SPEED CONTROL OF SEPERATELY EXCITED DC MOTOR USING THYRISTOR CHOPPERS

A DISSERTATION
submitted in partial fulfilment
of the requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
POWER APPARATUS AND ELECTRIC DRIVES

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CERTIFICATE

Certified that the dissertation entitled " SPEED CONTROL OF SEPERATELY EXCITED DC MOTOR USING THYRISTOR CHOPPERS " which is being submitted by Shri P.S. DOTIHAL, in partial fulfilment of the requirement for the award of the Degree of MASTER OF ENGINEERING in ELECTRICAL ENGINEERING (POWER APPARATUS AND ELECTRIC DRIVES) of the UNIVERSITY OF ROORKEE, ROORKEE is a bonafide work carried out by him under my supervision and guidance. The matter embodied in his dissertation, has not been submitted for the award of any Degree or Diploma.

It is further certified that he has worked for a period of about 6 months from March to 27th August 1976, for preparing this work at the UNIVERSITY OF ROORKEE, ROORKEE.

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SYNOPSIS

This dissertation describes the analysis and the experimental studies of a seperately excited dc motor fed by a thyristor chopper as a variable speed drive motor. A critical review of the various conventional schemes of adjustable speed drives is given in the introduction. The reasons for the accelerated trend in the use of thyristor control for variable speed drives in general and thyristor choppers in particular, are mentioned.

Chapter 1 consists of a study of chopper action, triggering and commutation circuits. The working of the two circuits are described in detail. The steady state operation of a chopper is analysed in chapter 2. Further, the general expressions for the current torque and speed of the motor are derived. The starting and braking methods of the motor with chopper circuits are described in chapter 3. The commutation and loss problems, in a motor operated on rectified power supply, are also given. The methods of improving the motor performance are suggested.

Chapter 4 gives the details of the experimental set-up, observations and results. A brief conclusion on the experimental results is given.

At the end, appendices carry the list of the components used, with their specifications and the references. are given.

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NOMENCLATURE

C - General Symbol for capacitance (μf)
D - General symbol for Diodes
Eb - Motor induced average voltage (V)
f - Supply frequency (H_z)
I_a - Armature current (A)
I_D - Average free wheeling current (A)
I_f - Field current (A)
I_{GT} - Gate tirgger current (mA)
I_s - Source current (A)
i - Instantaneous current (A)
ic - Capacitor current (A)
J - Moment of inertia of the armature (kg- M^2)
L_1, L_2 - Commutating Inductor (mH)
L_f - Field inductance, (mH)
L_s - Series inductor
N - Motor shaft speed (RPM)
No - Motor shaft rated speed (RPM)
K_t, K_e - Constants defined in the text.
Q - Quality factor defined in the text
R - Resistance (Ω)

T - Switching period (ms)

T_L - Average load torque (N - m)

T_e - Electromagnetic torque developed (N - m)

t - Instantaneous time (ms)

t_c - Conduction time intervals or on time (ms)

$t_{(ckt)}$ - Circuit turn off time

t_o - Off time (ms)

t_q - Turn off time of thyristor (μs)

t_p - Pulse width (u s)

V_s - Source voltage (V)

E_o - Output voltage (V)

V_f - Field voltage (V)

V_{GT} - Trigger pulse voltage (V)

α - Chopper frequency coefficient

γ - Duty factor

β - p.u. speed

ω - Angular frequency $2\pi f$.

ϕ - Magnetic flux (webers) .

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CONTENTS

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INTRODUCTION

A wide variety of electrical motors have been developed (21), capable of performing various duties required. Induction motors, on account of its extreme simplicity, have found universal applications where the speed requirement is almost at constant value. Synchronus motors are invariably used where precisely constant speed is required. For applications, requiring variable speed, there are good number of types of motors available. But, most frequently preferred in this field, is the dc motor. The speed of the dc motor can be controlled by varying either armature voltage or the field current. Former is for speed below the rated and the latter for the speed above the rated value. Hence, with dc motors smooth speed control over a wide range is possible. DC motors can closely match with the needs of the application as the speed- torque characteristic, can be varied to almost any useful form, for both motoring and regenerating applications. AC motors stall at the loads above twice their rated value and can not start on loads above

150% of the rated torque. On the other hand, dc motor can start at higher loads and also can take up overload upto 300 to 400% of rated load for a short period. Dynamic or regenerative braking is easily obtainable with the dc motors for application, requiring quick stopping or speed reversals (22).

As mentioned already, dc motors are easily adaptable to adjustable speed service. The speed characteristic of a seperately excited dc motor is given by:

$$N = \frac{V_s - I_a R_a}{K I_f}$$

It is clear that the speed control through the variation of armature voltage or the field current, requires an adjustable dc voltage. The adjustable dc voltage is obtainable by adopting any of the following schemes using,

i) Ward Leonard method

ii) Rotating amplifier

iii) Magnetic amplifier

iv) Grid - controlled Thyratron or mercury -arc rectifier.

v) Thyristor

i) Ward Leonard control, first introduced about eighty-two years back, is the most familiar method of obtaining adjustable voltage. It makes use of the motor-generator set and provides a smooth speed control, over a wide range down to a very low value, which is limited by the residual magnatism of the generator. At lower speed, the stability of operation is affected by a demagnatisation of the armature reaction (1).

ii) Rotaling amplifier is a special kind of dc machine, which has several windings (control and excitation windings). It possesses high voltage gain and the ability to provide optimum condition for handling transients. The power supplied to the load by it can be controlled by small signal inputs. Closed loop atomatic speed control schemes using amplidyne are very convenient and accurate.

iii) Magnetic amplifiers have found considerable application in the control of dc and ac motor drives. The power gain is very high and is of the order of few thousands. The most valuable feature of this apparatus is that the functioning is highly reliable. The only shortcoming of magnetic amplifier is its comparatively higher electromagnetic inertia.

iv) Grid controlled mercury arc rectifiers and thyratrons have found applications in providing adjustable dc voltages, required in connection with the adjustable speed dc drives. The merits of the controlled rectifier is that of low cost, small dimensions, saving in non-ferrous materials, higher efficiency and absence of moving parts. But the limitation being that of drop of power and power factor with the larger values of firing angle. Cooling and the protection problems limit the capacity of the device.

v) Thyristor was first introduced in 1957, as a semiconductor controlled rectifier, to replace the grid controlled mercury arc rectifiers and thyratrons. It is a solid state counterpart of the Thyratron. The word THYRISTOR owes its origin to <u>THYR</u>ATRON and TRANS<u>ISTOR</u>. Hence, it possesses the fine capabilities of the both. Since then, great progress has been made with semiconductor devices. The development of high power thyristors (with a negligible forward voltage drop while conducting and high reverse blocking voltage while not conducting, and their decreasing costs) has led to the creation of a new range of static converters which can be utilised for dc as well as ac motor drives (5-7).

Static converters enable in developing more accurate, efficient and compact control schemes for electrical motors. In addition, they help in obtaining characteristics, formerly accossiated with one type of motor from the other type. For example, using phase controlled cycloconverters, even induction motors or synchronus motors may be used as variable a speed drive. Hence, induction motors are becoming very popular for applications requiring variable speed.

The conventional methods of control are gradually being displaced by thyristor control. For, it has been found that in most of the cases, use of thyristors for power control, affords considerable advantages in comparison with the other systems, owing to the possibilities of obtaining better economy, effeciency reliability, fastness of response, speed- reversing facilities, braking facilities and their compatibility, to adopt for closed loop system of speed control (4).

Thyristor control for electrical motors in general is a very vast topic. Let us consider their applications to only dc drives. Thyristors are implied to produce adjustable dc voltages in the phase controlled rectifier and the chopper circuits. In such circuits the smoothness of voltage control depends upon how efficiently and smoothly the triggering is controlled. Therefore proper and accurate control of the triggering of the thyristor is a very important and basic requirement. The phase controlled rectifier may be half wave or full wave, fully controlled or semicontrolled, single pulse, three pulse or six pulse. The choice of the type of the rectifier depends upon the amount of the power handled, and its applications. Further the choice depends also upon the tolerable amount of harmonic content in the output. Where the speed reversal is essential, fully controlled converter is a must.

When only dc is available (3), time ratio control (TR C) is the most useful and efficient method of speed control. In this, the thyristor functions as a fast acting switch and is said to act as a chopper. It can be used for motors of different hp ratings over a wide range. An important feature of this chopper is that the maximum amount of the ripple content can be controlled by controlling the parameters, responsible for it. Where as, it is not a case in phase controlled converters. The type of the converter bridge will fix the minimum amount of harmonic content. In case of choppers, it is easy and convenient to filter out the ripples, whereas, in the phase controlled converters it is very difficult. Also, radio interference effect is considerable with the latter.

In the present work, the thyristor is used as a chopper to control the speed of a seperately excited dc motor. Suitable control circuit and power circuit are designed, fabricated and tested. The problems encountered with the operation of the chopper circuit have been dealt suitably and few remedies and suggestions for the improved performance are also given.

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LITERATURE REVIEW

Thyristors, like mercury - arc rectifiers, have short conducting and blocking periods, and can be actuated any number of times without risk of deterioration. They may be consequently used in conjunction with the capacitors in dc circuits in which they control the dc power by repeatedly making and breaking of the circuit. In 1963 W. Faust published a paper (25), giving a practical circuit, to get adjustable voltage to control the speed of a dc motor. This circuit was referred to as pulse converters. They perform the same task as a variable ratio transformer. They can, for instance, convert dc power at low voltage to high voltage. Another feature of the pulse converter is high efficiency. They also need little maintainance and can be used for feeding variable speed drive motors, e.g., for dc traction, aboardship, and for battery fed installations. In 1964, Gurvicz, in his paper (29), emphasised the use of pulsed control of the dc motor as a most practical, loss-free and useful method for obtaining variable speed. This method was recommended for traction applications.

Adjustable voltage obtained through pulse supply was succesfully utilized to control the field current of a dc motor to get higher values of the speed. Using this method, B.M. Bird, in his paper (23), described the speed controlling of a seperately excited dc motor. The motor performance was analysed and a wide range of speed control was shown to be possible.

Perimela lagan and Rajgopalan, in their publication (26) in 1971, gave the steady state analysis of the chopper fed seperately excited dc motor with simplifying assumptions, regarding the linearity of the magnetic circuit, commutation phenomenon, the commutating circuits and the mode of chopper operation. The general expressions for the current, during the duty and free wheeling interval, were derived. This method was found to be able to predict the motor characteristic that was found to be in good agreement with the experimental results.

The performance of a dc series motor operating on pulsed supply was analysed in greater details and rigourousness by P.W. Franklin (17). In the analysis the non linearity of the magnetic circuit was considered by suitable approximations . Equations for the current, speed and torque of a motor under steady state operation were developed . Further the problems arising out of the commutation were considered. Adaptability of dc series motors to electrical braking methods were discussed. Fourier series analysis of the armature current was made to get ripple current in it. Extra losses on account of ripples in the current were also worked out. The analysis given is simpler, more general and hence can be used for the case of dc shunt motor also.

Thyristors, in chopper circuits are working under dc supply and cannot be extinguished automatically but require forced commutation. Forced commutation is possible by making use of a commutating capacitor in a suitable circuit arrangement, such that it can be charged, discharged & recharged in the reverse sense, rapidly. A suitably charged capacitor is connected in series or in parallel with the Thyristor to provide a negative base, and thereby reducing the current in main thyristor to be turned off. A number of commutation circuits have been proposed. Therefore, the method of commutation has become a criteria for the classification of chopper circuit.. There are five different classes of commutation (4) depending upon the suitching arrangement of the resonant circuit.

Class A: Self commuted by resonating the load.

Class B: Self commuted by an LC load.

Class C: C or LC suitched by another load carrying thyristor.

Class D: Cor LC switched by an auxiliary Thyristor.

Class D: External pulse source for commutation.

Of these, the class D has found most applications because of its simplicity, good regulation, operation at high frequencies (4). There are three important types of chopper circuits, which fall under class D commutation. They are as follows:

i) Morgan's chopper

ii) Joan's chopper and

iii) Heuman's chopper.

The important features of these chopper circuits in brief are given in the following paragraphs.

In the Morgan's chopper (27,28), a saturable core reactor is used. As the design of the saturable core is difficult, it has been replaced by an auxiliary Thyristor in the modified Morgan chopper, and is dealt by Bedford and

Hoft (3) . The modified Morgan's chopper is simple, reliable. The circuit can be made to act as an inverter also with certain modification of the commutation and firing circuit.

Jone's chopper makes use of an autotransformer action. Whenever the load current flows in the circuit, the capacitor gets charged. The circuit requires large reactors and becomes economical only for higher loads. The design and analysis become~~s~~ a difficult problem.

Heuman's chopper circuit requires no saturable core reactor or achoke for transformer action, but an auxiliary thyristor is used. In this, the precharging of the capacitor is important. Recharging of the capacitor is obtained by means of a resonant circuit. The design and analysis of the circuit is simple but switching reliability is poor on account of the possibility that the capacitor may not be getting fully recharged . This drawback is overcome by providing an additional resonant circuit. This was suggested by Rudolf Wagner (20). The additional resonant circuit helps in charging the commutating capacitor to full voltage to ensure reliable commutation in next cycles.

G.N. Revankar (11), and A.Alexandrovitz (10) have given guide - lines in the design and optimisation of the commutation circuit. Accordingly, the optimum values of L and C of the commutating circuit are calculated. The chopper circuit used in this work, is as described by G.N. Revankar (11).

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CHAPTER - I.

CHOPPER CIRCUIT

1.1 INTRODUCTION:

The chopper circuits provides a smooth and contactless control to get variable dc voltage from a constt. dc voltage source. Hence it acts as a variable ratio dc transformer. It is possible to step - up or step down the dc voltage. However, in this dissertation, only step - down choppers are discussed.

An ideal chopper is shown in Fig.1.1 . The thyristor Th behaves like an ideal switch, which can operate at high speed, to conduct in one direction only. For the sake of simplicity, the triggering, commutation and snubber a circuits are not shown.

When the Thyristor Th (Fig.1.1) is in conducting state, the full voltage is applied across the load (assuming negligible forward voltage drop across the thyristor). The diode remains blocked throughout this conduction period. During this period, the load current rises exponentially. Under the steady state operation of the motor, this load current rises to a maximum value, depending upon the ON time (t_c) , the time constant of the load and the switching time. During OFF state of thyristor, no voltage is applied across the load as shown in (Fig.1.2). During this period the load current will decay to a minimum value (in continuous current mode of operation), which depends upon the off time, the load time constant and the switching period. The path for the decaying current is provided by the free wheeling diode connected across the load. Fig.1.3 shows the rising and decaying of the current during the ON and OFF period. From the Fig.1.2, it is obvious that the average chopper output voltage is given by :

$$E_o = \frac{t_c}{t_e + t_o} V = \sqrt{\ } V \qquad ....(1)$$

The ratio $\frac{t_c}{t_c + t_o}$ is defined as the duty factor ($\sqrt{\ }$) of the chopper and is always positive but less than the i.e. $0 > \sqrt{\ } > 1$.

From equation 1, it is clear that the average output voltage of the chopper depends upon duty factor, which is nothing but a time ratio. There are three methods of controlling the duty factor to control the output voltage. They are obtained by triggering the thyristor at,

i) variable frequency with constant ON time,
ii) constant frequency with variable ON time,
iii) variable frequency with constant OFF time.

The choice of the method of control depends upon its capability to effect an efficient transfer of power with continuous load current, but with less ripple. The method (i) has the disadvantage that the load current may be discontinuous at low frequency operation, which may cause increased harmonics. Filtering may require high capacity componants. This drawback is eliminated in the second method in which ripples can be minimised by a suitable design. In case of inductive loads filtering may not be necessary, but in resistive loads, filtering is convenient as ripples occur at particular frequency. Method (iii) has the advantage of getting continuous load current, but the complexity of the triggering circuit will be greatly increased. Therefore, second method is preferrable to the other two and is used in this work.

1.2 TRIGGERING CIRCUIT:

(A) TRIGGERING REQUIREMENTS:

A simple method of triggering a thyristor is to apply a pulse at the gate. Triggering circuits are to produce the pulses. It is desirable that the triggering circuit should be simple & reliable. The gating requirements for a thyristor are not set by thyristor and the circuit where it is being used. The minimum values of the gate current (I_{GT}) and the voltage (V_{GT}) should be specified while designing a triggering circuit which can be obtained from SCR manuals. To ensure the conduction of the thyristor, a pulse with a voltage and current, greater than the V_{GT} and I_{GT} must be present at the gate of the thyristor for a period long enough for the anode current, to reach its latching current value. The width of the pulse must be greater than the turn - on time of the thyristor. The voltage and current values and their rate of rises should not exceed the peak ratings of the device.

In a chopper circuit, in addition to the main thyristor, an auxiliary thyristor is used for the purpose of commutation. The main thyristor is turned off by switching on the auxiliary thyristor and vice versa.

Therefore it is necessary to have two sets of pulses required for the two thyristers. And that the instant of triggering the auxiliary thyristor should be well controlled. Because this will control the ON time (t_c) of the main thyristor. This control is obtained by means of a simple potentiometer arrangement as shown in Fig. (1.4), whose functioning is explained in more details in the following sections.

The choice of the triggering frequency is an important factor in the design of the triggering circuit. Its choice depends upon the mode of operation, the load time constant, its inertia and the allowable ripple current. For better performance, the ratio of switching time to the load time constant should be low.

(B) THE DESIGN OF TRIGGERING CIRCUIT:

The design of the complete triggering circuit consists of the design of (i) Saw - tooth voltage generator, (ii) Comparator (iii) Differentiator and (iv) Pulse transformer.

(i) Saw Tooth Voltage Generator(5):

$V_1 = 12v, \quad \eta = 0.66.$

R_3 is chosen as 100 ohms to limit the magnitude of positive resistance as negative resistance is developed across it.

$$R_2 = 10000/\eta V_1 = 10000/.66 \times 12$$

$$= 1260$$

(nearest practical value is 1.5 k)

$$R_2 = 1.5 \text{ K.}$$

$$T = 1/f = 2\text{-}3\ R_1\ C_1 \log_{10} \frac{1}{1-n}$$

C_1 is chosen as 0.1 u f.

$$R_1 = \frac{T}{2-3}\ C_1 \log 3$$

$$= 100\ k\Omega \qquad R_1 = 100\ \text{K} \quad \text{(ohms)}$$

(ii) <u>Reference Voltage is Obtained from a Pot</u>.

(R_4) of 100 K .

(iii) <u>Comparator</u>:

Operational amplifiers EC0709 are used. The output is a rectangular pulse (+ 12 V to -12 V). Use of this will eliminate pulse amplifying stage and infact an attenuator $R_{5,6}$ of 1 K is used.

(iv) <u>Differentiator</u>:

Pulse transformer acts as a differentiator. However, to have very sharp pulse, a capacitor of 0.1 μf $C_{2,3}$ are used. No resistance is required as in an ordinary differentiator on account of the primary winding of the pulse transformer.

(v) Switching diodes SH100 are used to block the negative portion of the pulse.

(vi) Pulse Transformer (24):

A small toroidal core is used for this purpose. The number of turns on it are calculated using the following equations.

$$N = \frac{E\ t}{\phi\ \mathrm{max.}}$$

N = No. of turns.

E = Pulse voltage (V).

t = Pulse duration (μ s).

$\phi_{\mathrm{max.}}$ = Allowable maximum flux change, in μ wb for a core under unidirectional pulse magnetization with the low pulse repetition frequently.

(C) WORKING OF THE TRIGGERING CIRCUIT:

Saw Tooth Generator (4): A unijunction transistor is used as a saw tooth generator. For its operation the circuit is biased for astable operation. As shown in Fig.(1.4), the capacitor C charges to the peak voltage and the device turns on, and the capacitor discharges to the valley voltage. Thus the cycle repeats and across C saw tooth voltage is generated and the wave form is shown in Fig. (1.5 i). The charging time is given by $T_1 = R_1C_1 \log_e \frac{1}{1-n}$ and hence by varying R_1, the frequency of saw tooth voltage can be varied.

__Comparator:__ An operational amplifier is used as a comparator. It compares two input voltages. (i) a saw tooth voltage and (ii) a reference voltage (obtained from a potentiometer). Comparator is very sensitive to detect the instant when the saw tooth voltage attains the magnitude equal to that of the reference voltage, and gives out an output signal at that instant, Thus a rectangular voltage pulse is obtained with two levels. (+ 12 v and -12 v) at a frequency corresponding to that of the saw tooth voltage. A second comparator, identical to the first, and gives an output which is inverse of that of the first, when inputs to it are interchanged. The output of comparators are shown in Fig. (1.5) ii and v.

__Differentiator:__ The comparator output is differentiated using an C- R differentiator and a pulse transformer. The output of the differentiator consists of series of positive and negative pulses as shown in Fig. 1.5 (iii and vi).

Using a switching diode to block negative pulses, only positive pulses are obtained at a frequency corresponding to that of the saw tooth voltage frequency as shown in Fig. 1.5 (iv & vii).

<u>Pulse transformer</u>: Pulse transformers acts as coupling agent between the triggering circuit and the power circuit, as well , it provides dc isolation between the two.

1.3 <u>COMMUTATION CIRCUIT</u> (10-13,20):

(A) <u>INTRODUCTION</u>:

Once the thyristor gains conduction state, the gate loses control over it. The thyristor can only be turned off by reducing the anode current to a value zero or below that of the holding current. This value although varies with the type of the thyristor, will be about 50% of the latching current. To ensure the safe commutation of the thyristor and to regain forward blocking capability, it is necessary that the thyristor current be zero for certain time, called as turn-off time of the thyristor, lest the thyristor cannot block forward anode voltages immediately after current has been reduced to zero. The process of bringing down the thyristor current to zero is known as commutation.

Commutation may be natural or artificial. The natural commutation is possible in ac operated thyristor circuits. Forced commutation is essential in dc operated thyristor circuits. In the forced commutation method, the thyristor current is forced to zero by the application of reverse anode to cathode voltage, which is produced by an auxiliary component, present in an extra circuit. This extra circuit is called as commutation circuit. The component that is most suitable for providing a bias voltage is a commutation, capacitor C, which is called as a commutating capacitor. It should be preferably a fail type or paper type (13) and must have optimum value. During the operating condition, this capacitor discharges and recharges in the opposite sense to the full voltage, by resenance circuits present in the commutation circuit.

(B) DESIGN OF THE COMMUTATION CIRCUIT (21):

The commutation circuit described by Wagner (20), Revankar (11), and Alexandroritz and Zabar (10) is illustrated in Fig. (1.6). It is a class D type of commutation makes use of an auxiliary thyristor and two resonant circuits. The outstanding features (4) of this commutation circuit are that i) commutation is reliable, on account of auxiliary thyristor. ii) The commutation energy may readily be transferred to the load and so, high efficiency is possible. iii) The circuit is versatile.

Choice of the values of L and C for the commutation circuit. The optimum values for a commutating capacitor and inductors is obtained by using the following equations.

According to (ii).

$$L_{1,2} = x R (4.5/\pi) t_q ,$$

$$C = \frac{1}{x R} (4.5/ \pi) t_q .$$

where x is the ratio of the maximum load current to be commutated to the peak discharge current of the commutating capacitor. For $Q \geqslant 12$, the optimum values of L and C are obtained by using x as 1. obtained from curves.

According to (10).

$$C = 1.57 t_q \cdot \frac{I}{V}$$

$$V = \frac{t_q^2}{C}$$

Therefore, the values of L and C used are: 0·18mH and 5μf

(C) WORKING OF THE COMMUTATING CIRCUIT:

The working of the commutation circuit is described in the following sequence.

i) Pre-charging of the commutating capacitor: It is done by triggering the auxiliary thyristor (Th_2) only, and the capacitor C is allowed to be charged such that the plate near to the main thyristor is positive. When the charging process is completed, the charging current falls to zero or a value below that of holding current and the thyristor becomes non-conductive. The commutation circuit operation consists of duty interval, commutation interval and free - wheeling - interval.

ii) Duty interval: With the triggering of the main thyristor, the duty interval starts and the source voltage appears accross the load terminals. The current flows in two parths as shown in Fig.1.7.

1. Source, Th_1; load.
2. C, Th_1; L_1 and D_1 .

Capacitor C is discharged through the path 2 as the time constant of this circuit is low and is again re-charged in the reverse direction i.e. the plate near Th_1 is negative. This occurs by the end of 1/4th period of the first resonant cycle of the circuit formed by L_1, D_1 and C. The charge on C is held by the hold - off - diode D_1. As soon as Th_2 is triggered, the duty interval is terminated.

iii) The Commutation interval: The triggering of the auxiliary thyristor marks the end of the duty interval and the beginning of the commutation interval. The load current through the main thyristor is transferred to the commutation capacitor, and the auxiliary thyristor. The capacitor voltage is applied accross the anode and cathode terminals of the main thyristor as an inverse voltage. It is necessary that this voltage be maintained for at least the turn- off time of the main thyristor, lest the thyristor fails to regain its forward voltage blocking capability (2). C discharges mainly through the resonant path formed by D_2, L_2 and C where the period of oscillation is smaller than that of the other path. The capacitor C gets charged from the dc source through the load and changes its polarity as shown in the Fig. (1.8) . The commutation period can last until the capacitor is fully charged or can terminate when the main thyristor is triggered. The capacitor voltage will be greater than the source voltage in case of inductive or emf loads and hence during this period there will be conduction of free- wheeling - diode which marks the beginning of the free- wheeling period. When the commutation period is terminated by re-firing of the main thyristor, capacitor fails to get fully charged and in the next few cycles of operation, effective commutation may not be possible. Therefore it may be noted that when the duty interval approaches to the period of the chopper or is less than the turn - off time of the thyristor, commutation failure may result. The control over the duty factor may be obtained only after the pre- charging operation.

iv) Free- Wheeling - Interval (12,16): Over swing of the condenser voltage results in the conduction of the free wheeling diode D_F. This marks the beginning of the free wheeling interval. Current through the load during this interval depends only on the value of the current at the end of duty interval and gradually decreases with the time constant of the load. For a small value of duty factor, the current through the load may reach a value of zero.

For high duty factor, current through the load is flowing when Th_1 is again triggered. In that case an over lapping of commutating and freewheeling interval may take place. In other words, commutating interval may end but free wheeling interval may continue depending upon the duty factor.

RESUME:

The thyristor is considered as an ideal and fast acting switch. The working of thyristor as a chopper or a variable ratio dc transformer is described. Further, the output voltage of the chopper is expressed as a function of a time ratio (duty factor). Methods of controlling the output voltage by controlling the duty factor are given.

The basic requirements of the triggering and the commutating circuit for a chopper are considered. The design and the working of the two circuits are dealt in detail.

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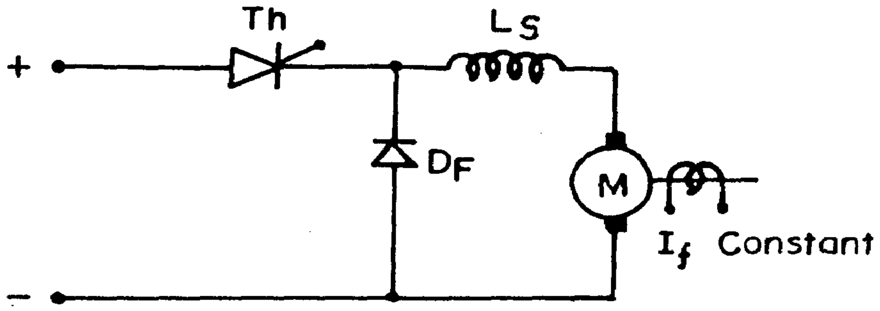

FIG.1.1 SCHEMATIC DIA OF THYRISTOR CHOPPER.

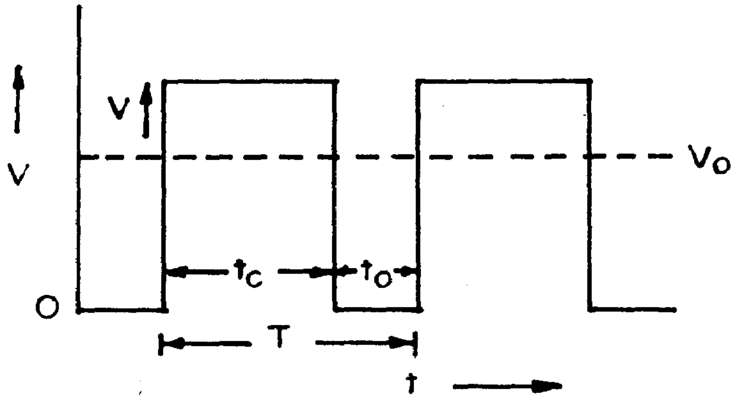

FIG.1.2 VOLTAGE APPLIED TO MOTOR.

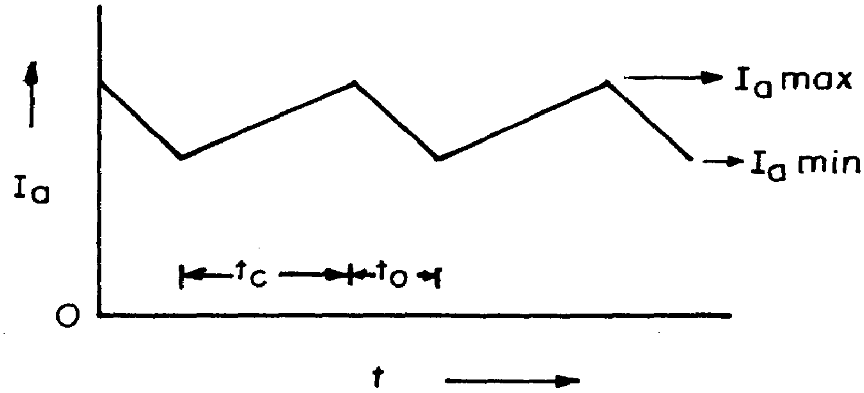

FIG.1.3 MOTOR CURRENT.

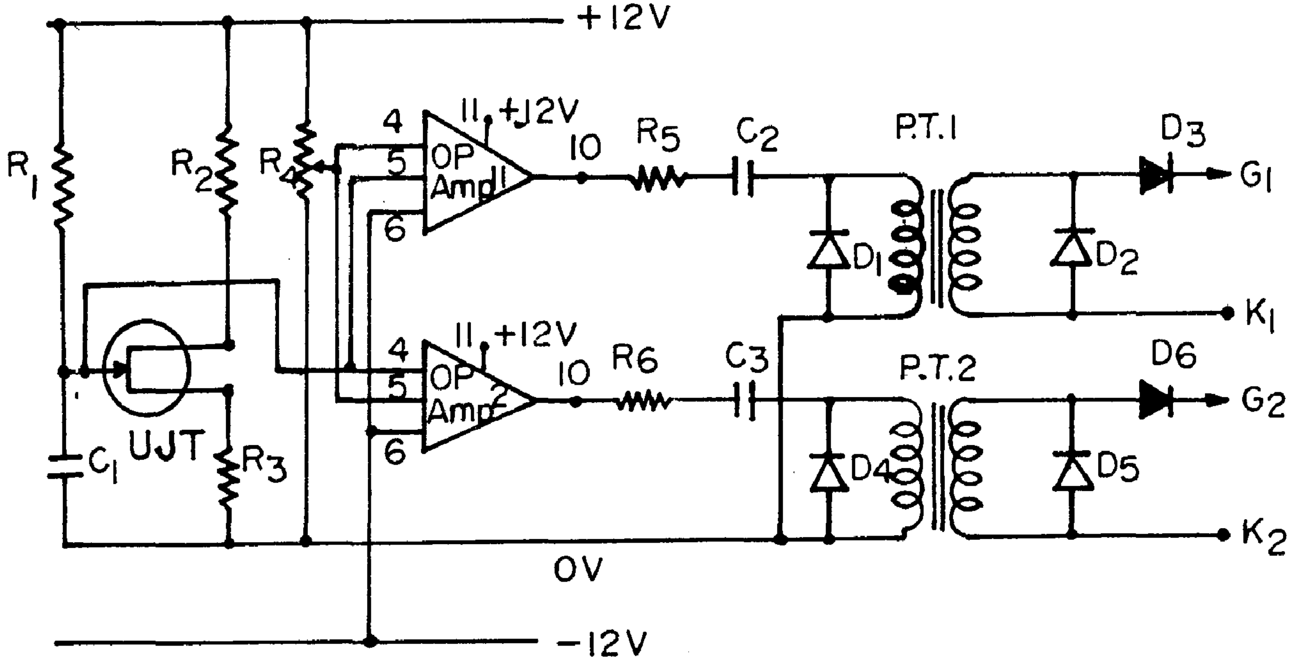

FIG.1.4 TRIGGERING CIRCUIT.

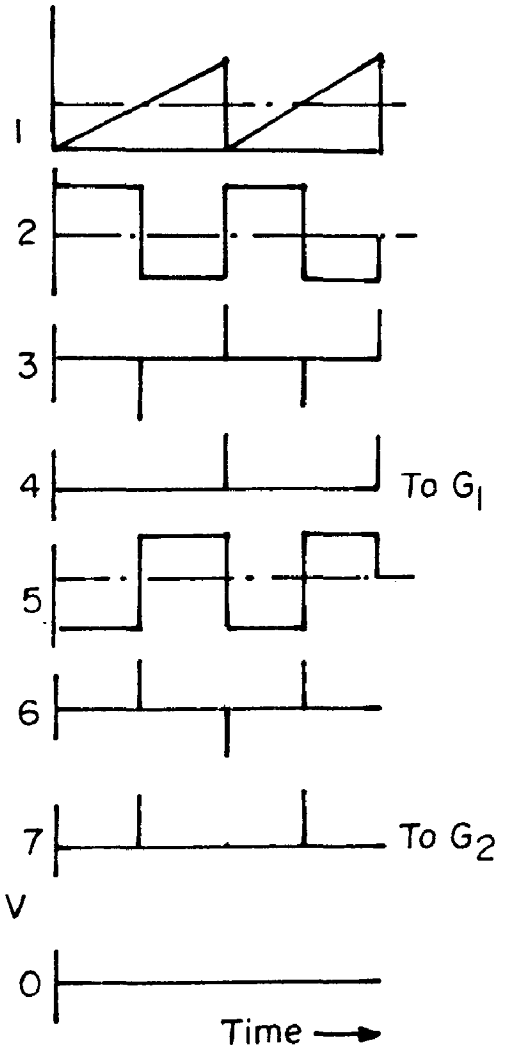

FIG.1.5 WAVE FORMS IN THE FORMATION OF PULSE

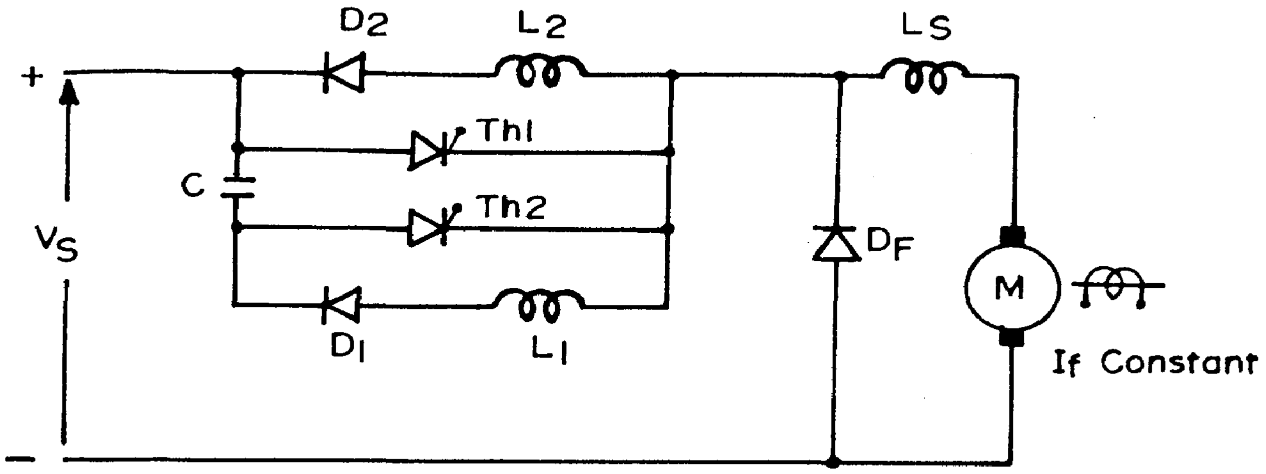

FIG.1.6 COMMUTATION CIRCUIT.

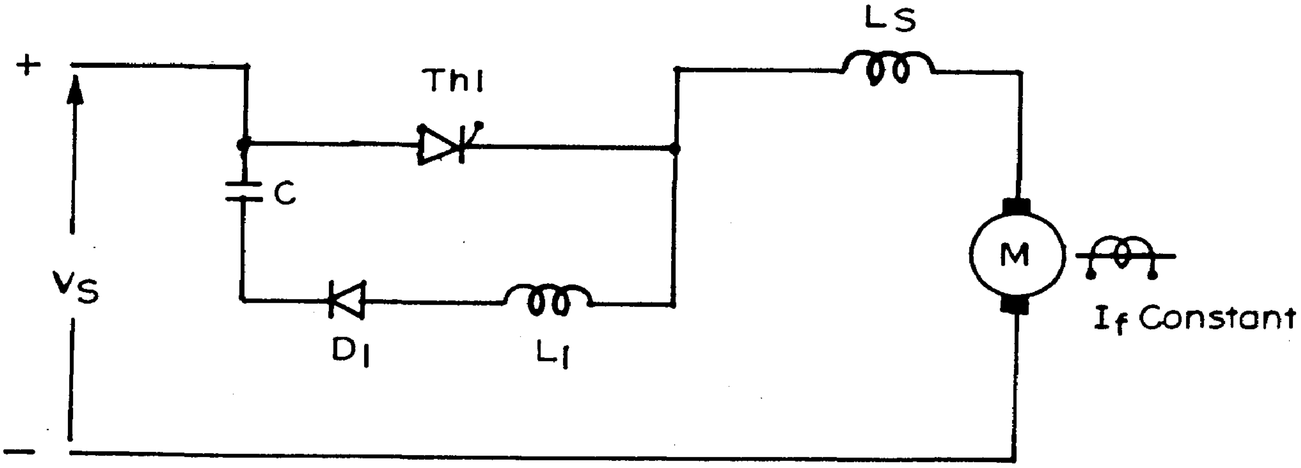

FIG.1.7 EQUIVALENT CIRCUIT DURING DUTY INTERVAL.

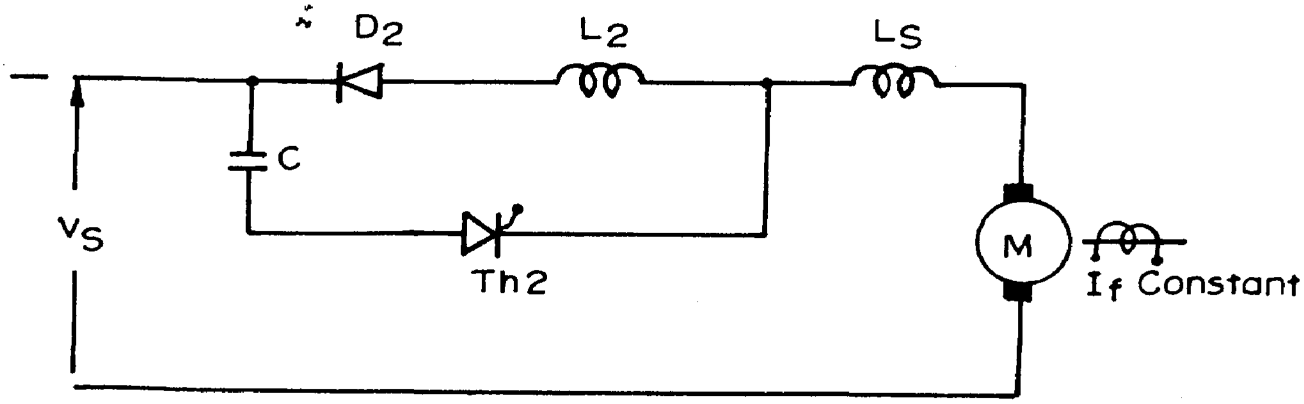

FIG.1.8 EQUIVALENT CIRCUIT DURING COMMUTATING INTERVAL.

CHAPTER - II.

MOTOR OPERATION WITH CHOPPER CIRCUIT

The chapter gives a description about the method of starting and braking of the motor. Further the commutation problems and additional losses caused by the ripple in the armature current are discussed. Finally, certain remedies for the improvement of the motor performance are suggested.

2.1 STARTING (9):

The chopper controlled motor is started on line but with a low value of duty factor to limit the inrush of the current. The usual limit of average starting current is about twice its rated value, and is given by:

$$I_{av} = \frac{\gamma . v - E\,b}{R}$$

At starting $Eb = 0$, $\gamma = \gamma_s$; and $I_{st} = 2I = 2$ p.u. as shown in Fig. 2.1. For any dc motor, the duty factor, at starting can be calculated from the above equation. During the starting period, the commutating capacitance must be as high as of the order of twice the normal value because of the starting current. Otherwise, the commutation may fail. This may be obtained by using an additional capacitance connected across the normal capacitor during starting as shown in Fig.(2.2) and then disconnecting it after the required speed is obtained. As an alternative a variable commutating capacitor may also be used.

2.2 BRAKING (17):

One of the major advantages of the chopper controlled motor is its adaptability to several methods of braking, particularly, regenerative braking with a partial return of power to the source. To stop the motor dynamic braking may be used. The motor is disconnected from the supply, the chopper connections are reversed, the armature is shorted by a resistance, RB_1, and a suitable resistance RB_2 is to be inserted in series with the armature as shown in Fig.(2.3). The nature of the speed torque characteristic is shown in the Fig. (2.4). The motor acts as a seperately excited dc generator and the thyristor is triggered during the braking period.

Regenerative braking is of particular advantage when a battery is used as a power supply (17). It will have to be assumed that the power source is capable to accept instantaneous pulses without increase in terminal voltage; i.e. the internal resistance is zero. The regenerative braking operation is schematically shown in Fig.(2.5). The motor current increases during on period of the thyristor chopper and decreases during the off period. But the electromagnetic field energy is then returned through the blocking diode into the power source. The regeneration is possible only when the maximum and minimum values of the current through the chopper are higher than that of the motor current. The failure of regenerative braking may take place for a given resistance RB_1. To achieve further braking, the resistance is to be lowered. Hence, a rheostat is necessary. The speed torque characteristic during braking condition are shown in Fig. (2.6).

2.3 COMMUTATION AND LOSSES (18,19):

In case of dc motor fed by a dc generated power, the motor current during commutation must decrease to zero and reverse to the negative value linearly. If the reversal of the current is incomplete, sparking occurs. In a chopper controlled dc motor, the current to be commutated is shown in the Fig.(2.7). There is a ripple in the armature current which produces the following undesirable effects. (i) additional transformer voltage in the commutating coil, (ii) the eddy currents are induced in the interpole stator core and frame. (iii) a flux in the interpole axis which is difficult to be compensated. The sparking decreases the life of the brushes. It increases the RI effect, the noise level and losses. In order to improve the commutation the following changes in the motor design are suggested (18).

i) Ripple is to be minimised using reactors.

ii) The use of large number of commutating segments and fewer turns per coil are preferred.

Because of the ripple in the armature current, the r.m.s. value of it, is greater than the average value. This causes more losses, more heat generation in a motor, to produce a given torque, as compared to that case when the motor is operated on dc generated power. Hence, extra copper losses, in the armature and interpole winding and iron losses in interpole body and frame of the motor are produced. Copper losses increase as the square of form factor. It is about 1.05 for a three pulse 1.01 for a six pulse , and 1.35 for single pulse full wave converter. Therefore, increase in copper losses could be from 2[illegible] 2% in six pulse converter to 82% in single pulse full wave converters. Therefore, for motors of over 150 hp, six pulse converters are preferred and for motors up to 150 hp three pulse converters are more useful and for integral hp motors, single phase converters are recommended for use (18).

Experimental results have shown that the increase in loss and heating on an average is about 7% for six pulse and 18% for a three pulse converter. The inter coil temperature followed the increase in loss which sees both the pole and frame losses can become a limiting factor in the design of motor operated on converter supply (19).

As regards a dc chopper, there is an inherent advantage that the ripple content can be minimised by using a very high chopper frequency or filters if necessary. Hence, the extra loss occuring can be kept will within the tolerable limits and it is not a severe problem. However, attempts to improve commutation will be helpful to limit the loss. And therefore, chopper circuits can be used for motors over wide range of hp applications.

RESUME:

In this chapter the starting and braking methods are described. The regenerative breking can be obtained conveniently. The presence of the ripples in the motor current which cause certain undesirable effects which affect the motor performance are mentioned. The increase in the loss due to ripples are considered for the choice the thyristor converters for motor control application. But thyristor choppers provide for the better performance of the motors with wide range of hp ratings. As the starting and braking methods are very efficient, with chopper control circuits, These are widely used for traction applications.

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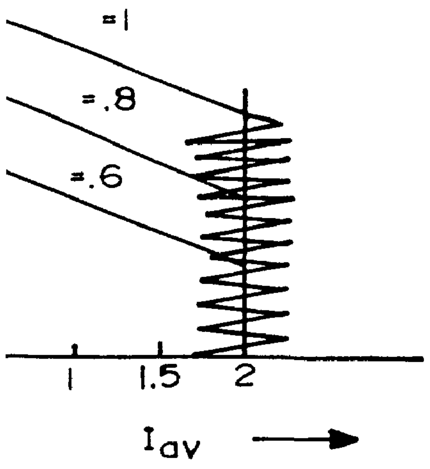

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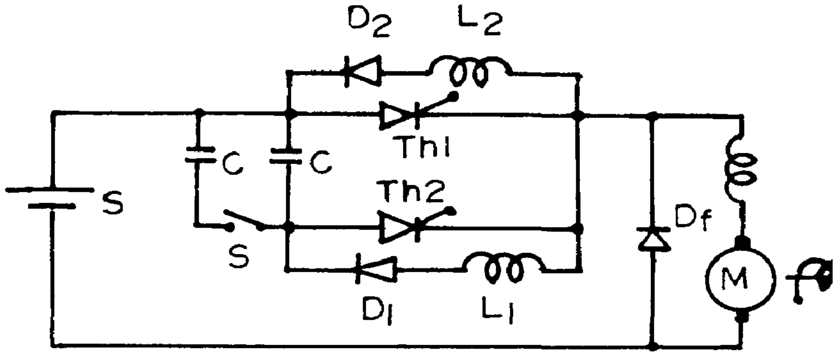
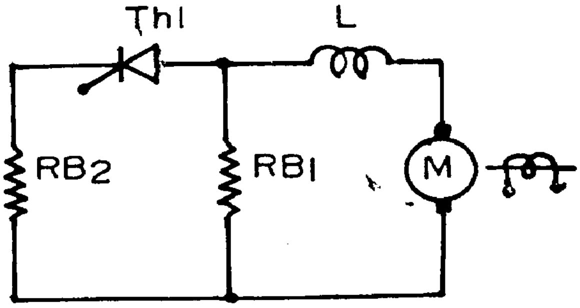


S is closed during starting

FIG. 2.2 CHOPPER CIRCUIT.



.2.3 DYNAMIC BRAKING.

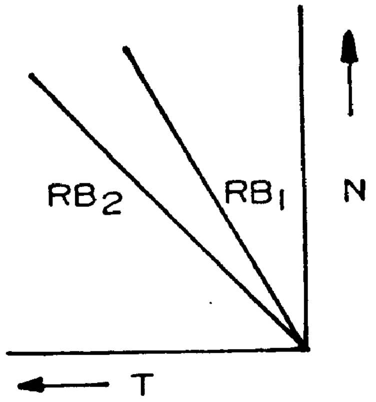


FIG.2.4 SPEED TORQUE CH.

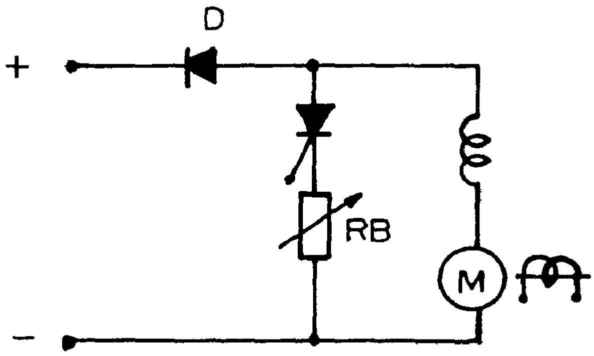


FIG. 2.5 REGEN BRAKING.

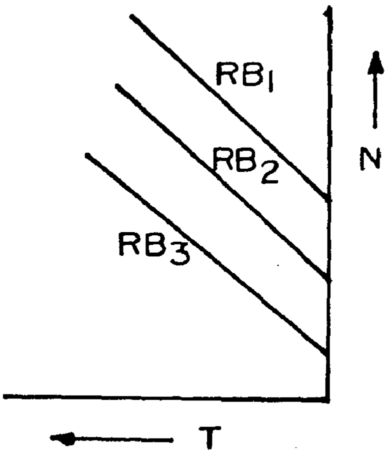


FIG. 2.6 SP. TORQUE CH.

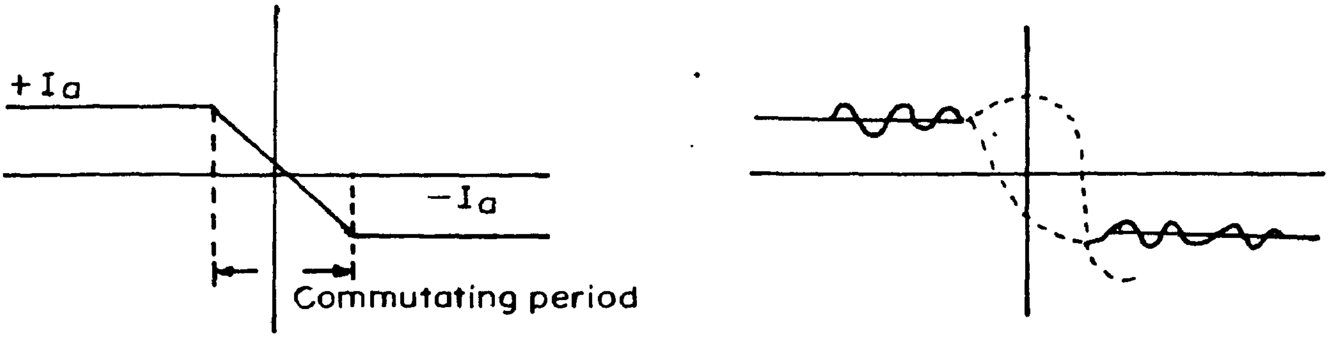


FIG. 2.7 COMMUTATION.

CHAPTER - III.

STEADY STATE ANALYSIS OF SEP EXCITED DC MOTOR CONTROLLED BY THYRISTOR CHOPPER

3.1 INTRODUCTION:

The thyristor chopper performs the function of connecting and disconnecting the supply voltage to the motor. The principle of the working of the chopper circuit has been described in detail in chapter 1. In this chapter, the motor controlled by the thyristor chopper is analysed. For this purpose equivalent circuits are developed for the conducting and non conducting period (t_c and t_o respectively) describing the motoring action. Further circuit equations are developed and solved to get general expressions for currents, torque and speed, in terms of circuit parameters. The ripple and the source current are graphically represented as a function of the duty factor.

3.2 ASSUMPTIONS:

For simplicity the following assumptions are made in the analysis.

1) Thyristors are ideal. In other words, the forward voltage drop across the thyristor is negligible and the reverse recovery voltage is instantaneous.

2) The chopper is working under steady conditions and is supplying a constant load current.

3) The chopper operates in a continuous current mode. i.e. $I_{a\,(min)} > 0$.

4) Chopper control frequency is fixed. But the on time is controlled.

5) Saturation effects are neglected i.e. the circuit parameters remain constant.

6) Friction, windage and iron, losses are neglected. However they may be assumed to be constants and may be considered in a detailed design.

7) Speed variation due to pulses in the armature current are neglected.

8) Effect of commutating coil current is neglected as its is small in large and properly designed motors.

9) Load current during commutation is constant.

10) Field is seperately excited and is constant.

3.3 STEADY STATE ANALYSIS (14.17):

F.F. Mazda (14) has analysed high frequency thyristor chopper circuits. A.K. Datta & M.M. Roy (16) have dealt with the chopper circuit analysis with a static inductive load, P.W. Franklin (17) has carried out the analysis of dc series motors controlled by power pulses. Based on the similar lines, an attempt is made to analyse the performance of a seperately excited motor controlled by thyristor chopper.

Fig.3.1 and 3.2 represent the equivalent circuits durin ON and OFF intervals of a pulse period. The circuit equations are given by, (1) and (2) respectively.

$$V = Eb + R_o i + L_o p_i \qquad \ldots\ldots\ldots(1)$$

$$0 = Eb + R_o i + L_o p_i \qquad \ldots\ldots\ldots(2)$$

Under steady state conditions the motor armature current builds up from $I_{a(min)}$ to $I_{a(max)}$ during ON time. During ON time,

$$i_1(t) = \left(\frac{V - E_b}{R_o} \right) \left(1 - e \right)^{-t/T_o} + I_{a(max)} e^{-t/T_o} \qquad \ldots\ldots\ldots(3)$$

During OFF time,

$$i_2(t) = I_{a(max)} \, e^{-t/\tau_o} - \frac{EB}{R_o} \left(1 - e^{-t/\tau_o} \right) \quad \ldots\ldots\ldots(4)$$

As t approaches t_c and t_o in 3 and 4, respectively, the above equations give the maximum and minimum value of armature current as in (5) and (6).

$$I_{a(max)} = \left(\frac{V - Eb}{R_o} \right) \left(1 - e^{-t_o/\tau_o} \right) + I_{a(min)} e^{-t_c/\tau_o} \quad \ldots\ldots(5)$$

$$I_{a(min)} = I_{a(max)} \, e^{-t_o/T_c} - \frac{Eb}{R_o} \left(1 - e^{-t_o/T_o} \right) \quad \ldots\ldots\ldots\ldots(6)$$

Equations 5 and 6 are further simplified and expressed in terms of the variables α, β and γ which are defined as below.

$$\alpha = T/T_o = \frac{\text{Switching period (ms)}}{\text{Time constant of the load (ms)}} \quad \ldots\ldots\ldots\ldots(7)$$

$$\beta = E_b/V = n/n_o \; . \; \text{P.u. speed of the motor} \quad \ldots\ldots(8)$$

$$\gamma = t_c / T_o \; . \; \text{Duty factor} \quad \ldots\ldots(9)$$

(t_c) and decays again to $I_{a(min)}$ from $I_{a(max)}$ during OFF time, exponentially as shown in Fig. 3.4. The solution of the above equations 1 and 2 give the following expression for the current at any time 't' during ON or OFF intervals of the pulse.

$$I_{CL} = V/R_o \quad \text{(Starting or S.C. Current)} \qquad \text{.........(10)}$$

We have,

$$I_{a\,(max)} = I_{CL} \frac{(1 - e^{-\gamma\alpha})}{(1 - e^{-\alpha})} - \beta \qquad \text{...(11)}$$

$$I_{a(min)} = I_{CL} \frac{(1 - e^{-\gamma\alpha})\,(e^{-(1-\gamma)\alpha})}{(1 - e^{-\alpha})} - \beta \qquad \text{.........(12)}$$

The ripple current defined as the difference between the maximum and minimum value of armature current is given by

$$I_{(rip)} = I_{CL} \frac{(1 - e^{-\gamma\alpha})\,(1 - e^{(1-\gamma)\alpha})}{(1 - e^{-\alpha})} \qquad \text{........(13)}$$

The maximum value of the ripple current will occur at a duty factor $\gamma = 0.5$. Therefore we have

$$I_{(rip)max} = \frac{\left(1 - e^{-0.5\alpha}\right)^{2}}{\left(1 - e^{-\alpha}\right)} \qquad \text{.......(14)}$$

During ON time current supplied by the source I_s is given by A/T i.e.

$$I_s = \frac{1}{T} \int_0^{t_c} i_1(t)\, dt.$$

$$= \frac{1}{T} \int_0^{t_c} \left\{ \frac{V - E_b}{R_o} \left(1 - e^{-t/T_o}\right) + I_a\,(min)\, e^{-t/T_o} \right\} dt.$$

i.e.

$$I_s = I_{CL} \left\{ (1 - \beta)\gamma - \frac{1}{\alpha} \frac{\left(1 - e^{-\gamma\alpha}\right)}{1 - e^{-\alpha}} \left(1 - e^{-(1-\gamma)\alpha}\right) \right\} \qquad \text{.......(15)}$$

Similarly, the current flowing through the freewheeling period is given by

$$I_D = \frac{1}{T} \int_0^{t_o} i_{2(t)}\, dt.$$

$$= \frac{1}{T} \int_{0}^{t_o} \left\{ I_{a\,(max)} \; e^{-t/T_o} - \frac{Eb}{R} \left(1 - e^{-t/T_o} \right) \right\} dt.$$

$$= I_{CL} \left\{ (\gamma - \beta) - (1 - \beta) \gamma + \frac{ (1 - e^{-\gamma \alpha}) (1 - e^{-(1-r) \alpha}) }{ \alpha (1 - e^{-\alpha}) } \right\} \quad ..(16)$$

The average current in the armature during a pulse is the sum of the source and freewheeling current.

$$I_{av} = I_D + I_S$$

$$= I_{CL} \; (\gamma - \beta) \quad ....(17)$$

The average torque produced $= T_{av}$

$$= K \cdot \phi \cdot I_{av}.$$

$$= K' \; I_{av} \quad .....(18)$$

Therefore torque - speed characteristics are identical to that of current - Speed characteristics.

Pulsation in armature currents causes the pulsation in the instantaneous speed. Ripples in speeds will be less if motor inertia is more. A ratio of $\frac{N_{(max)} - N_{(min)}}{N_{(max)} + N_{(min)}}$

is a measure of the speed ripple.

RESUME:

The analysis of the seperately excited dc motor is very much simplified by making various possible assumptions. The equivalent circuits are formed, and the circuit equations are written for the ON and OFF intervals. Further they are solved to get general expressions for the average current torque and speed, in terms of duty factor and other circuit parameters. The general expressions are quite helpful in knowing the effect of the chopper frequency and the duty factor over the motor performance. They can also be helpful in giving the guidlines for the design of the chopper circuits. The use of the analytical expressions is made to get the ideal characteristics of a thyristor chopper and the important ones are graphically shown.

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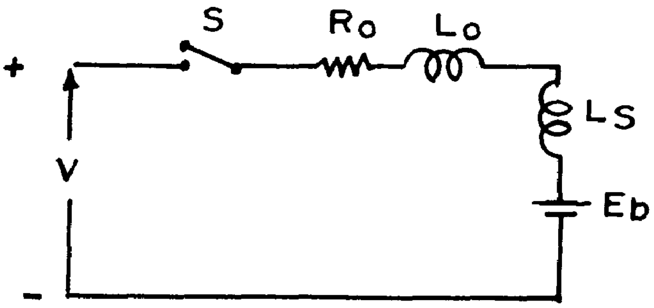


FIG.3.1 EQUIVALENT CIRCUIT DURING ON PERIOD.

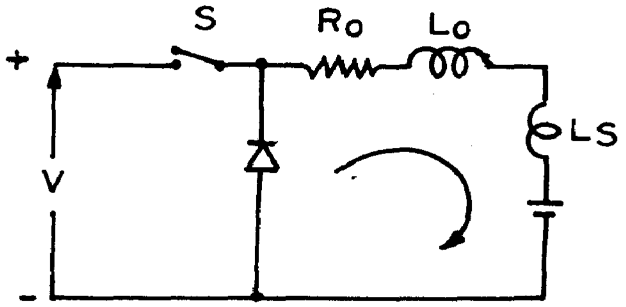


FIG.3.2 EQUIVALENT CIRCUIT DURING OFF PERIOD.

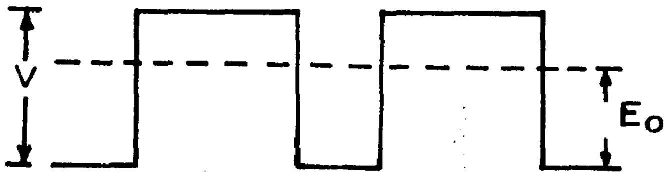


FIG.3.3 ARMATURE VOLTAGE.

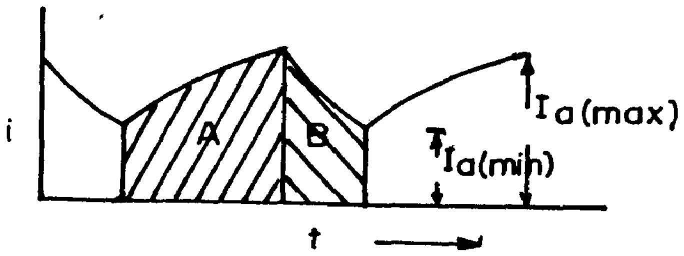
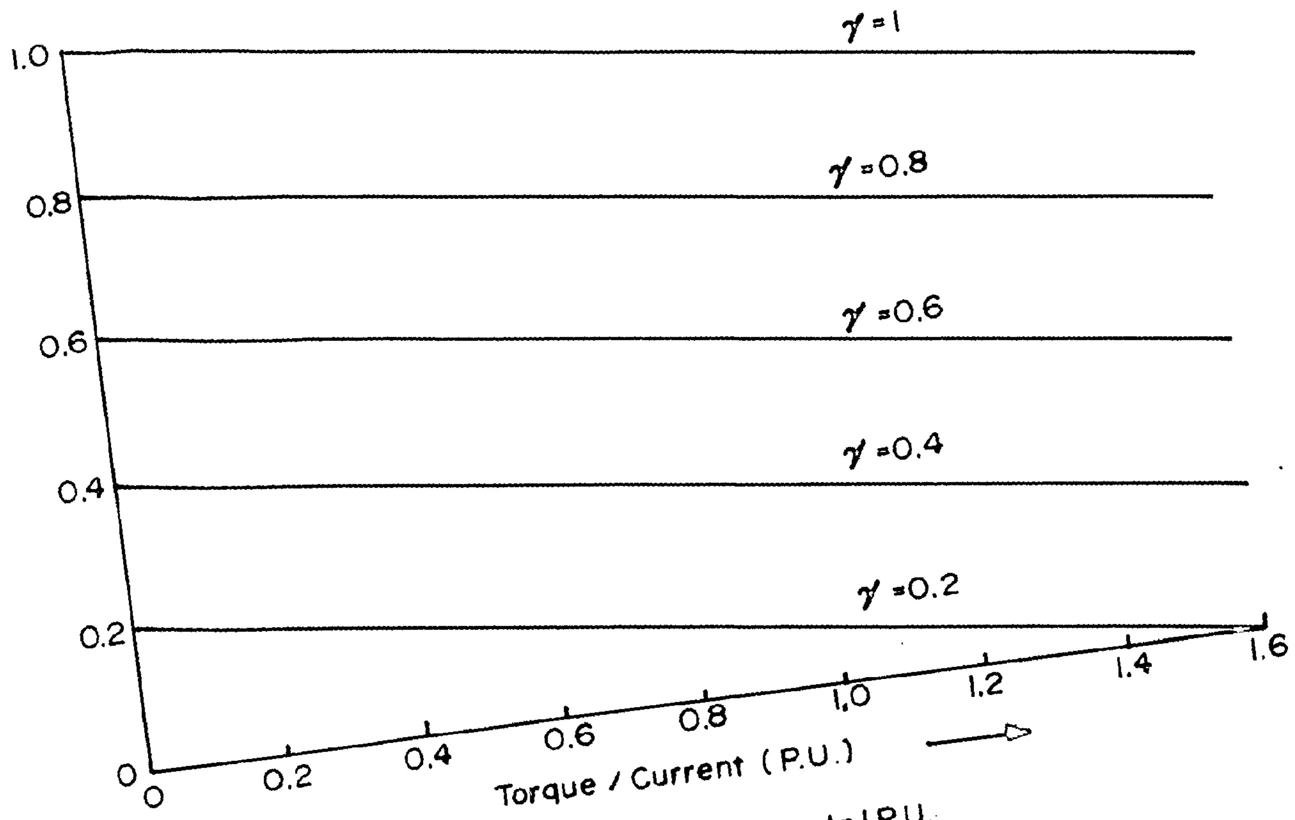


FIG.3.4 ARMATURE CURRENT.



Rated current = 1 P.U. , Rated speed = 1 P.U.

Rated torque = 1 P.U.

FIG. 3.5 SPEED TORQUE CH.

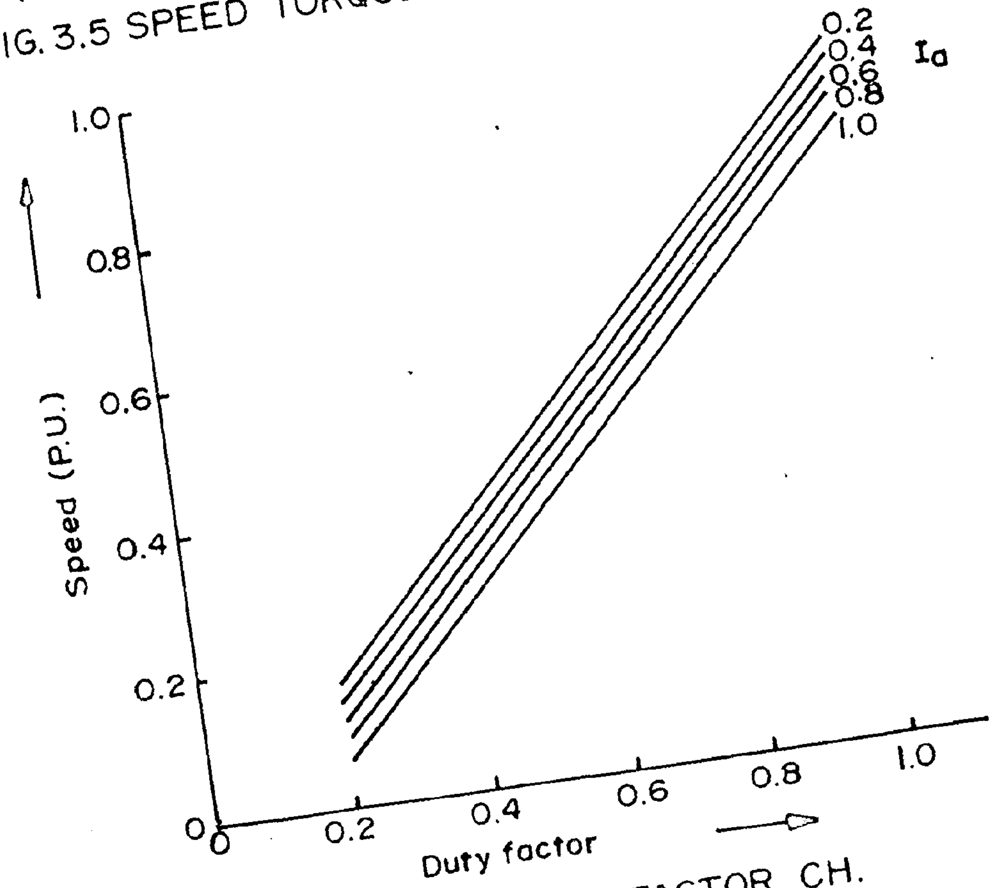


FIG. 3.6 SPEED DUTY FACTOR CH.

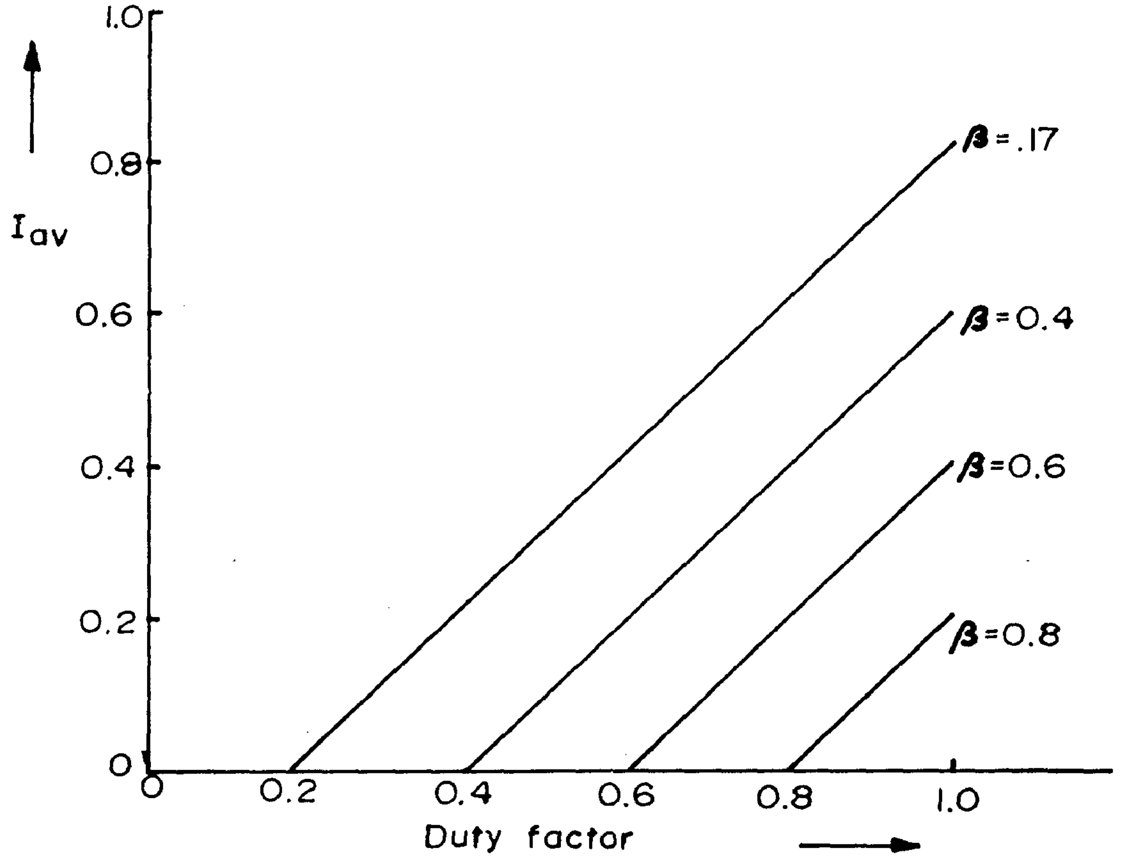


FIG. 3.7 CURRENT DUTY FACTOR CH.

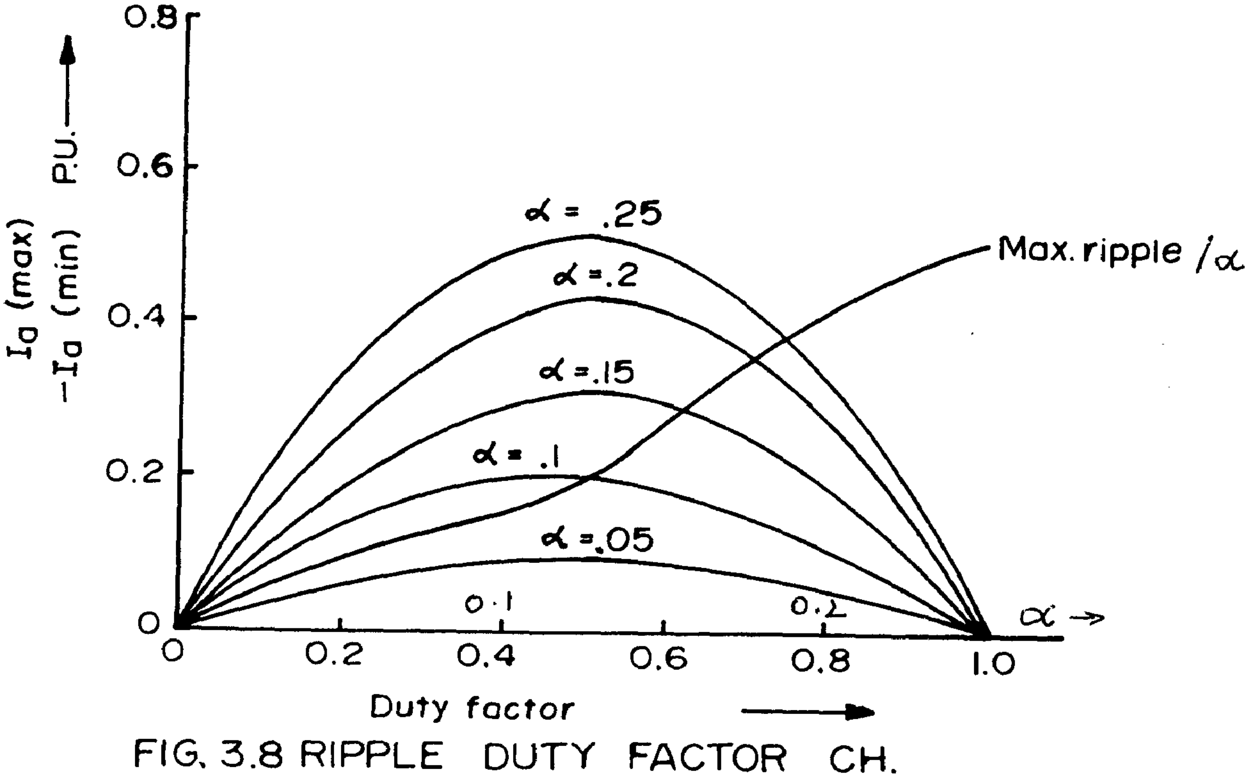


FIG. 3.8 RIPPLE DUTY FACTOR CH.

CHAPTER - IV.

EXPERIMENTAL DETAILS, OBSERVATIONS, CONCLUSIONS AND APPLICATIONS

A complete and more practical circuit for a thyristor chopper requires the following, in addition to the triggering and commutating circuits, which have been already described.

4.1 EXPERIMENTAL DETAILS:

Protective Circuits: Because of the low heat capacity, thyristor devices are sensitive to overload. Moreover, the chopper circuit conducts in one direction only and has a very low resistance in the reverse direction, and is very sensitive to the polarity of the supply. Therefore, an efficient fusing of the circuit is essential and the same is provided to protect the thyristor and the power diodes. Protection must also be provided against the effects of spurious turn-on and the dv/dt effect which could turn-on a nonconducting thyristor. Therefore a simple snubber circuit is connected across the anode and cathode of the thyristors, as shown in the Fig. (4.1). Spurious turn-on is prevented by using a thyristor, with a break down voltage, greater than the maximum supply voltage. A switch is used in the gate circuit of the main thyristor to enable the pre-charging of the capacitor , as shown in the Fig. (4.2). A transformer winding is used as a series choke to smoothen out the ripples in the current. A free - wheeling diode is made use of across the load to supress the noise effect. To optimise the circuit performance, linearisation of the saw- tooth - voltage and a facility to get a variable triggering frequency, are introduced.

4.2 OBSERVATIONS:

The chopper frequency is set to its maximum value (1.4 KH_3) , for which a better commutation and circuit performance are possible. This depends upon the available inductors and capacitors, for the commutation circuit. The speed and output voltage variations,as a function of the duty factor, are observed and expressed by means of the characteristic curves in Fig. (4.4). The wave forms corresponding to the speed of the motor and the current are observed, using a tachogenerator and a signal from the ammeter terminals respectively.

4.3 CONCLUSIONS:

i) Very smooth control of voltage and speed are possible with the chopper circuit, Of course with the help of a linear saw- tooth- voltage and a sharp triggering pulses. Linearity is obtained by charging the capacitor with a constant current, as shown in Fig.(4.3).

ii) The speed of the motor is found to be free from ripples; because the thyristor chopping period (.07 ms) is negligible in comparison with the motor time constant (600 ms). Any torque pulsations due to ripples in current, are absorbed by the motor inertia.

iii) There are three regions of operation, of the chopper circuit where in, duty factor possesses :

(a) No control,

(b) Soft control, and

(c) Hard control,

over the output voltage and the speed.

At very low and very high value of duty factor (below 2% and above 97%), the control is lost. Because, the capacitor fails to get fully charged. Hence, in the next few cycles of operation, ~~The~~ the commutation fails.

With duty factor (between 2% to 20%), a soft speed control is possible. A wide range but hard speed control is possible which is more stable and useful, when the duty factor lies between 20% and 97%. Therefore, it is safe to use the chopper circuit in its hard control region only.

4.4 APPLICATIONS:

Thyristor chopper fed dc series motors have already found a rich field of application in the transportation systems viz. electric fraction, battery-fed electric cars, etc. The seperately excited dc motors afford a wide range of speed control and the provision of sufficiently hard characteristic, may be employed for driving metal industries, lathes, shapers, machine tools etc; and also in hoists and excavators.

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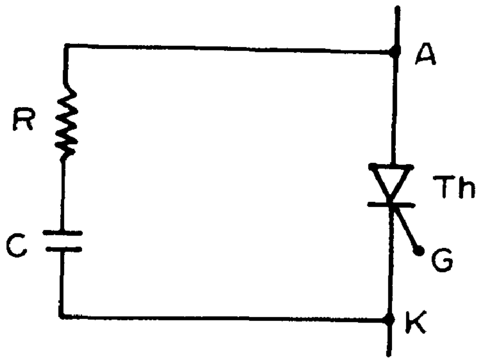

FIG. 4.1 SNUBBER CIRCUIT.

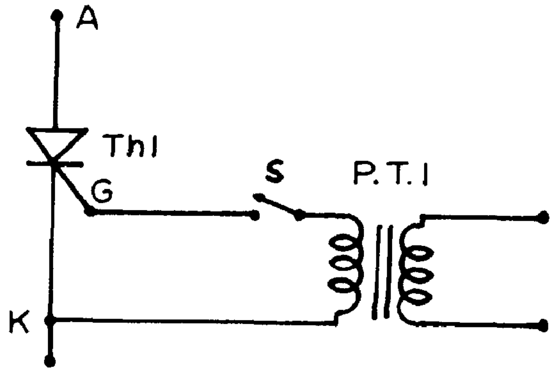

FIG.4.2 A SWITCH IN THE GATE CIRCUIT OF THE MAIN THYRISTOR.

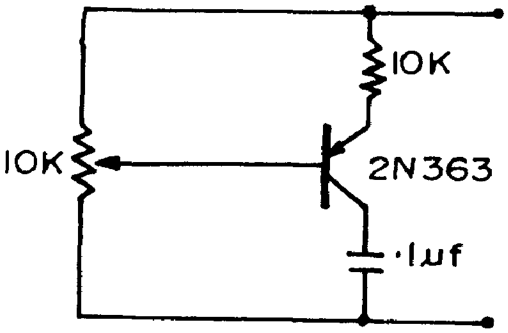

FIG.4.3 CONSTANT CURRENT CHARGING.

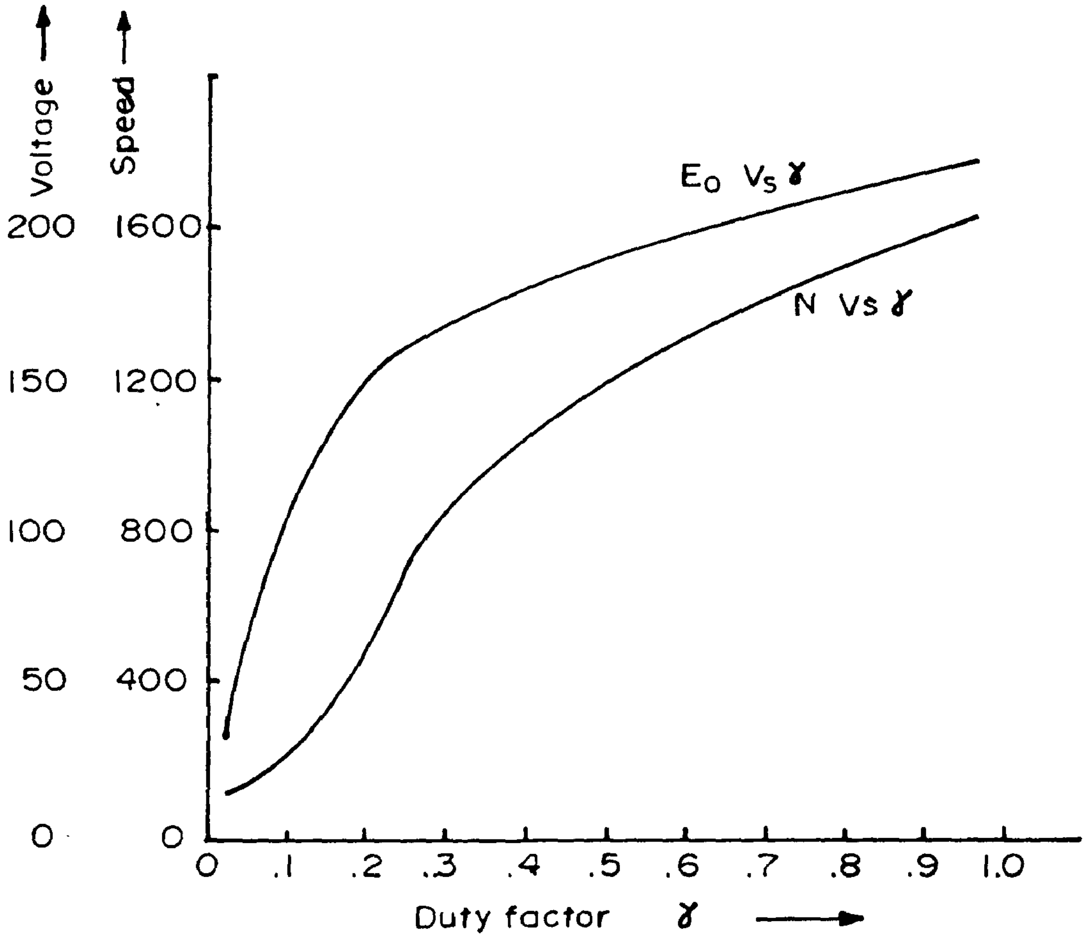

FIG.4.4 DUTY FACTOR CONTROL CHARACTERISTIC.

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APPENDIX - A.

LIST OF COMPONENTS USED

i) Triggering Circuit:

NAME	SYMBOL	QTY. IN NO.
UJT (2N2646)	UJT	1
Capacitors 0.1 uf ,10V.	$C_{1,2,3}$	3
Pot 100 K Ohms.	R_1, R_4	2
Resistor 1 K. Ohms.	R_2, R_5, R_6	3
Resistor 100 ohms.	R_3	1
Switching Diodes (SH 100)	D_{1-6}	6
Pulse Transformers	$P.T_{1,2}$	2
Operational Amplifiers (EC0709)	OP. AMP	2

ii) Power Circuit:

NAME	SYMBOL	QTY. IN NO.
Thyristors (2N3670)	Th_1, Th_2	2
Inductors	L_1, L_2	2
Commutating Capacitor	C	1
Power Diodes	D_1, D_2, D_f	3
Capaicitors 0.05 uf,600 V	C_4, C_5	2
Resistors 100 Ohms.5W.	R_7, R_8	2

iii) <u>Specifications of the Thyristor</u>:

The thyristors used in the chopper circuit are 2N3670 RCA. Some of its important specifications are given below:

Allowable forward blocking voltage - 220 V ac
Repetitive peak inverse voltage - 400 V
Average allowable current - 8 - 10 A
Surge Current (1 cycle) - 200 A
DC holding Current - 0.5 to 50 mA
Gate Voltage (V_{GT}) - 3 V (max)
Gate Current - 40 mA
Critical dv/dt - 10-100 typ. V/μs
Critical di/dt - 200 A/us
Turn - on time - 10 u s max.
Turn off time - 20 typ.(us)
50 us max.

iv) <u>DC Motor Specifications</u>:

HP of the motor - 1
Armature supply voltage - 220V
Full Load Current - 4.6 A
Field current - 0.26 A
Rated Speed - 1450 RPM

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