of silicon rectifier bridge. The d.c. terminal of rectifier are connected in series with the shunted control winding, to the armature terminals of the motor. The motor field is seperately excited and kept constant. The motor is mechanically coupled to a d.c. generator which along with connected load serves the purposed of load on the motor. The generator armature voltage is compared with d.c. reference voltage . The error voltage is fed to the another control winding 1,2 of saturable reactor. The third control winding 3 , is seperately provided with constant voltage d.c. source.

2.3.3. Working of the System:

The aim of the system is to keep the motor speed constant, irrespective of motor load variation, at a present value, so as to make the speed of the motor independent of torque i.e. load current.

The a.c. supply voltage is rectified by silicon rectifier bridge, which is controlled by the saturable reactor. The load winding are supplied by 230 volt a.c. and the voltage across the armature of motor is adjusted by controlling the current in control winding 3, to get the desired speed at a load in between no load and maximum load condition of the motor. The output voltage at the generator armature is compared with constant d.c. reference voltage so that no error voltage comes across the control winding 2; of saturable reactor. The reference signal corresponding to desired speed and the generator armature terminal voltage which

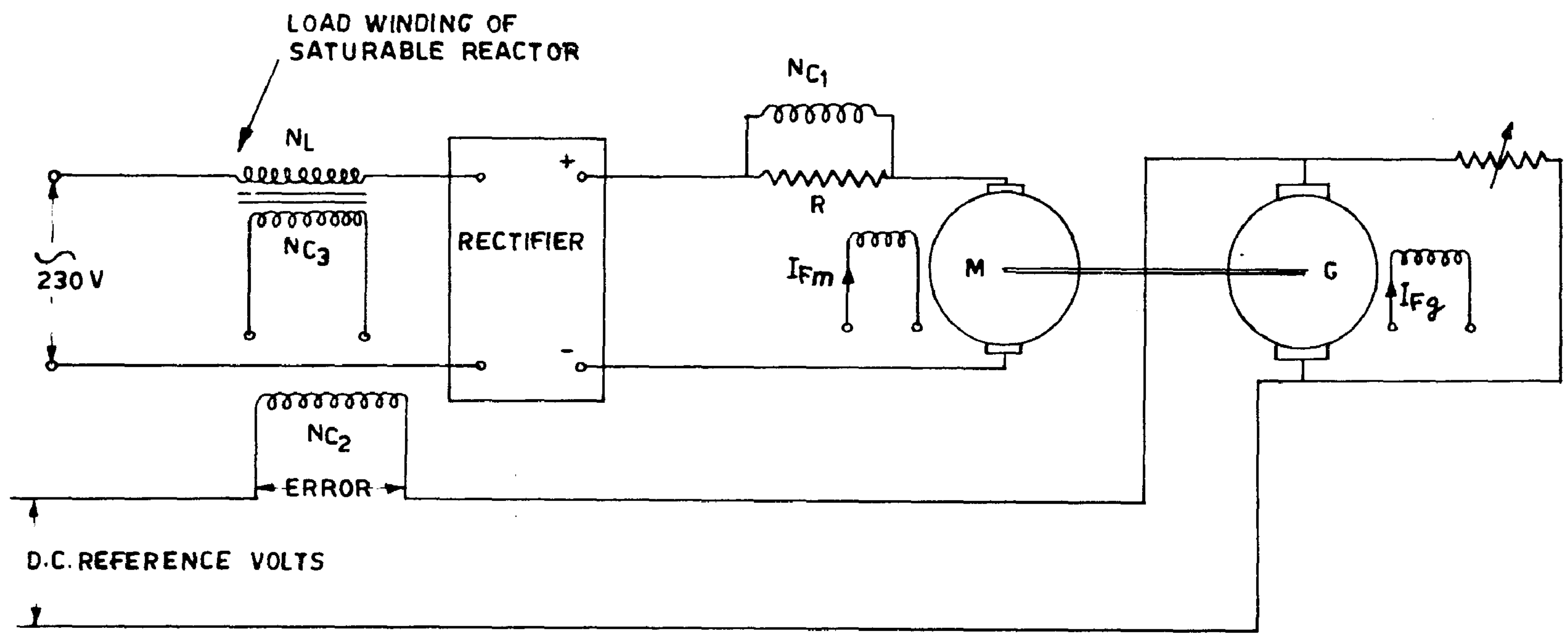


FIG.1_SCHEMATIC DIAGRAM OF SYSTEM

is proportional to speed are compared. The entire system orks to keep these two voltages as nearly equal as possible . When additional load is thrown on the motor the current in the series circuit and hence control winding 1 increases. Also with consequent speed drop generator armature terminal voltage drops and an error voltage developes across control winding 2. Thus the d.c. control ampere turns increases on saturable reactor core, which consequently decreases the reactance of the reactor and so the drop across it reduces, so that the rectifier supplies somewhat higher armature voltage necessary to maintain the operation of the motor at desired speed under condition of increased load.

For operation with reduced load reverse phenomena takes place. Less current flows in control winding 1, and the direction of current in control winding 2 is reversed due to reversal of error voltage polarity. This causes reduction in control ampere turns on saturable reactor core increasing its reactance and so the drop across it increases, so that the armature rectifier supplies the somewhat lower armature voltage necessary to maintain the operation of the motor at desired speed under condition of reduced load.

For operation at any other speed, the reference voltage and the control current in control winding 2, are adjusted which means reference level of control ampere turns is changed . Similar operation occurs for this speed setting.

Thus the system is designed for maintaining the speed between the range of 600 to 1400 r.p.m. constant at the set value.

CHAPTER III

3.1. COMPONENTS OF THE SYSTEM

3.2. D. C. MOTOR

3.3. SERIES SATURABLE REACTOR

3.4. DETAILS OF SATURABLE REACTOR PREPARED

3.5. D. C. GENERATOR.

3.6. RECTIFIER - BRIDGE.

3.1. COMPONENTS OF THE SYSTEM

As described in last Chapter, the system of speed control consists of the following main components.

1. D.C. Motor, speed of which is to be controlled.
2. Series saturable reactor.
3. Rectifier bridge.
4. D.C. Generator etc.

A brief description of these components is given in the following pages:

3.2. D.C. MOTOR

The most commonly available adjustable speed device of today use the d.c. motor. The motor used was built as a compound wound motor. The ratings of the motor being, 300 watts, 125 volts, 2.4 amperes and 1725 R.P.M. The armature of the motor has 48 coils each of 10 turns would with No. 22 A.W.G. wire. The shunt field coil consists of 2600 turns of No. 29 A.W.G. (0.0113 inch) heavy formex magnet wire and the series field coil has got 150 turns of No. 18 AWG. (0.0403 inch). heavy formex magnet wire. The motor is also provided with a cooling fan. The armature terminals are marked as A_1 and A_2, series

series field terminals as S_1 and S_2 and shunt field terminals as F_1 and F_2 on terminal board.

As a shunt motor it may be operated by disconnecting the series field. It makes an ideal adjustable speed motor for driving small drill presses, band saws or other shop machines.

In the present speed control system, this motor is used as separately excited d.c. motor.

This d.c. motor is coupled to a d.c. generator which serves the purpose of loading the motor. The motor is tested for variation of speed with rectified d.c. voltage variation to armature when field current and torque on motor shaft was kept constant. It is found for the variation of speed from 500 R.P.M. to 1600 R.P.M. The corresponding variation required in armature voltage is from 80 volts to 180 volts which again corresponds to variation on a.c. side of rectifier from 70 volts to 209 volts r.m.s. The speed torque curve for the motor, when armature is supplied from a full wave rectifier, is drawn.

The resistances and inductances of field and armature was also measured and the values found to be

r_f	=	370 Ohms.	R_a	=	1 Ohm.
L_f	=	1.9 henry	L_a	=	1.7 milli henry.

Results for d.c. motor tests are given below.

1. Variation of speed with voltage when output torque is constant I_{m} = 0.4 amp.

V_m volts	40	60	80	100	120	140	160	180
Speed r.p.m.	290	500	660	860	1020	1200	1375	1600

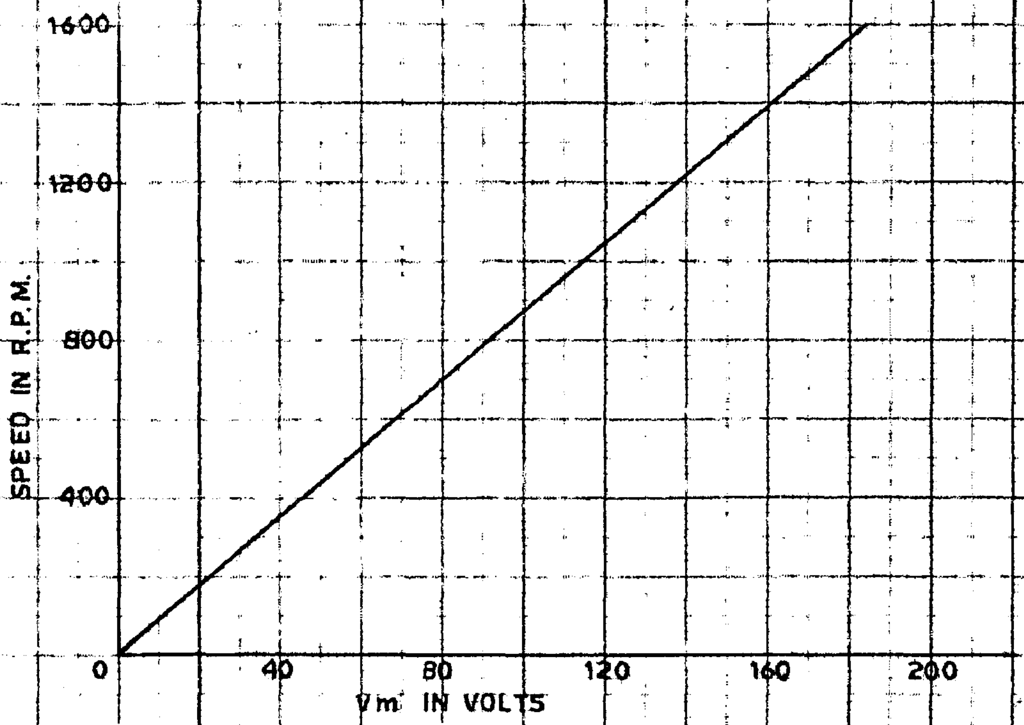
2. Variation of speed with torque change with constant applied voltage

Supplied from Rectifier Bridge

Voltage Kept constant at 1250 volts

Torque in. lb.	0	3.15	3.75	4.5	5.25	8.25	9	12	13.5
Speed in r.p.m.	1400	1265	1225	1170	1120	1080	1020	950	920
I_{ma} Amp.	0.5	0.7	1	1.2	1.3	1.6	1.9	2.2	2.4

These results are shown graphically in Figure 2 and Figure 3 respectively.



IG. 2 SPEED VS VOLTS CHARACTERISTIC OF D.C. MOTOR

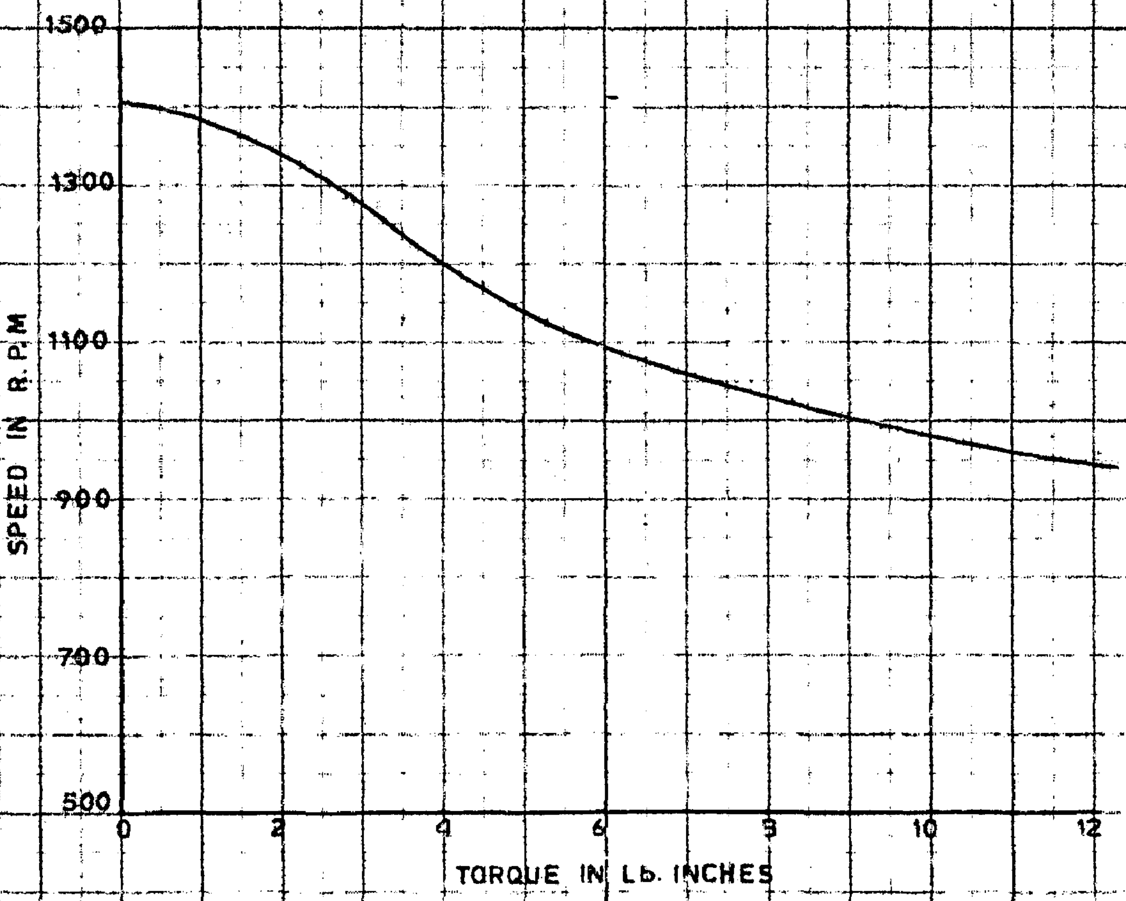


FIG.3 SPEED VS TORQUE CHARACTERISTIC OF D.C. MOTOR

3.3.1. Series Saturable Reactor

This is the important component of the system. 'Saturable Reactor' is defined in 'Standard definitions for Magnetic Amplifiers"[8] as an electromagnetic device, employing one or more non linear magnetic cores, used in a.c. circuits to secure amplification or control commonly by means of a d.c. signal which influences the non linearity.

The original purpose of 'Saturable reactor, as disclosed by Burger and Frankenfield is 'to provide a method regulating and controlling the current and potential in an electrical circuit or system of circuits whereby the use of heavy movable parts and expensive apparatus is avoided and simple effective means are provided in place thereof and smooth and uniform variations in the circuit are obtained for the purposes of regulation without use of multiplicity of contacts carrying load currents". Thus in short a saturable reactor is an adjustable inductor in which the current voltage relationship is adjusted by control of m.m.f.s applied to core.

Control of a.c. impedence of an electrical circuit is needed in many branches of electrical engineering and the saturable core devices have been used to a small extent for this purpose since the beginning of century. Saturable core devices offered a robust alternative to electronic equipments. Saturable reactors and magnetic amplifiers challanged their electronic equivalents in several fields.

3.3.2. Basic Principle

The simplest saturable reactor consists of a single ferromagnetic core (either rectangular or circular) having two windings, namely a.c. coil or load winding and a d.c. or control winding. For circuit operation the d.c. winding is connected to a d.c. source of control voltage and the load winding is connected in series with the load and a supply of a.c. voltage . When the current in the control winding is varied, the m.m.f. of the core and hence the impedence of the load winding is changed, thereby determining the voltage output appearing across the load.

3.3.3. Core Materials:

The core material selected for saturable reactor should have certain distinct characteristics. This material should have a square (or rectangular) B-H curve. In addition the core materials should have the following properties.

a. Low hysteresis and eddy current losses. This may be obtained from materials having high resistivity a lowcoercive force and ability to be produced in thin laminations.

b. High saturation flux density, B_s . this characteristic permits a given weight of core material to have a larger power capacity and is extremely important where low weight units are required.

c. Stability of magnetic characteristics under conditions of varying temperature and mechanical strain.

Some of the more common and useful core materials are,

i . Silicon - iron alloy : Silectron, Trancor, Hipersil, corosil.

ii. Nickel-iron alloy - Deltamax, permenonr, orthonal, Nicaloi , Hypernik, copernik, permalloy, Molypermalloy , Mumetal.

3.3.4. Core Construction

The various types of cores used in saturable reactor construction can be broadly summarised into two main groups.

i. Laminated cores of either silicon steel, grain oriented silicon steel or nickel iron alloy.

ii. Ring or spirally wound strip cores usually of grain oriented silicon steel or nickel iron alloy.

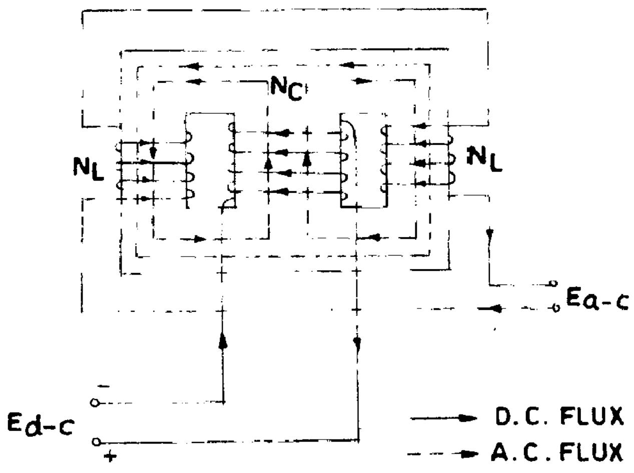
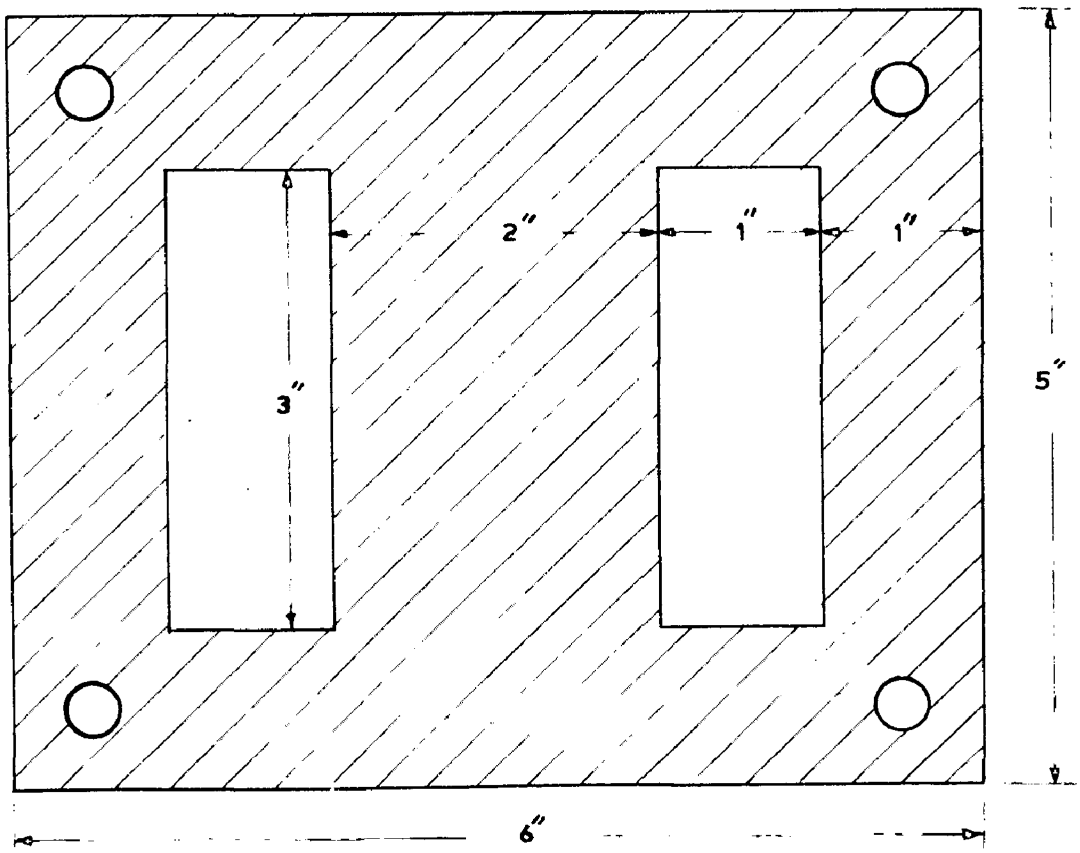


FIG.4_TOTAL MAGNETIC FLUX PRODUCED IN THREE LEGGED SATURABLE REACTOR



SHAPE OF THE STAMPING USED FOR SATURABLE REACTER

The laminated cores are built from E and I punchings of cold rolled steel. The cores are so built that the butt joints do not all occur in the same position in each complete lamination. Saturation takes place in the region of the joints before the main body of the core. The result is that a sharp saturation point on the magnetisation curve of the core cannot be obtained.

Single Phase Single Core Construction

The three legged saturable reactor in which d.c. winding is provided on the central limb and load windings on the outer limbs and connected in series as shown in Figure (6); the centre limb of the core is used purely as a d.c. flux path as shown in Fig. the a.c. winding being so connected that no a.c. flux of fundamental frequency passes through this part of the core. The outer limbs are used as return paths for d.c. flux. Neutralisation of transformer effect, so far as voltage of fundamental frequency are concerned is accomplished magnetically in this arrangement. The a.c. flux completes the path as shown through outer limbs.

3.3.8. Windings

For windings practice follows very closely that of transformer technique. The coils are wound on bakelite formers. The formers remain an integral parts of the windings. The use of formers is preferred in smaller reactors where large number of turns and relatively fine wire are used. Inter layer and inter coil insulation again follow transformer practice.

3.3.6. Assembly

End frames for clamping the case such as would be used in shell type transformer assembly cannot be used as the a.c. coils are assembled on the outer limbs. Clamping of cores must therefore confined to the top and bottom yokes by means of strip or angle material; care being taken to avoid yoke to yoke flux leakage. Packing strips of bakelite may be used to hold the core limbs tightly in the spool. Terminal board is also mounted.

3.4. DETAILS OF THE SATURABLE REACTOR PREPARED

In the present circuit the saturable reactor is used to vary the impedance of the circuit and thereby variation of armature voltage to control the speed of the motor.

The test on d.c. motor shows that for constant output torque, for variation of speed from 500 r.p.m. to 1500 r.p.m. the corresponding voltage change is from 180 volts to 60 volts d.c. The rectifier test shows that for this voltage change corresponding a.c. input voltage to the rectifier terminals be 200 to

66.6 volts r.m.s. This means if we supply the a.c load terminals with 230 volts mains then there should be voltage drop varying between 30 to 164 volts due to saturable reactor, for speed control from 1600 to 500 r.p.m. It is assumed that all this drop is across the saturable reactor reactance.

3.4.2. Core Material:

The core is built out of cold-rolled - silicon steel 'E' and 'I' laminations. A specimen of it, along with dimensions is shown in Figure (5). The depth of core is used equal to 4 inches for which nearly 8.5 Kg. of stampings are used.

3.4.3. Design Procedure

Specifications

Supply voltage 230 volts.

Supply frequency f = 50 c/s

Available material for core is cold rolled Silicon steel.

Saturation flux density B_s = 1.5 wb/m^2

Stacking factor K = 0.9

Height of stack d = 4"

Width of the core leg b = 1"

Therefore cross sectional area of the core

$A_c = b \times d \times K$

$= 1" \times 4" \times 0.9 \text{ in}^2 = 23.2 \times 10^{-4} \text{ meter}^2$

We have,

$E = 4.44\ f\ B_s\ A_c\ N_L$

$$\therefore\ N_L = \frac{230}{4.44 \times 50 \times 1.5 \times 23.2 \times 10^{-4}}$$

$= 298 \cong 300$

$\therefore$ Turns / leg = 300 / 2 = 150.

Mean length of the magnetic path = 2 x 5" + 2 x 4" = 18"

= 18 x 2.54 = 45.6 cms.

From B-H curve for the material the ampere turns corresponding to flux density of 1.5 wb/m^2 is 1650 amp.turns/m^2. Therefore,

$$N_c\ I_c = \frac{45.6 \times 1650}{100}$$

$\cong 750$

Now limiting the control current to 0.6 amperes. So the number of control turns to be provided = 750 / 0.6

= 1250.

These may also be derived from the load current and turns value as follows:

Our load current will be determined by the rated current of the d.c. motor which is 2.4 amperes. So deciding the load current to be 2.5 amperes.

Taking the average value of control current =0.6 amp.

For equal ampere turns

$N_L\ I_L = N_c\ I_c$, $300 \times 2.5 = N_c \times 0.6$

Therefore the number of turns provided on control winding is 1250. There are also two more control windings provided with 1000 and 500 turns. There is also tappings provided at 500 , 750 and 1000 turns.

For load winding the 20 s.w.g. conductor is used.

The dia. of the conductor = 0.915 mm. cross sectional area of the conductor = 0.650 mm^2

The winding is provided in 3 layers.

Width of the winding = 3 x .915 + 4 insulation

= 2.745 + 4

= 6.745 mm = 7 mm.

The former size = 4" x 1.1"

= 10.2 + 2.8 mm.

So mean length of turn = 2(10.2 + .7) + (28 + .7) 2

= (218 + 70)

= 288 mm.

= .288 meter.

So resistance of the load winding = $\frac{p. L_{mt} N_L}{a}$

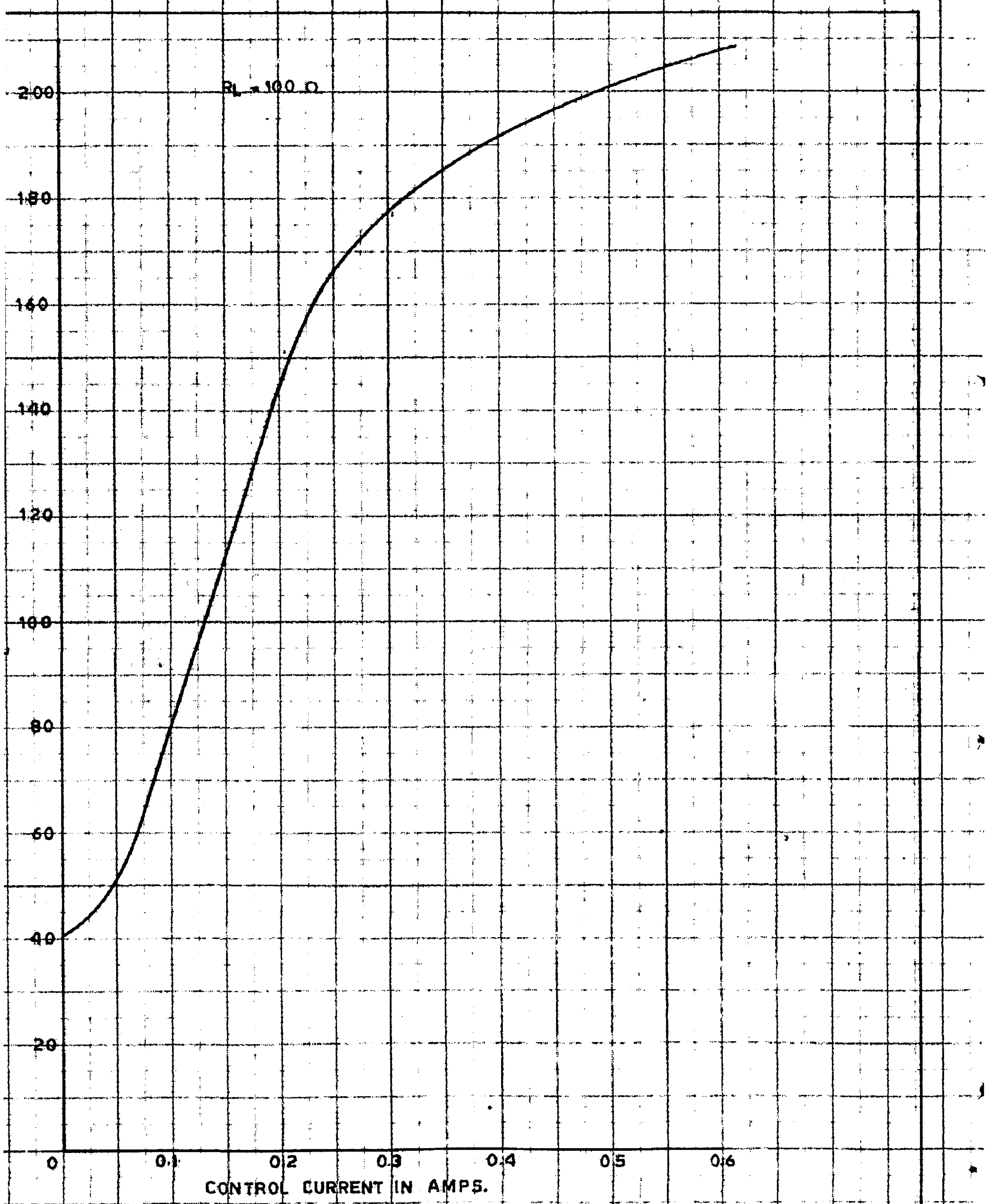
$$= \frac{0.021 \times (.288)(300)}{0.656}$$

= 2.76 ohms.

Inductance of Load Winding

$$L = \frac{N \phi}{I} = \frac{N B A_c}{I} \text{ Henries}$$

$$= \frac{300 \times 1.5 \times 23.2 \times 10^{-4}}{2.5} = 0.418 \text{ Henries.}$$



. 6 LOAD VOLTAGE VS CONTROL CURRENT CHARACTERISTIC OF SATURABLE REACTER

The winding is done by copper conductors using 30 s.w.g. for load winding and 32 swg. for all the three control windings. The saturable reactor is constructed on 3 legged core with load windings being on outer limbs and all the control windings on the central limb of the core. The method followed for windings and assembly is similar to that described earlier. A terminal board is also provided for making connections. The saturable reactor thus prepared is tested and the following results were obtained.

3.4.4. Test Results

1. Resistance of load winding = 2.75 Ohms.
2. Resistances of control windings:

   Winding No. 1 (Having 1250 turns) = 78 Ohms.
   Winding No. 2 (Having 1000 turns) = 59.6 Ohms
   Winding No. 3 (Having 500 turns) = 35 Ohms.

3. Experimental Data for Transfer Characteristics with input voltage 230 and load resistance, R_L = 100 Ohms

I_c d.c. amp.	0	0.05	0.1	0.15	0.20	0.25	0.30	0.35	0.40
V_{Load} a.c.	40	50	84	114	150	165	175	184	190
I_{load} a.c.	.4	0.5	0.84	1.14	1.5	1.65	1.75	1.84	.19

I_c d.c.	.45	0.50	.55	0.60
V_{load} a.c.	200	202	204	206
I_{load} a.c.	2.00	2.02	2.04	2.06

PHOTOGRAPHIC VIEW OF SATURABLE REACTOR PREPARED

Thus it can be seen that by varying the control ampere-turns level the voltage across the load can be varied. A photograph of the saturable reactor prepared is shown on the adjoining page.

3.8. D.C. GENERATOR

A. d.c. generator is coupled to the motor under test, which serves the purpose of load on motor The generator also serves the purpose of giving voltage proportional to motor speed. This voltage is compared with reference voltage and serves the purpose of voltage feedback to saturable reactor.

The ratings of the generator used are 220/230 volts, 4.6 amperes, 1450 R.P.M., output 1 h.p. The generator is used as a separately excited gaberator.

3.9. RECTIFIER BRIDGE

Rectifiers play an important part in magnetic amplifier circuits. In many of these applications, low maintainance, long life expectancy and mechanical shock resistance appear to be items of great importance With the present state of art metalic rectifiers meet these requirements. The use of rectifiers for furnishing power to d.c. motors is becoming more common particularly for variable voltage drives.

The full wave rectifier-bridge used in the assembled circuit consists of 4-silicon diode type rectifiers (17 RSD 4), the ratings for which are given.

Voltage Ratings

10 mili second transient P. R. V.	600 volts
Maximum repitative P. R. V.	400 volts
Recommended working P. R. V.	240 volts
Recommended working R. M. S.	180 volts
Peak forward voltage drop	1.2 volts.

Current Ratings

Maximum rated current	17 amperes.
Maximum one cycle surge current	320 amp.
Operating temperature	150°
Operating frequency	15 to 1000 c/s

All these ratings are for R_4 - Seniemen. Medium Power silicon half wave maximum / diode.

All the above mentioned components along with necessary measuring instruments were assembled as shown in the circuit (Fig. 5·1). The circuit is checked for the required polarities and then tested for the required speed control for a particular pore set value of speed. The experimental details alongwith results are given in the subsequent chapters.

CHAPTER IV

ANALYSIS OF THE SYSTEM

4.1. BLOCK DIAGRAM

An attempt is made to analyse the system. The block diagram representation of the speed control system is given in Fig. 4.1 .

In the following section transfer functions of individual components are found out.

4.2. TRANSFER FUNCTIONS OF COMPONENTS

4.2.1. Saturable Reactor

The equation for ampere turns balance for the saturable reactor can be written as

$$N_{c1} I_{c1} + N_{c2} I_{c2} + N_{c3} I_{c3} = N_L I_L = N_c I_c \quad \ldots(1)$$

Where $N_{c1} = N_{c2}$ and N_{c3} are turns in control windings 1, 2, and 3 and N_L is the load winding turns. I_{c1}, I_{c2}, I_{c3} and I_L being corresponding currents.

$N_c I_c$ is the total control ampere turns.

$$\therefore N_c I_c = N_L \frac{E_o}{R_o (1 + T_o S)} \quad \ldots(2)$$

$$\therefore \frac{E_o}{N I_c} = \frac{R_o (1 + T_o S)}{N_L} \quad \ldots(3)$$

Where $T_o = L_o / R_o$ is load time constant.

4.2.2. D.C. Motor

The d.c. motor whose speed is to be controlled is a seporately excited one. Speed of the motor can be varied by varying the voltage impressed on the armature. Following assumptions are made in the derivation of motor transfor function.

a. The motor airgap flux is proportional to field current $\phi = K_f \; I_f$

b. The torque developed by the motor is proportional to the air gap flux and armature , current.

$$T_m = K'_m \phi \, I_a = K'_m K_f \, I_f I_a$$

c. The back e.m.f. is proportional to motor speed

$$V_b = K_b \, S \, \theta m$$

A schematic representation of the circuit is given in Fig. 4.2 . In the armature circuit the transformed equation is

$$V_{d.c.}(s) = (R_a + SL_a) \; I_a(s) + V_b(s)$$

$$= (R_a + L_a S) \, I_a(s) + K_b \, S \, \theta m$$

$$\therefore \; I_a(s) = \frac{V_{d.c.}(s) - K_b \, S \, \theta m(s)}{Ra + La \, S} \quad \ldots (6).$$

$$T_m(s) = K'_m \, K_f \, I_f \; \frac{V_{d.c} - K_b \, S\theta_m(s)}{R_a + L_a S} \qquad \ldots(7)$$

also

$$T_m(S) = (J_m S + f_m) \, S \, \theta_m \qquad \ldots(8)$$

From 7 and 8 ,

$$\frac{\theta_m(s)}{V_{dc}(S)} = \frac{K'_m \, K_f I_f}{S\,(R_a + SL_a)(J_m S + f_m) + K_b S \, K'_m \, K_f I_f} \qquad \ldots(9)$$

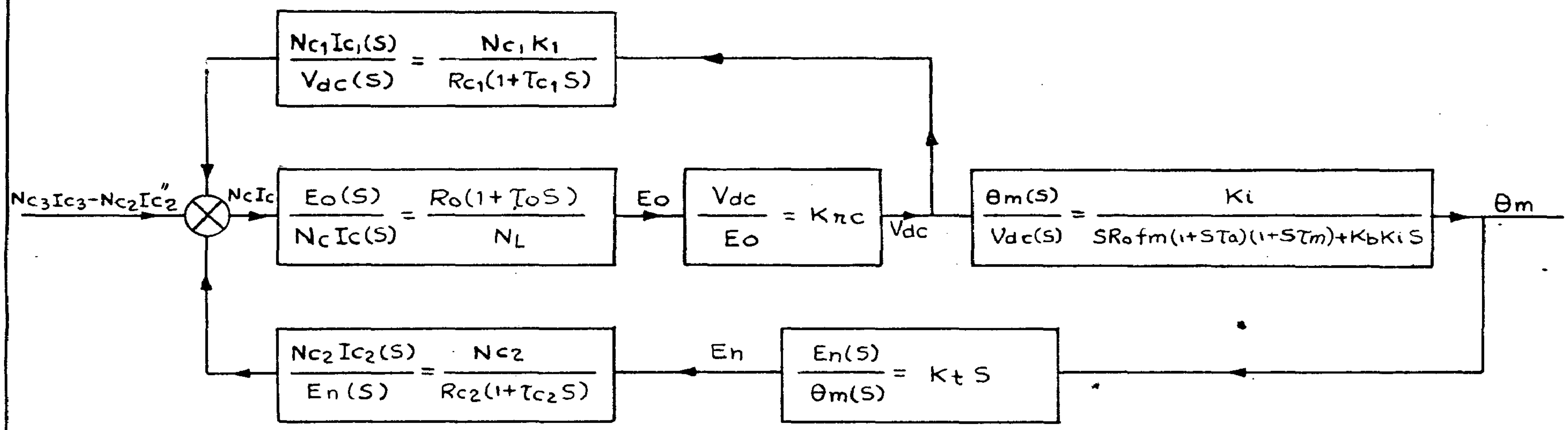
$$\frac{\theta_m(S)}{V_{d.c}(S)} = \frac{K_i}{S \, R_a f_m (1 + ST_a)(1 + S\,T_m) + K_b K_i S} \qquad \ldots(10)$$

4.23. <u>Rectifier and Speed Sensing Element</u>

It is assumed that the input a.c. volts E_b and the output d.c. volts V_{dc} bears a constant ratio, it may be written as

$$\frac{V_{dc}(S)}{E_b(S)} = K_{re} \qquad \ldots(11)$$

The generator coupled to d.c. motor is used as a speed sensing element, in the system. The armature terminal voltage developed in the generator is assumed proportional to speed. So now a relation may be written as follows .



$N_{c3}I_{c3} - N_{c2}I''_{c2}$
N_cI_c
$\frac{N_{c1}I_{c1}(S)}{V_{dc}(S)} = \frac{N_{c1}K_1}{R_{c1}(1+\tau_{c1}S)}$
$\frac{E_o(S)}{N_cI_c(S)} = \frac{R_o(1+\tau_oS)}{N_L}$
Eo
$\frac{V_{dc}}{E_o} = K_{\pi c}$
Vdc
$\frac{\theta_m(S)}{V_{dc}(S)} = \frac{K_i}{SR_ofm(1+S\tau_a)(1+S\tau_m)+K_bK_iS}$
θm
$\frac{N_{c2}I_{c2}(S)}{E_n(S)} = \frac{N_{c2}}{R_{c2}(1+\tau_{c2}S)}$
En
$\frac{E_n(S)}{\theta_m(S)} = K_tS$

FIG. 4.3

$$\frac{E_n(S)}{\theta_m(S)} = K_t\, S \qquad \ldots(12)$$

4.24. Control Windings (1) and (2)

In the control winding 1 which is shunted with resistance a fraction of d.c. voltage, V_{dc}, causes current I_{c1} and so the ampere turns developed by this winding are $N_{c1} I_{c1}$ so now,

$$N_{c1}\, I_{c1} = N_{c1} \frac{K_1\, V_{dc}}{R_{c1}(1 + T_{c1}\, S)} \qquad \ldots(13)$$

In the second control winding the ampere turns developed are due to error volts = $V_r - E_n$

So

$$N_{c2}\, I'_{c2} = \frac{N_{c2}\, E_{(n)}}{R_{c2}\,(1 + T_{c2} S)} \qquad \ldots(14)$$

4.3. SOLUTION OF BLOCK DIAGRAM

With the above developed transfer functions put in block forms the composite block diagram reduces to Fig. 4·3 .

$$G_1(S) = \frac{V_{d.c}}{N_c\, I_c} = \frac{R_b\, K_{re}(1 + T_0\, S)}{N_L}$$

$$\ldots(15)$$

$$H_1(S) = \frac{N_{01}\,K_1}{R_{01}(1 + T_{01}\,S)} \qquad \ldots(16)$$

$$\therefore \frac{G_1(S)}{1 + G_1(S)\,H_1(S)}$$

$$= \frac{R_{01}R_0\,K_{F0}\,(1 + T_0\,S)\,(1 + T_{01}S)}{N_L R_{01}(1+T_{01}S) + R_0 K_{F0} N_{01} K_1\,(1 + T_0 S)} \qquad \ldots(17)$$

So now,

$$G_2(S) = \frac{R_0 K_{F0} R_{01} K_1\,(1 + T_0 S)\,(1+T_{01}S)}{\left[N_L R_{01}(1+T_{01}S) + R_0\,(1+T_0\,S) K_{F0}\,N_{01}K_1\right] \times \left[S R_a\,f_m(1 + ST_a)\,(1+ ST_m) + K_b K_1 S\right]}$$

Which on simplification

$$G_2(S) = \frac{R_0 K_{F0} R_{01} K_1\,(1 + T_0\,S)\,(1 + T_{01}\,S)}{\begin{aligned} & S\left[R_a f_m N_L R_{01} + K_b K_1 N_L R_{01}\right](1 + T_{01}\,S) \\ & + S\left[R_a f_m R_0 K_{F0} N_{01} K_1 + K_b K_1 R_0 K_{F0} N_{01} K_1\right](1+T_0 S) \\ & + S^2\left[R_a f_m N_L R_{01}(T_a + T_m)\,(1 + T_{01}S) + R_0 K_{F0}\,N_{01} K_1\,R_a\,f_m (T_a + T_m)\,(1 + T_0 S)\right] \\ & + S^3\left[R_a f_m N_L R_{01}\,(T_a T_m)(1+T_{01}S) + R_0 K_{F0} R_a f_m N_{01} K_1 (T_a T_m)\,(1 + T_0\,S)\right] \end{aligned}} \qquad \ldots(18)$$

For ease of writing, putting

$$R_0 R_{e1} K_{re} K_1 = M$$

$$R_a R_{e1} f_m N_L = N$$

$$K_b K_1 N_L R_{e1} = A$$

$$R_a f_m R_0 K_{re} N_{e1} K_1 = B$$

$$K_b K_1 R_0 K_{re} N_{e1} K_1 = C$$

Expression (18) can now be written as

$$G_2(S) = \frac{M(1 + T_0 S)(1 + T_{e1} S)}{S\left[(N+A)(1+T_{e1}S) + (B+C)(1+T_0 S)\right] + S^2\left[N(T_a+T_m)(1+T_{e1}S) + B(T_a+T_m)(1+T_0 S)\right] + S^3\left[\left[N(T_a T_m)(1+T_{e1}S)\right] + \left[B(T_a T_m)(1+T_0 S)\right]\right]} \quad \ldots(19)$$

$$H_2(S) = \frac{S K_t N_{e2}}{R_{e2}(1 + T_{e2} S)} \quad \ldots(20)$$

From (19) and (20) we have

$$\frac{G_2(S)}{1 + G_2(S) H_2(S)}$$

$$= \frac{M(1+T_0S)(1+T_{e1}S)\; R_{c2}(1+T_{e2}S)}{R_{c2}(1+T_{e2}S)\left[\begin{array}{l} S(N+A)(1+T_{c1}S)+S(B+C)(1+T_0S)+S^2(N)(T_a+T_m) \\ (1+T_{c1}S)+S^2B(T_a+T_m)(1+T_0S)+S^3(N\,T_a\,T_m) \\ (1+T_{c1}S)+S^3(B\,T_a\,T_m)(1+T_0S) \end{array}\right] + M(1+T_0S)(1+T_{c1}S)(S K_t N_{c2})}$$

...(21)

So now the characteristic equation of the system is

$$S^4\left[R_{c2}T_{c2}(N\,T_aT_mT_{c1}+B\,T_aT_m\,T_0)\right]$$

$$+S^3\left[\begin{array}{l}\left[R_{c2}(N\,T_aT_mT_{c1}+B\,T_aT_mT_0)\right]+R_{c2}T_{c2}\Big[(N\,T_aT_m \\ +B\,T_aT_m)+N(T_a+T_m)T_{c1}+B(T_a+T_m)T_0\Big]\end{array}\right]$$

$$+S^2\left[\begin{array}{l}R_{c2}\left[(NT_aT_m+B\,T_aT_m)+N(T_a+T_m)T_{c1}+B(T_a+T_m)T_0\right] \\ +M\,T_0T_{c1}N_{c2}K_t+R_{e2}T_{e2}\Big[N(T_a+T_m)+B(T_a+T_m) \\ +(N+A)T_{c1}+(B+C)T_0\Big]\end{array}\right]$$

$$+S\left[\begin{array}{l}R_{c2}\left[N(T_a+T_m)+B(T_a+T_m)+(N+A)T_{c1}+(B+C)T_0\right] \\ +R_{c2}T_{c2}\left[(N+A)+(B+C)\right]+K_tN_{c2}(T_0+T_{c1})\end{array}\right]$$

$$+R_{e2}\left[(N+A)+(B+C)\right]+N_{e2}K_tM \qquad ...(22)$$

Thus the characteristic equation is found to be of 4th order. If we neglect armature time constant which is generally found to be small in case of shunt motor and also load time constant. T_e which is also very small due to predominatly resistive load, characteristic equation (22) reduces to the form:

$$S^3 \left[(N T_m T_{c1}) R_{c2} T_{c2} \right] + S^2 \left[R_{c2} \left[N T_m T_{c1} \right] + R_{c2} T_{c2} \left[(N T_m + B T_m) + (N+A) T_{c1} \right] \right] + S \left[R_{c2} \left[(N T_m + B T_m) + (N+A) T_{c1} \right] + R_{c2} T_{c2} \left[(N+A) + (B+C) \right] + M K_t N_{c2} T_{c1} \right] + R_{c2} \left[(N+A) + (B+C) \right] + N_{c2} K_t M = 0$$

...(23)

Equation (23) can now be written as:

$$S^3 + S^2 \left[\frac{1}{T_{c2}} + \frac{1}{T_{c1}} + \frac{B}{N T_{c1}} + \frac{(N+A)}{T_m N} \right] + S \left[\frac{1}{T_{c2}} \left[\frac{1}{T_{c1}} + \frac{B}{N T_{c1}} + \frac{(N+A)}{N T_m} \right] + \frac{(N+A)+(B+C)}{N T_m T_{c1}} + \frac{M K_t N_{c2}}{N T_m T_{c2} R_{c2}} \right] + \left[\frac{(N+A) + (B+C)}{N T_m T_{c1} T_{c2}} + \frac{N_{c2} K_t M}{N T_m T_{c1} R_{c2} T_{c2}} \right] = 0$$

...(24)

4.4. STABILITY OF THE SYSTEM

The characteristic equation of the system is obtained in the last section. Now after putting the values the equation (24) reduces to

$$S^3 + 26.70\,S^2 + 300\,S + 905 = 0 \qquad \ldots (25)$$

Now applying "Routh - Hurwitz Criteria" for stability study of the equation (25)

S^3	1	300	
S^2	26.70	905	~~905~~
S^1	$\dfrac{26.70 \times 300 - 905 \times 1}{26.70}$ $= 261.7$	0	
S^0	905		

Since there is no sign change in the first column, the polynomial has no root located in right half of the S- plane. This establishes the stability of the system.

4.5. RESPONSE OF 3rd ORDER SYSTEM

For any 3rd order system the equation may be written in the form

$$(\lambda - \lambda_1)\ (\lambda^2\ 2\zeta\omega_o\lambda + \omega_o^2) = 0$$

The transformed equation of motion with zero initial conditions can then be given as

$$(S-\lambda_1)(S^2 + 2\delta w_o S + w_o^2) X = -\frac{\lambda_1 w_o^2}{S}$$

$$\therefore \quad X = \frac{-\lambda_1 w_o^2}{S(S-\lambda_1)(S^2 + 2\delta w_o S + w_o^2)}$$

After expansing in partial fractions and applying the inverse transform, we find general solution, is

$$x = 1 - \frac{w_o^2 e^{\lambda t}}{(\delta w_o + \lambda_1^2) + w^2} - \frac{w_o \lambda_1 e^{-\delta w_o t} \operatorname{Sin}(wt + \psi)}{w\sqrt{(\delta w_o + \lambda_1)^2 + w_1^2}} \quad \ldots (1)$$

Where $\psi = \psi_1 + \psi_2$

and $\psi_1 = \tan^{-1} \dfrac{w}{\delta w_o} = \operatorname{Cos}^{-1} \delta$

$$\psi_2 = \tan^{-1} \frac{w}{\delta w_o + \lambda_1}$$

From Equation (I)

$$X = 1 + c_1 e^{\lambda_1 t} + c_2 e^{-\delta w_o t} \operatorname{Sin}(wt + \psi)$$

Where $c_1 = \dfrac{-w_o^2}{(\delta w_o + \lambda_1)^2 + w^2}$

$$c_2 = \frac{-w_o \lambda_1}{w\sqrt{(\delta w_o + \lambda_1)^2 + w^2}}$$

The amplitude factors c_1 and c_2 can be seen

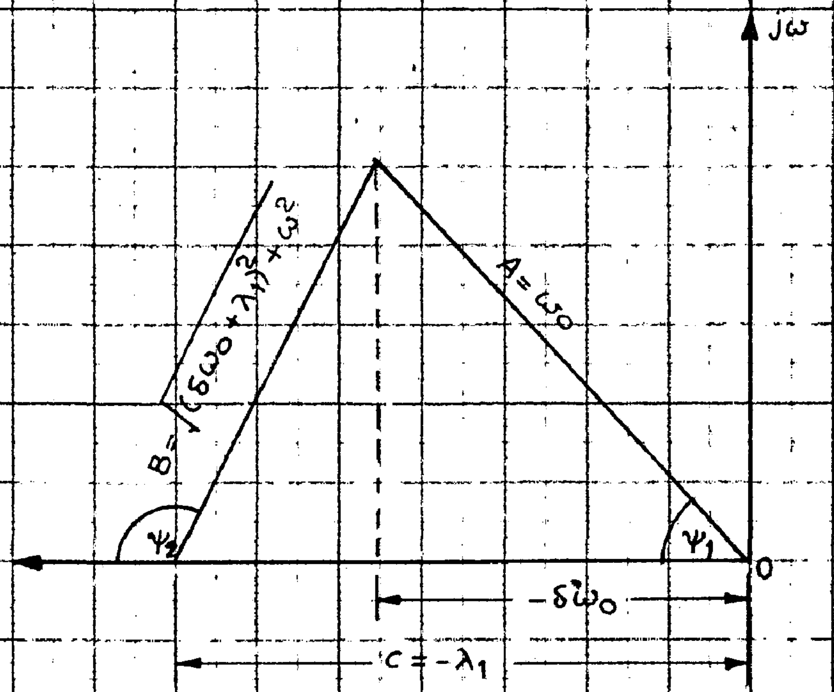


FIG. 4·4 THIRD ORDER SYSTEM RESPONSE FROM ROOT LOCATION

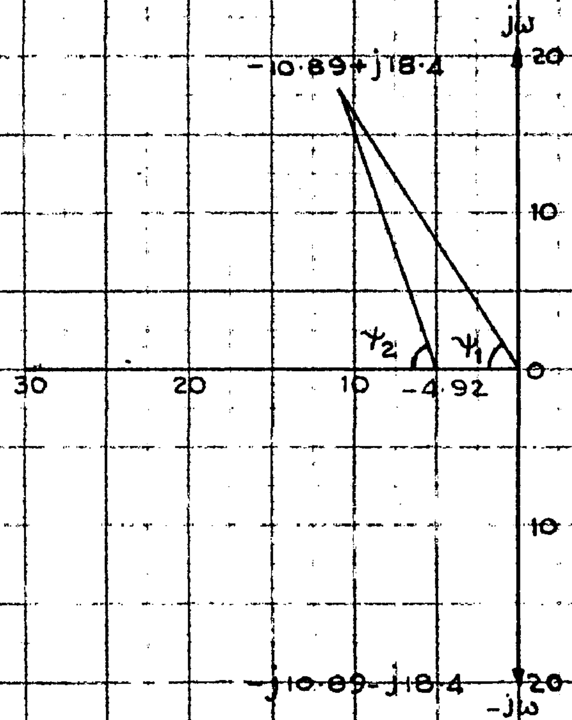


FIG. 4·5 ROOT LOCATION FOR THE SYSTEM ANALYSED to represent simple function of the vector lengths, A, B, C and D in the complex plane as shown in Fig.

Thus constants c_1 and c_2 can be expressed as

$$c_1 = -(A/B)^2$$

$$c_2 = (A/B)(C/D)$$

The angle ψ is given by

$$\psi = \psi_1 + \psi_2$$

Consequently, the third order step response can be obtained simply by plotting the stability roots, measuring the vector lengths and angle and then putting the response equation. The response characteristics are governed by relative root locations. When the real root is displaced to the left of real part of the complex pair, c_1 will rapidly decrease, where as c_2 will remain nearly constant. As a result, the oscillatory mode will tend to dominate the response and the response time will be essentially a function of δ and wo value. Conversely when the real root lies to the right of the complex roots, the aperiodic mode will characterise the total response.

When the real root is equal to the real part of the complex pair, that is $\lambda_1 = -\delta$ wo

The third order response equation is

$$x = 1 - \frac{e^{-\delta wo\, t}}{1-\delta^{2}} \left[1 - \delta \, Sin\, (vt + Cos^{-1} \delta + \pi/2 \right]$$

If we assume critical damping ratio δ = 0.707 the response based on θ_o = wo t , in order to make the analysis independent of wo is

$$x = 1 - 2\, e^{-0.707\, \theta_o} \left[1 - 0.707\, Sin\, (0.707 + \frac{3\pi}{4}) \right]$$

Response of the System to Unit Step Function

The characteristic equation is

$$S^3 + 26.70\, S^2 + 309\, S + 965 = 0$$

$$or\ (S+4.92)\,(S^2 + 21.78\, S + 201.85) = 0$$

$$\therefore \lambda_1 = -4.92$$

For the quadratic equation

$$S^2 + 21.78\, S + 201.85 = 0$$

$$X = \frac{-21.78 \pm \sqrt{(21.78)^2 - 4 \times 201.85}}{2}$$

$$= -10.89 \pm j\, 18.4$$

So $\lambda_{2,3} = -10.89 \pm j\ 18.4$

So now $A = \sqrt{(10.89)^2 + (18.4)^2}$

$= 21.35$

$B = \sqrt{\left[(10.89) - 4.92\right]^2 + (18.4)^2}$

$= 19.25$

$C = 4.92$

$D = 18.4$

$\psi_1 = \tan^{-1} \dfrac{18.4}{10.89} = \tan^{-1} 1.69$

$= 1.02$ radians

$\psi_2 = \tan^{-1} \dfrac{18.4}{10.89-4.92} = \tan^{-1} 3.08$

$= 1.26$ radians.

So $\psi = \psi_1 + \psi_2 = 2.28$

Constants:

$e_1 = -\left[\dfrac{21.35}{19.25}\right]^2 = -(A/B)^2$

$= 1.23$

$e_2 = (A/B)(C/D)$

$= \left(\dfrac{21.35}{19.25}\right)\left(\dfrac{4.92}{18.4}\right)$

$= 0.296.$

So final response solution to unit step function is then $x = 1 - 1.23\, e^{-4.92t} + .296\, e^{-10.89t} \times \sin(18.4t + 2.28)$

CHAPTER V

EXPERIMENTATION AND METHODOLOGY

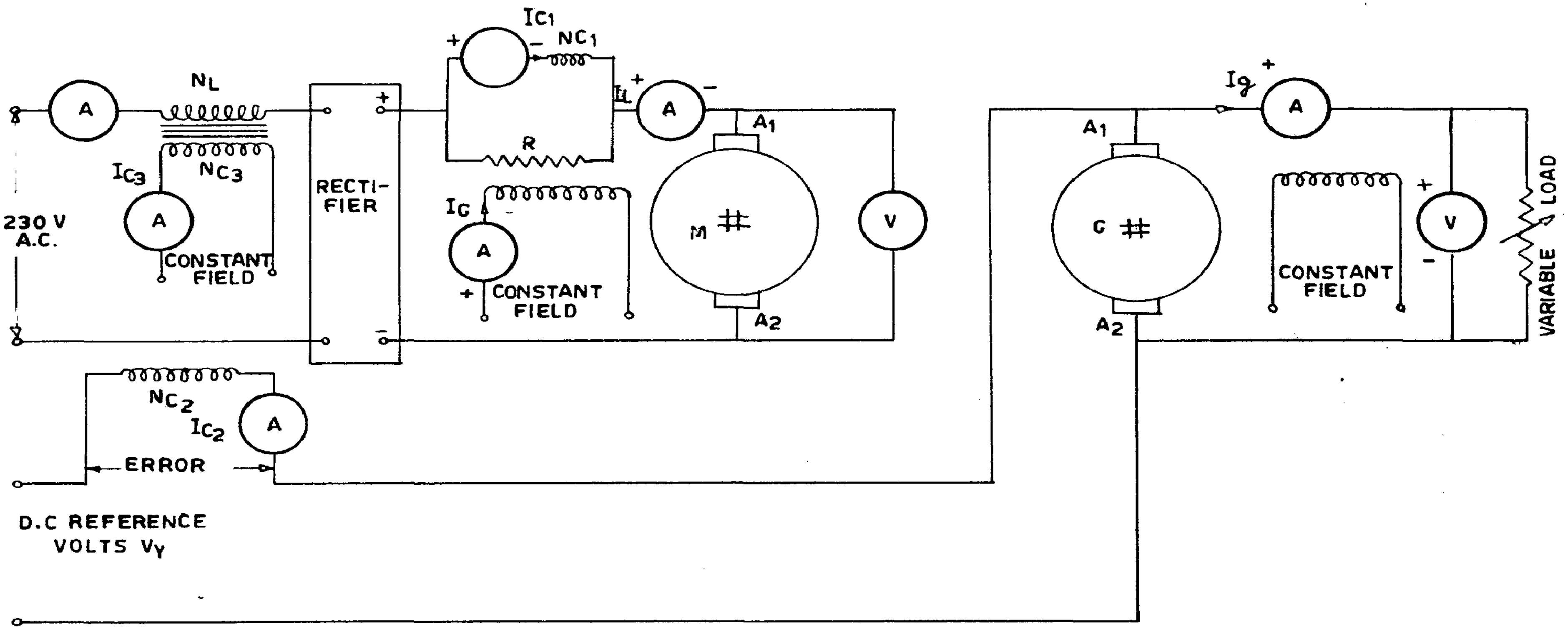


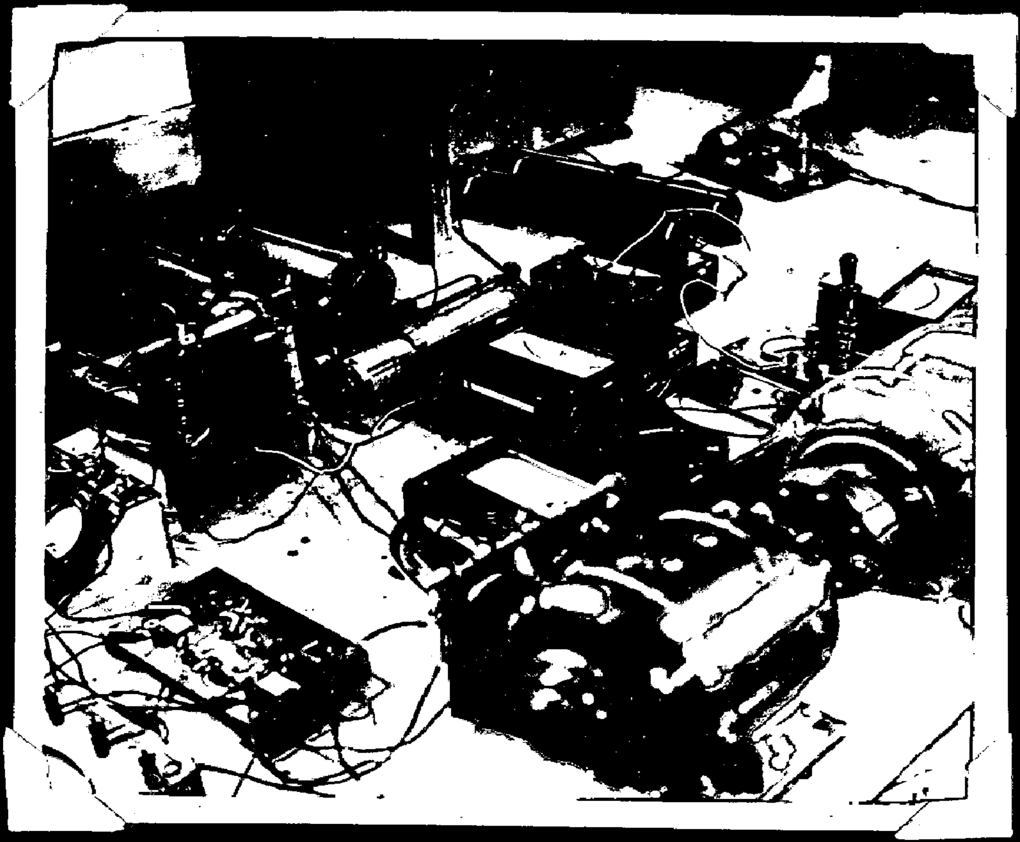
FIG. 5·1 CIRCUIT DIAGRAM FOR EXPERIMENTAL PURPOSE

5.1. EXPERIMENTAL DETAILS

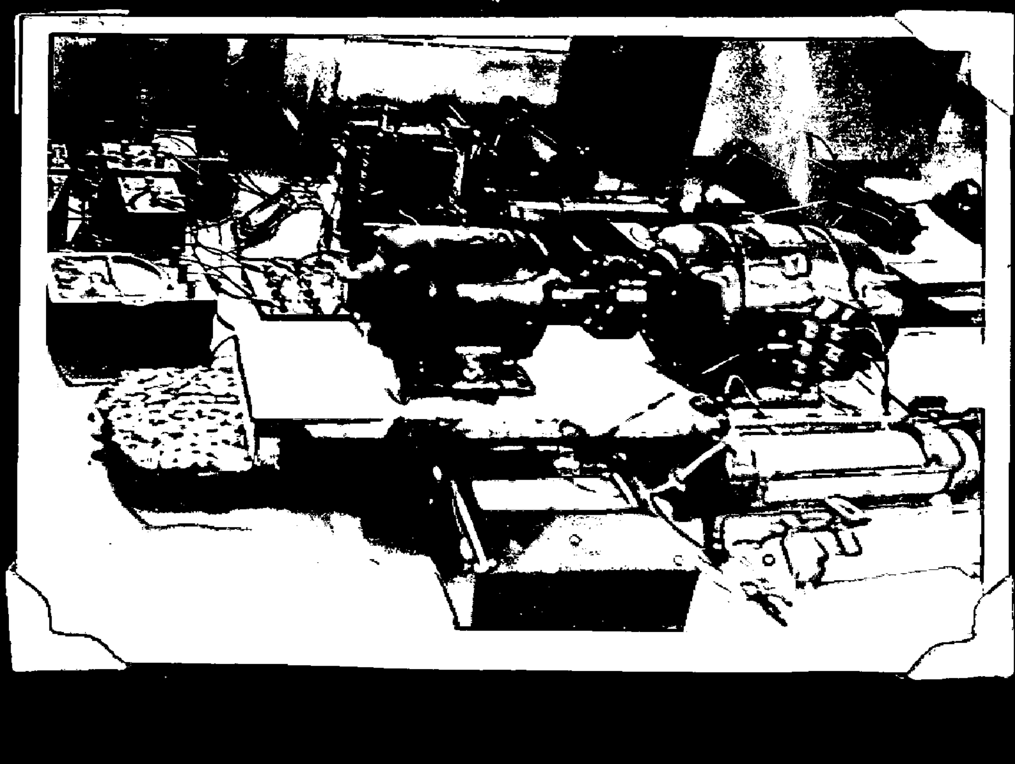
The system described in Chapter II was assembled using all the components along with necessary measuring instruments. The circuit diagram is shown in Fig 5·1 . The system thus assembled is then tested.

Firstly the D.C. motor field is excited to rated value which is kept constant throughout the experiment. Then alternating supply of 230 volts is applied to series saturable reactor load windings. This causes current and voltage across the armature of the motor and also current across compensating winding of saturable reactor. The control winding 3 is supplied with voltage, so as to obtain desired speed at half full load on the motor. Then reference voltage V_r is so adjusted that the error voltage, $V_r - E_{(n)}$ is equal to zero . Under this condition control winding 2 carries no current. If necessary the reference volts may be adjusted so as to cause some desired value of current in the control winding 2.

After these preliminary settings the load is gradually put on the motor by loading the d.c. generator. This causes more current in the motor



PHOTOGRAPHIC VIEWS OF SYSTEM
ASSEMBLED



armature and so also more current in compensating winding i.

Thus now with increase in load, there is increase in control ampere turns on saturable reactor. This results into less inductance and hence less reactance of the reactor and so there will be less voltage drop across, it . So the voltage at the armature terminals of the motor increases, the increase being decided by level of compensation. The compensating ampere turns can be varied by changing the value of shunting resistance across the compensating winding. This all takes place instantaneously and speed again goes to its previous value. The speed can be made constant irrespective of load by obtainingideal condition by proper adjustment of shunting resistance which changes the value of compensating current in compensating winding. Thus to obtain closer speed regulation, armatture current compensation, as well as a signal proportional to generated voltage which is proportional to speed is fed back to the saturable reactor.

The system is tested for following values of present speed:

825 , 1000 , 1100 , 1200 ,1250 and 14 R.P.M.

The experimental results are given in tabular form and also graphically shown in Fig. .

5.2. EXPERIMENTAL RESULTS

A. SPEED PRE SET AT 825 R.P.M.

Initial Conditions: Shunting Resistance = 8 ohms

I_{c3} = 0.08 amp.

Error volts adjusted zero for 1 amp. load.

I_{fm} = 0.4 amp. , I_{fg} = 0.2 amp.

Sl. No.	I_L amp.	V_m Volts	$I_{compen.}$ amp.	Speed	% change from the Desired speed.
1	1.0	90	0.14	825	0
2	1.2	91	0.175	830	0.62
3	1.4	93	0.21	830	0.62
4	1.7	94	0.235	830	0.62
5	1.85	95	0.260	830	0.62
6	2.4	95	0.300	815	1.25
7	0.6	83	0.085	810	1.87

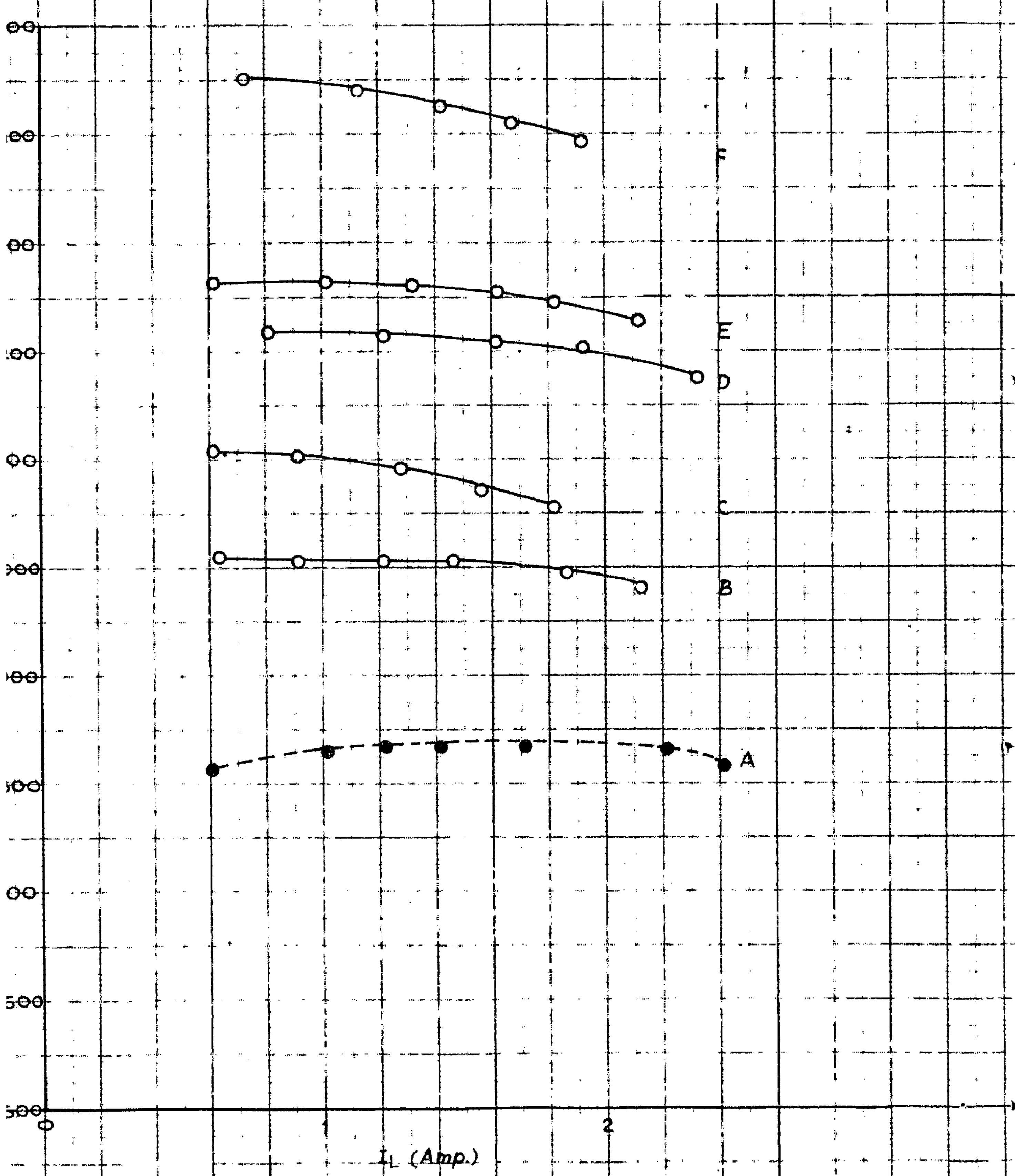
B. SPEED PRE SET AT 1000 r.p.m.

Initial Conditions: Shunting resistance = 10 ohms

I_{c3} = 0.10 amp.

Error voltage zero for I_L = 1.2 amp. load.

Rest conditions are same as in A.



CURVES FOR RESULTS UNDER SECTION 5.2

FIG. 5.2 CURVES SHOWING DEVIATION OF SPEED FROM DESIRED VALUE WITH LOAD

Sl. No.	I_L amp	V_{ma} volts	$I_{com.}$ amp.	Speed	% change from desired speed.
1	1.2	110	0.125	1000	0
2	1.45	112	0.150	1000	0
3	1.65	113	0.180	985	1.5
4	2.1	113	0.210	975	2.5
5	0.9	109	0.10	1000	0
6	0.6	106	0.070	1005	0.5

C. SPEED PRE SET AT 1100 R.P.M.

Initial Conditions

Shunting resistance = 3 ohms

I_{c3} = 0.08

Error volts zero for I_L = 0.6

Sl. No.	I_L amp.	V_{ma} volts	$I_{comp.}$ amp.	Speed	% change from desired speed.
1	0.6	112	0.06	1100	0
2.	0.9	115	0.09	1095	0.45
3	1.25	116	0.12	1085	1.36
4.	1.53	118	0.145	1065	3.1
5	1.80	118	0.165	1045	5
6	2.15	119	0.20	1020	7.27

N. B.

Here speed deviation is too much from desired value due to less number of turns i.e. 600 instead of 1250 as being used in compensating winding for other settings.

D. SPEED PRE SET AT 1200 R. P. M.

Initial Conditions

R_{sh} = Shunting resistance = 11 ohms

I_{c3} = .09 amp.

Error volts zero for I_L = 1.6 amp.

Sl. No.	I_L amp	V_{ma} volts	$I_{comp.}$ amp	Speed R. P. M.	% change from desired speed.
1	1.6	130	0.225	1200	0
2	1.9	130	0.27	1195	0.5
3	2.3	130	0.325	1165	3.0
4	1.2	128	0.17	1205	0.5
5	0.8	122	0.11	1210	0.833

E. SPEED PRE SET AT 1250 R. P. M.

Conditions: R_{sh} = Shunting Resistance = 11 ohms.

I_{c3} = 0.05 amp

Error volts zero for I_L = 1.3 amp.

Sl. No.	I_L Amp	V_{ma} Volt	$I_{comp.}$ amp	Speed R.P.M.	% change from desired speed.
1	1.3	138	0.235	1250	0
2	1.6	137	0.280	1245	0.4
3	1.8	138	0.325	1235	1.2
4	2.1	138	0.370	1215	2.8
5	1.0	134	0.180	1255	0.4
6	0.6	130	0.120	1255	0.4

F. SPEED PRE SET AT 1400 R.P.M.

Conditions: 1. R_{sh} = Shunting Resistance = 17 Ohms.

I_{c3} = 0.09 amp.

Error volts zero for 1.65 amp. load.

Sl. No.	I_L amp	V_{ma} volts	$I_{comp.}$ Amp.	Speed. R.P.M.	%Change from desired value
1	1.65	158	0.40	1400	0
2	1.9	157	0.46	1380	1.43
3	1.4	153	0.33	1420	1.43
4	1.1	152	0.27	1430	2.14
5	0.7	150	0.19	1440	2.85

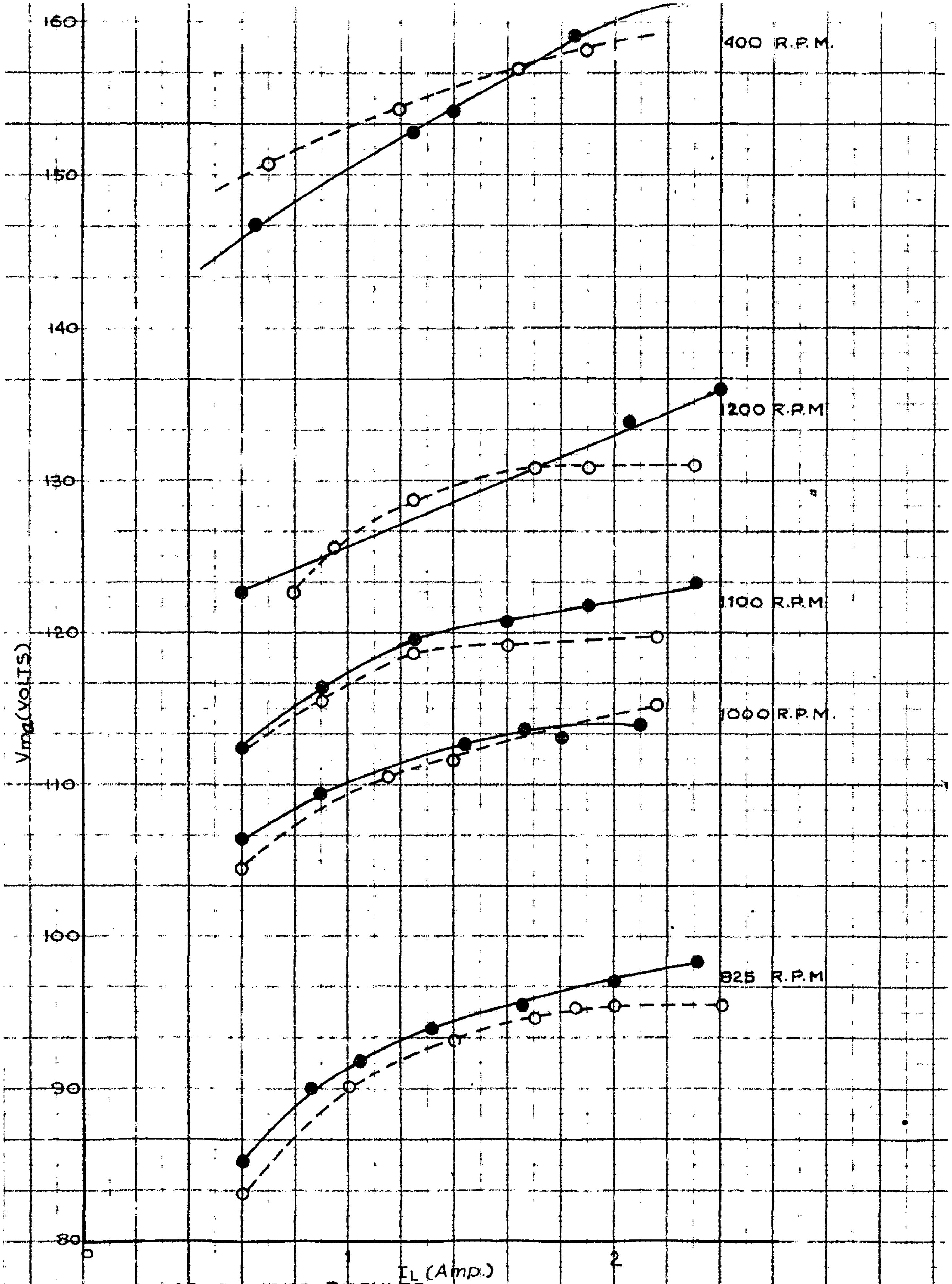
To compare the speed variation with load obtained with the control system with the (i) uncompensated motor speed cariation and (ii) When only voltage compensation is provided and current compensation is absent, the results in these two cases are given.

Case (i)

Sl. No.	I_L amp.	V_{ma} Volt	Speed. R. P. M.	Total speed change
1	0.7	146	1400	
2	0.45	133	1330	
3	1.1	126	1260	Total speed change
4	1.3	124	1200	580 R.P.M.
5	1.5	119	1150	
6	1.9	100	960	
7	2.2	92	820	

Case ii. When only feed back voltage compensation is applied

Sl. no.	I_L amp	V_{ma} volt	Speed R. P. M.	Total Percentage speed change from desired
1	1.05	126	1200	0
2	1.25	1.21	1140	5
3	1.4	119	1080	10
4	1.6	113	1030	14.1
5	2.2	109	960	20



OLID CURVES FOR DESIRED RESULTS
OTTED CURVES FOR RESULTS OBTAINED USING THE CONTROL SCHEME

FIG. 5.3

Comparison Between the Desired and Obtained Voltage at Motor Terminals at Different Loads

The motor speed is maintained constant by adjusting the voltage at motor terminals externally with different loads. The curves showing the relation between load on the motor and the voltage at armature terminals required to maintain the speed constant at desired value are drawn. The actual relation obtained under the control system given under 5.2, are also plotted on the same graph. It shows that these curves follows quite closely the desired curves. The results for the case when speed maintained constant at different loads by external adjustment of voltage are given below:

Sl. No.	Speed constant at 828		Speed constant at 1000	
	I_L amp	V_{ma} volt.	I_L amp.	V_{ma} volt
1	0.6	88	0.60	104
2	0.85	90	0.85	108
3	1.05	91.5	1.15	110
4	1.3	93.5	1.4	111
5	1.65	95	1.8	112.5
6	2.0	96.5	2.15	114.5
7.	2.3	98		

S1S No.	Speed constant at 100 R. P. M.		Speed adjusted at 1200 R. P. M.		Speed constant at 1400 R. P. M.	
	I_L amp.	V_m a Volt	I_L amp.	V_{ma} volt	I_L amp.	V_{ma} volt.
1	0.6	112	0.6	122	0.85	146
2	0.9	116	0.95	125	1.05	148
3	1.25	119	1.25	128	1.35	152
4	1.6	120	1.7	130	1.55	155
5	1.9	121	2.05	133	2.25	160
6	2.3	122.5	2.4	135		

METHODOLOGY

When a d.c. seporately excited motor is supplied by converting a.c. single phase voltage into d.c. voltage using a converting unit as described in our scheme it is found that with increase in load the voltage lead to the armature drops. It is noticed that the speed also drops.

To maintain the speed of motor constant with increase in load, the terminal voltage should increase in a particular fashion. This indicates that with increase in load, we have to provide overcompensation for voltage drop. Also the compensation should be such that it will lead to required mode of voltage rise with increase in load current.

This particular mode of increase of voltage, required to maintain the speed constant with increase in load, can be achieved by using a series saturable reactor and rectifier as a converting unit. The control winding of saturable reactor is to be connected in series with motor armature . As the load current increases current through the control winding and hence the control ampere turns on the core increases thereby causing higher saturation and consequently reduction in reactance of saturable core reactor. Thus the voltage drop across the reactor reduces. So the voltage at the armature terminals increase with increase in load. Thus the desired speed can be maintained by providing proper compensation by selecting proper control winding turns.

In actuality as it was previously proposed to obtain speed control only by voltage feedback by tacho-generator, the control windings were designed for small value of current using conductors of smaller cross section. But it was found that this compensation alone is insufficient. So the present scheme using series compensation was used. In this scheme as the control winding was incapable of takingf full load current. Shunts were provided to limit current through it. But it was found that due to this arrangement the winding is incapable of developing desired ampere turns to produce the required voltage rise with increase in load. Also due to high resistance of the winding some voltage also drops across it. So the methodology based on simulation is given below :

The curves showing relation between the increase load current and the voltage to maintain the motor speed constant are drawn as given in Section 5.3.

The same relation is obtained by saturable reactor series compensating, control winging current adjusting externally . As given below the test results were obtained. As given in Section 5.3. for 825 R.P.M. speed setting the control current in series compensating control winding is givenin the following table.

Sl. No.	I_L Amp.	V_{ms} Volts	I_{c1} Amp.	Turns required on control winding. *
1.	0.6	85	0.1	208
2	0.85	90	0.14	206
3.	1.05	91.5	0.17	203
4.	1.30	93.5	0.22	211
5	1.65	95	.28	211
6.	2.0	96.5	0.34	212
7.	2.3	98.0	0.38	208

* In actuality the control winding has got 1250 turns . But if we desire that the same load current is to circulate in control winding when

it is connected in series with load, then the turns required on that control winding can be found out from the observations given above.

$$\text{The number of turns} = \frac{1250 \times 0.1}{0.6}$$

$$= 208 \text{ turns.}$$

The turns from other observations in the table are given in the last column of the table No. 1 . So it can be seen as an average we should provide 210 turns of wire of higher cross section in this control winding. This number of turns is found suits to all other speeds. So if properly designed compensating control winding is provided desired speed control can be obtained.

CONCLUSION

Foregoing experiment and analysis shows that it is possible to control the speed of a d.c. motor, when a.c. single phase supply is available and the motor is supplied through a series saturable reactor and rectifier set. It also shows how to evaluate the characteristic and parameter of saturable reactor so that it can behave in a fashion necessary for speed control of a given d.c. motor.

APPENDIX 1

CALCULATION OF CHARACTERISTIC EQUATION

The characteristic equation obtained is

$$S^3 + S^2\left[\frac{1}{T_{c2}} + \frac{1}{T_{c1}} + \frac{B}{NT_{c1}} + \frac{(N+A)}{T_m N}\right]$$

$$+ S\left\{\frac{1}{T_{c2}}\left[\left[\frac{1}{T_{c1}} + \frac{B}{NT_{c1}}\right] + \frac{N+A}{NT_m}\right] + \left[\frac{(N+A)+(B+C)}{NT_m T_{c1}} + \frac{MK_t N_{c2}}{N T_m T_{c2} R_{c2}}\right]\right\}$$

$$+ \left[\frac{N+A+D+C}{NT_m T_{c1} T_{c2}} + \frac{MK_t N_{c2}}{NT_m T_{c2} R_{c2} T_{c1}}\right]$$

Where

$M = R_o \; R_{c1} \; K_{re} \; K_i = 54 \times 1 \times .0 \times .08$

$= 33$

$N = R_d R_b N_L f_m = 1 \times 1 \times 300 \times 0.02$

$= 6$

$A = K_b K_1 N_L R_{c1} = 0.012 \times 0.68 \times 300 \times 1$

$= 186$

$B = R_a f_m N_{c1} K_1 \cdot R_0 K_{re} = 1 \times .02 \times 210 \times .018 \times 54 \times$

$= 3.68$

$C = K_b K_1 N_{c1} K_1 R_0 K_{re}$

$= .012 \times .68 \times 210 \times .018 \times 54 \times .9$

$= 114$

Now putting the values of constants we have

$$S^3 + S^2\left[\frac{1}{.203} + \frac{1}{.28} + \frac{3.68}{6\times.28} + \frac{6+186}{6\times.2}\right]$$

$$+ S\left[\frac{1}{.203}\left[\frac{1}{.28} + \frac{3.68}{6\times.28} + \frac{6+186}{6\times 2}\right] + \frac{(186+6)+(3.68+114)}{6\times 2\times .28} + \frac{(33\times240\times1.7)}{6\times2\times.203\times15}\right]$$

$$+\left[\frac{6+186+3.68+114}{6\times2\times.28\times.203} + \frac{240\times.7\times33}{6\times2\times.208\times.203\times15}\right] = 0$$

So now the characteristic equation reduces to

$$S^3 + 26.70\,S^2 + 300\,S + 993 = 0$$

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