DEVELOPMENT AND PERFORMANCE ANALYSIS OF A NEW GENERATION SOLID-STATE SPEED CONTROLLER

A DISSERTATION
submitted in partial fulfilment
of the requirements for the award of the Degree
of
MASTER OF ENGINEERING
in
ELECTRICAL ENGINEERING
(Power Apparatus and Electric Drives)

By
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C E R T I F I C A T E

This is to certify that the dissertation entitled "DEVELOPMENT AND PERFORMANCE ANALYSIS OF A NEW GENERATION SOLID-STATE SPEED CONTROLLER" which is being submitted by JITENDRA KAUSHIK, in partial fulfilment for the award of Master of Engineering - Power Apparatus and Electric Drives - Electrical Engineering Department of University of Roorkee, Roorkee is a bonafide 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 Degree or Diploma.

This is to further certify that he has worked for a period of about 6½ months from 20th February, 1976 to 7th September, 1976, for preparing this dissertation at the University of Roorkee, Roorkee.

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JITENDRA KAUSHIK

S Y N O P S I S

The present work deals essentially with the development, design and testing of a new generation solid state d.c. speed controller employing advance techniques of comparision and firing of controlled converters. The developed scheme employes comparision of phase angle characteratics of the reference and feedback signals by an extremely versatile and accurate phase comparator which has definite superiority over not only the conventional methods of comparision but also over the standardised types of phase comparators. Another novelity of the present scheme is the use of the pulse width modulation type of firing scheme for the control of the converter. The order of accuracy of speed control effected by the present scheme is a whole order of magnitude times more than that of conventional solid state d.c. speed controller of closed loop type.

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CHAPTER - 1

PRESENT STATUS OF ELECTRIC DRIVES ---- GENERAL SURVEY & BASIC CONCEPTS

1.1 Historical Evolution of Electric Drives : [7]

The growth of electric drives has closely paralleled the growth of automation in industry. Electric - drive system provide a convenient means for controlling the operation of industrial machinery. The high reliability and great versatility of electric drives has resulted in their wide - spread application. In size, electric drives range all the way from fractions of one h.p. upto thousands of h.p. speeds range from stalled positioning systems upto 15000 r.p.m. and higher.

Historically, the first electric - drive system to gain real prominence was the ward Leonard system, patented by H. Ward Leonard in the 1890's. The history of d.c. electric drives proceeded from the basic Ward Leonard principle to various modifications thereof, in approximated the following steps :

a. Rheostat control of Generator Field.

b. Tandem Field rheostat control of Generator and Motor Fields.

c. Thyratron control of Generator & Motor Fields & later thyratron control of the armature voltage of small d.c. motors.

d. Ignitron and Mercury pool control of the armature voltage of d.c. machines too large for thyratrons.

e. Magnetic Amplifier control of Generator Field & armature voltage. and

f. Thyristor control of Generator and motor fields and later thyristor control of armature voltage.

Although d.c. drives by virtue of their superior characterstics of precise and continuous control of speed with long term stability and good transient response were the first to become popular in Industrial Control Systems. The presence of the mechanical commutator in d.c. motor and its attendent problems of maintenance is a serious deterrant wherever reliability and maintenance costs assume importance. This led to a growing interest in the field of a.c. drives and a number of workers truned their attention towards the development of a.c. drives. There again the very large Industrial popularity of this squirrel cage Induction Motor by virtue of its extremely rugged rotor construction and consequent reliable maintenance free operation at high speed made it virtually impossible for drive Engineers to completely neglect the area of a.c. electric drives. However till the advent of high power solid state devices like power transistors and S.C.R's no real break throughs of industrial significance were achieved in this otherwise highly promising area. During this period variable frequency converters were invariably of the rotating types which required Auxiliary Rotating Machines. A motor-generator set with an adjustable speed drive, establishing the speed of a Rotating Alternator was the first practical, Adjustable frequency converter.for many years these sets were used (and are still being used) to supply multiple a.c. motors in applications such as Run Out Table in the Steel Mills. However in addition to the maintenance problems involved with Rotating Motor-Generator sets, control of the a.c. output voltage amplitude and response is limited by the inherent excitation of the Alternator. Most signeficantly the resistance and the reactance of the alternator and its motor load limit the performance of the motor over a wide speed range.

The next stage of development in the area of a.c. drives took place with the availability of thyratron and mercury arc rectifiers. Invertors using these devices were developed but their performance did not reach the expected standards as the switching times of these components is too long for optimum operation. It was only with the availability of power transistors and semiconductor devices of the thyristor type having switching times of the order of micro seconds that significant results were achieved in this otherwise extremely promising area. Since the sixties there have been many developments in the field of solid state invertors and a very genuine interest has been revived in the area of a.c. drives.Historically the first of the S.C.R. type variable frequency invertors were of the d.c. link type involving both static rectification and inversion. This was soon followed by developments in the area of direct a.c. to a.c. conversion with a controlled frequency output ---- Cycloconvertors.

1.2 Classification & Comparisions of Solid State Converters for D.C. Drives :

The low forward voltage drop of the thyristor provides an efficient rectifier when used with the standard

L.V. supply of 240 & 440 volts. For this reason thyristor converters are rapidly being accepted for the control of d.c. machines, both as field controls for Ward Leonard systems and in ever increasing powers as converters to replace the motor-generator set. In the latter case the semiconductors handle the full power of the supply.[9]

The basic rectifier circuit takes many forms depends on the power that is to be handled and the degree of control required. In order to reduce the cost it is desirable to use uncontrolled rectifiers (silicon diodes) where possible so that the number of controlled rectifiers (thyristors) is kept to a minimum, while still obtaining full control over the output voltage. The extent to which this can be done depends on the duty of the converter and the power of the drive, if regeneration is required the converter must be capable of inverting and all arms of the bridge must be controlled. For high power drives the harmonic currents taken from the supply must be reduced. This implies an increase in the ripple frequency of the direct current and hence an increase in the number of controlled rectifier arms.

1.2.1 <u>Popular Configurations</u> :

1 - Ø half controlled bridge with a free wheeling diode is used for fraction h.p. drives if regeneration is not required. If regeneration is required 1 - Ø full controlled bridge is used.

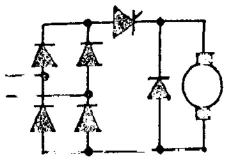
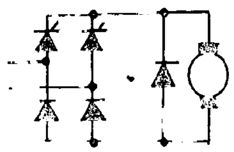
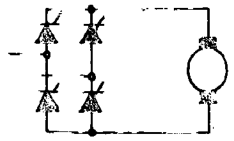
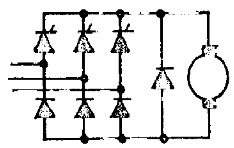
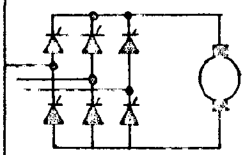
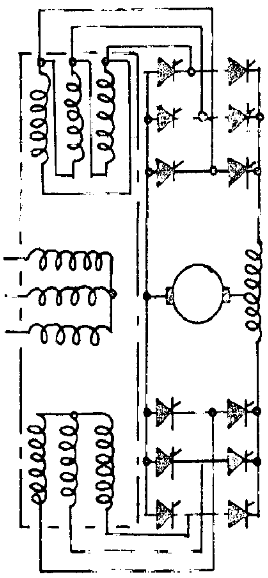
Supply	CIRCUIT	TYPICAL POWER H.P.	RIPPLE (c/s) FREQUENCY 50 c/s SUPPLY	V.A. OF DIODES / V.A. OF MOTOR (ASSUMING NO SAFTY FACTOR)	V.A. OF THYRISTOR / V.A. OF MOTOR (ASSUMING NO SAFTY FACTOR)	FACILITY OF REGENERATION
SINGLE PHASE SUPPLY		$\frac{1}{4}$ - 1	100	7·17	1·87	NO
		1 - 20	100	2·65	2·65	NO
		$\frac{1}{4}$ - 20 WHERE REGENERATION IS REQUIRED	100	0	5·3	YES
THREE PHASE SUPPLY		15 - 150	150 (300 AT MAXIMUM VOLTAGE)	2·18	2·18	NO
		100 - 350	300	0	4·36	YES
		300 - 2000	600	0	4·36	YES

TABLE 1·1 - THYRISTOR CONVERTER POWER CIRCUITS

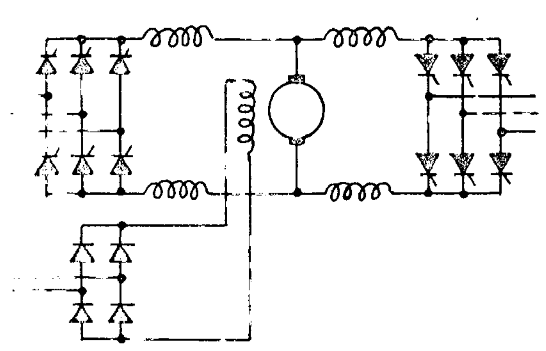
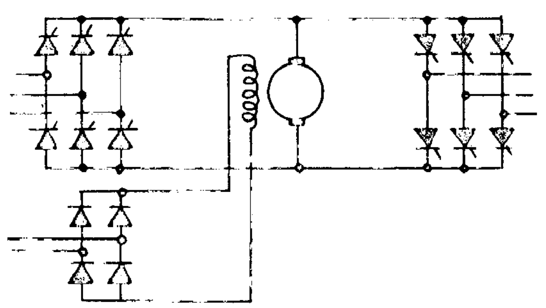
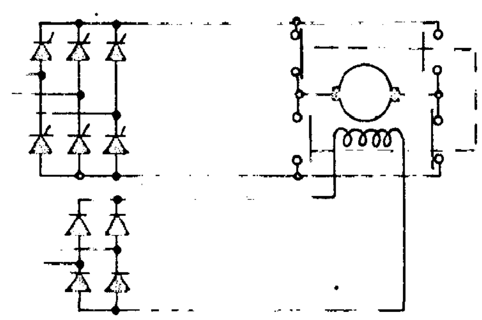
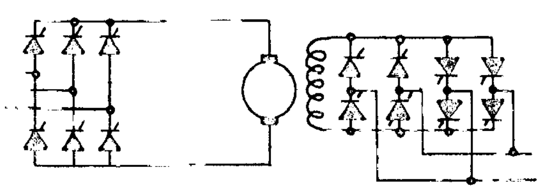
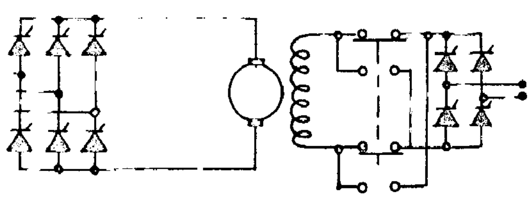
TYPE OF REVERSAL	METHOD OF REVERSAL		CIRCUIT DIAGRAM	REMARKS	
ARMATURE CURRENT REVERSAL	DOUBLE BRIDGE	BOTH BRIDGES FIRED TOGETHER		EXPENSIVE NO MOVING PARTS	FASTEST RESPONSE BUT d.c. CHOKES REQUIRED TO LIMIT THE CIRCULATING CURRENTS BETWEEN BRIDGES
		ONE BRIDGE FIRED AT ONCE			FAST RESPONSE. NO D.C. CHOKES REQUIRED BUT CURRENT DETECTOR OR DELAY REQUIRED TO PREVENT FIRING OF BOTH BRIDGES TOGETHER
	CONTACTOR CHANGE-OVER			CHEAPER, SIMILAR COST CHOICE DEPENDS ON APPLICATION	GOOD RESPONSE CURRENT DETECTOR REQUIRED TO PREVENT CHANGE OVER WHILE ARMATURE CURRENT IS FLOWING
FIELD CURRENT REVERSAL	DOUBLE BRIDGE				RESPONSE DEPENDS ON THE DEGREE OF FIELD FORCING.
	CONTACTOR CHANGE-OVER				

TABLE 1.2 - POWER CIRCUITS FOR REVERSING DRIVES

3-Ø half controlled bridge for higher h.p. drives is used if regeneration is not required and if required then 3-Ø full controlled full wave converter is used.

A comprehensive survey of the solid state converter field is contained in the Table 1.1 and of reversing drives is contained in Table 1.2. [9]

1.3 Basic Concepts :

1.31 Open Loop V/S Closed Loop Control Systems :

The outstanding features of the open-loop control systems are :

a. Their ability to perform accurately is determined by their calibration. To calibrate means to establish or re-establish the input-output relation to obtain a desired system accuracy.
b. They are not generally troubled with problems of instability.

The most important features of the closed-loop control systems are :

a. Increased accuracy e.g. the ability to faithfully reproduces the input.
b. Reduced sensitivity to the ratio of output to input to variations in system characterstics.
c. Reduced effects of nonlinearities and distortion.

d. Stability is always a major problem in the closed-loop control system since it may tend to overcorrect errors which may cause oscillations of constant or changing amplitude.

1.32 <u>Static V/S Rotating Control Systems</u> :

Salient features of static system are :

a. Extremely stable and accurate output available.

b. Lower installation cost on account of no elobrate foundation and no careful allignment of machine is involved.

c. Lower floor space requirement.

d. Lower noise level.

e. Superior control and ease of operation of operating parameters of controllers.

f. These converters are readily compatable with the closed-loop feedback technique.

g. Lower operational cost and less maintenance.

h. Increased reliability as ~~it~~ converter does not have any mechanical part, through introduction of moduller constructional technique, of integrated circuits and facility of spare modules present.

1.33 <u>Analog V/S Frequency (Digital) Control Systems</u> :

Essential features of digital scheme are :

a. Its very great accuracy which is inherent in the system itself, [redacted] is unattainable by any of the analog schemes.

b. They are compatible with the requirements of digital output devices e.g. computers, punch tape and counters etc.

c. The digital schemes are particularly suitable in remote control application where accurate transmission of a signal is a must.

d. Over all scheme is more sophisticated. performance characterstics of the control schemes are superior to analog schemes.

e. Digital devices are less susceptable to inaccuracies because of the envioremental effects like temperature increase, humidity increase and radiation effects etc.

1.34 <u>Specifications of a Solid-State Speed Controller</u> : [8]

<u>Adjustable maximum & minimum speeds</u> : The maximum or minimum speeds at which the motor will run can be set by a knob in the drive cabinet. Though the speed setting potentiometer reads full speed or zero, the motor will run slowely for maximum speed or at some speed above zero for minimum speed.

<u>Base speeds, standard</u> : Base speeds refer to the maximum speed at which the motor can run with full field applied. Most

manufacturers offer several standard speeds while many also offer gear reducers for a wide choice of top speed.

Controlled acceleration by current limit : By setting the maximum allowable armature current, the accelaration of the load can be kept down to a safe level on startup of the drive . Controlled accelaration of this type is inherent in all drives that have a built in current limit.

Controlled accelaration by timing : The accelaration of the motor and load is controlled by delaying the full application of the speed reference signal. With this feature, accelartion is controlled through out the speed range and not only during startup as in the case with current limit control. Electronic delay circuits or auxiliary motor-driven potentiometers are commonly used to delay the reference signal.

Current Limit : Armature current must be limited by the drive controller to protect both the motor and the S.C.R's from overheating due to excessive currents, and also to limit the torque applied by the motor to the load. When the armature current reaches the set limit, speed regulation becomes ineffective and the motor speed will drop sharply with increased load until the load demand that caused the current to reach its limit is removed.

Current limit, adjustable : This is the same as current limit but the limiting current value can be adjusted to match the drive to a particular load and motor.

Disconnect switch : Drive packages incorporate a contactor or switch to start & stop the motor. An external a.c. disconnect switch or contactor is desirable to shut down the entire drive for safety, to allow for remote tripping.

Dynamic Braking : Dynamic braking is a means of electrically loading the motor as a generator to extract its stored mechanical energy and reduce its speed. It is usually done by connecting a resistor across the armature terminals while maintaining full field excitation. The resistor is connected by an auxiliary contactor or by a set of midposition contacts of a manual reversing switch. Dynamic braking is most effective when the motor is running at high speed.

External speed reference : The speed reference signal normally derived from a potentiometer, can be supplied from an external voltage source.

IR-Drop compensation : When CEMF speed sensing is used, the armature terminal voltage is detected as a measure of the motor's actual speed. But the terminal voltage comprises two elements, the counter e.m.f. voltage generated by the armature and the voltage drop in the resistance of the armature windings. (IR drop). Since only CEMF voltage is actually proportional to motor speed (the IR drop is proportional to armature current) by eliminating the IR-drop. Component from the terminal voltage, a more accurate indication of actual motor speed is possible. Thus IR-drop compensation is a means of subtracting a signal proportional to the IR-drop, from the terminal voltage. But because the IR-drop varies with different motors, the compensation must be set for a specific motor.

Jog : Jogging controls are used to operate the drive at very low speeds during setting up operations. The jog control can be designed to run the drive while the pushbutton is held down, or it can be designed to run the drive continuously at very low speeds for threading operations.

Pre-set speeds : By providing multiple speed-setting potentiometers and relays to switch in whichever potentiometer is required, speeds can be preset and selected by operating push buttons or by some othermeans of operating the relays.

Quick slow down : By including dynamic braking in the drive, the motor slows down at a faster rate than it would if simply allowed to coast to a stop.

Regenerative braking : Regenerative braking, like dynamic braking, is a means for extracting mechanical energy electrically from the armature terminals. The electrical energy is pumped back into the supply line instead of being dissipated in a resistor. This form of braking allows the motor to be braked to standstill.

Remote speed control : If the operator's station is located remotely from the drive, the speed reference potentiometer is usually mounted in the station and the pot. signal extended to the drive through a 3-wire circuit.

Speed sensing, CEMF : Because the counter e.m.f. voltage generated a d.c. motor's armature is proportional to the speed at which the armature is rotating by detecting this voltage, a signal proportional to speed is obtained. This voltage is compared with the reference speed, any error between the two causing the drives circuits to increase or decrease the speed accordingly.

Torque limit : This is essentially current limit where the torque output from the motor is kept down by limiting the armature current.

Torque Regulation : Torque regulation (or torque control) means one of two things, simply an a adjustable torque limit (current limit) where the drive maintains constant set speed out to a preset torque than maintains constant torque at a declining speed for further mechanical loads, or the incorporation in the drive of a particular drooping torque-speed characterstic which can be varied.

1.4 Applications of D.C. Drives : [9, 10]

Thyristor controlled d.c. drives have a wide field of application in the industries now a days. It is widely accepted now in Paper, Printing, Plasting, Aluminium foil mill, Rubber and where multi-section scheme are used.

In the printing industry thyristor controlled d.c. drives have been extensively applied to replace commutator motors. Here the requirements are for a wide speed range of 60:1 with a regulation of about 10% at minimum speed. The minimum speed is required for the frequent inching during re-plating the printing cylinders.

In the Paper Industry thyristor drives have been used for reeling applications. The paper reel may be either a re-wind or an unwind stand when the power converter may be selected off load to operate in either a motoring or regenerating mode. Under certain conditions of operation e.g. when the loss torque exceeds the required braking torque on an unwind stand, or during a rapid stop with a large inertia reel on a rewind stand, an on load change of operating mode may be required control for constant tension reeling is normally obtained from tension sensing arms.

In multi-section schemes where helper drives are required and for certain reeling applications where taper tension is required the thyristor controlled motor has been operated under torque control by using motor armature current rather than a tachogenerator voltage as the resulting signal.

For multi-section schemes standard thyristor drives can readly be adapted to operate together from common speed signals with intersection draw by armature control.

This compares directly with an individual generator per section Ward Leonard scheme. For less precise duty one power convertor can be used to control parallel motors with inter-section speed trim by motor field control.

A single-ended thyristor convertor is applied in the speed control of the mill motor of a cold strip rolling mill. The converter supplies uni-directional current to the motor armature, deceleration torque is produced by reversing the motor field.

Thyristor controlled drives upto 150 h.p. have been applied to both the plastic and rubber industries for extrusion processes. Here the thyristor drive is replacing the Ward Leonard and commutator drive, when a wide speed range with precise transient and steady state control is required. Speed holding to within 1% together with good barrel temperature control is essential to give the degree of plastic film thickness accuracy that is being increasingly required by the industry.

CHAPTER - 2

NEW GENERATION SOLID STATE SPEED CONTROLLERS: REVIEW OF PRESENT TRENDS

The phenomenal developments in the different areas of solid state electronics have also perfoundly influenced. The technology of solid state electric drives perhaps the most significant influence has been as a result of application of radically new techniques and concepts of signal processing and comparision (developed primarily for the use in communication systems) to the all together new area of electric machine control. Just as the adoption of these concepts and techniques have resulted in far reaching improvements in the performance of communication system, their application in the area of machine control has also brought about very significant improvements in the performance electric machine control systems.

2.1 Review of Present Trends:

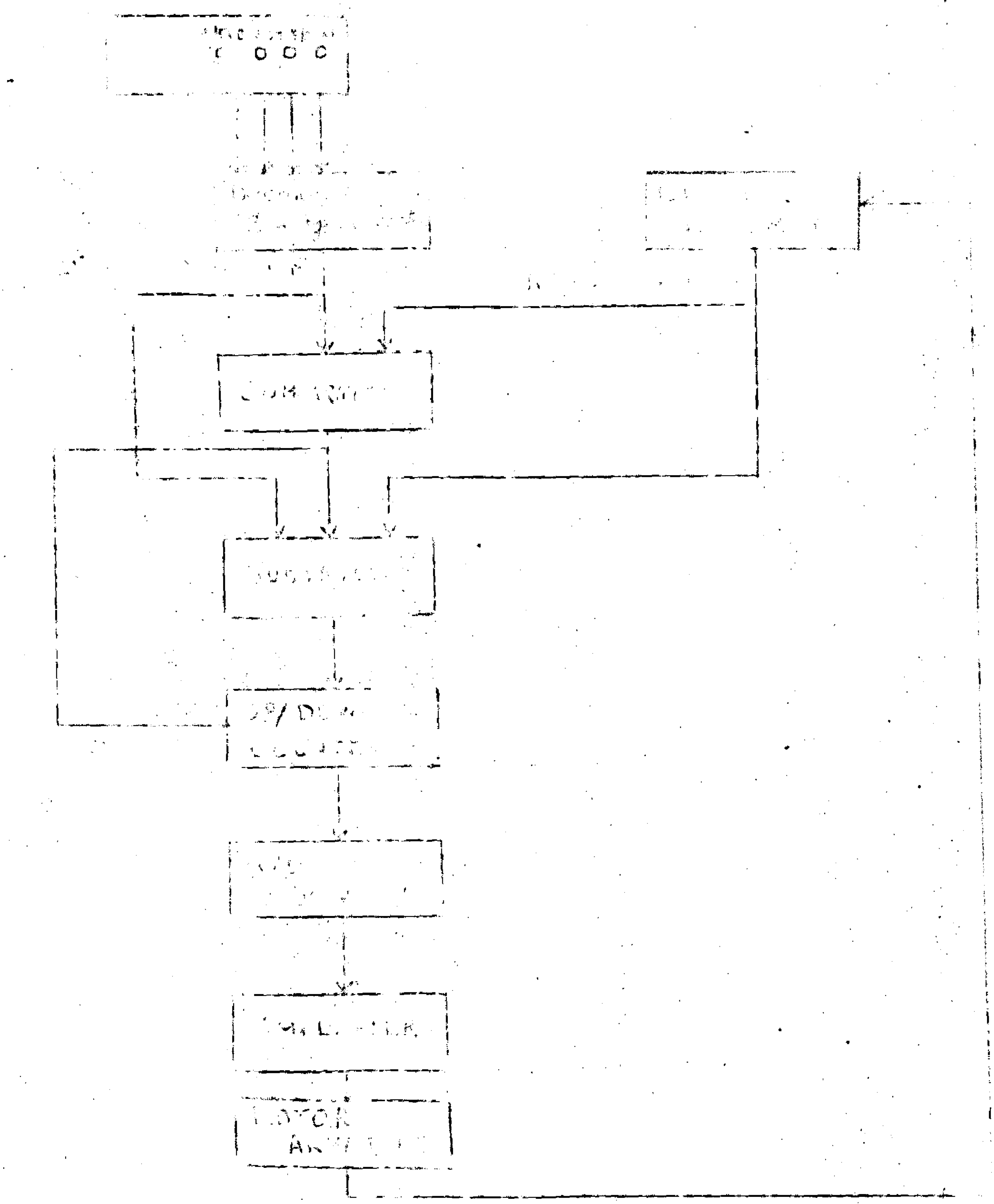
Following are the most recent trends used towards the speed control of d.c. motor now a days.

a) Digital method of D.C. motor speed control.

b) Pulse width modulation motor control system.

c) Phase locked loop motor control system.

2.1.1 Digital method of D.C. Motor Speed Control: [11] In industrial process control it is sometime necessary to be able to adjust a motor's speed over a wide range with good speed resolution



and reproducibility. Conventional analog control methods suffer on several accounts, including nonlinearity in the analog speed transducer and difficulty in accurately transmitting the analog signal after it has been obtained from the transducer. Also, while manipulating the signal to effect control action on the motor, errors are incurred which are related to temperature, component aging, and extraneous disturbances.

A digital speed control system is superior in that there is no nonlinearity in the speed e-transducer, the digital signal representing speed can be transmitted long distences with no degradation of the original accuracy, and the digitally developed control signal is not subject to temperature variations, component changes or noise.

The digital d speed control of d.c. motor system consists; a compurator, a subtracter, a up/down counter, a D/A converter, an amplifier, a digital tachometer, a set point selector switch and decimal to binary counter. It is shown in Fig 2.1

This system is not continuous but measures and corrects motor speed at discrette intervals. The order of events in a complete control cycle is as follows;

a) Measure the actual motor speed,

b) Compare the actual speed to the desired speed (set point).

c) Find the error.

d) Change the contents of the up/down counter an amount proportional to the error. The direction of the change depends on the result of the comparision made in step b.

e) Wait while the motor responds to the increase or decrease in its armature voltage, then reset the appropriate counters and logic devices in preparation for the next control cycle.

Motor speed is detected optically by an arrangement of three pairs of light sources and photocells. Pulses from the photocells are gated into a ten - bit digital counter during a precisely controlled time period, so the e number stored in the counter at the end of the sampling time represents the actual motor speed. This speed is then compared with the desired speed, which is also represented by a ten - bit binary number. This desired speed is obtained via four decimal set point switches and a decimal to binary converter.

The output of the comparison circuit depends on which of three conditions prevails: either the set point is larger than actual speed, the set point is smaller than actual speed, or the set point and actual speed are exactly equal. The comparator output is used in two ways. First, it decides whether the up/down counter is to be driven in the up direction or the down direction. Driving the up/down counter in the up direction raises the motor armature voltage and

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c) Find the error.

increases motor speed. If the actual speed and desired speed are exactly equal, the comparator inhibits the up/down counter from changing state.

Following determination of the speed difference, the content of the up/down counter is adjusted an amount proportional to that difference. The digital content of the counter is converted to an analog voltage raising from 0 to 12 volts by a [redacted] D/A converter. This analog voltage is then amplified and applied to the armature of the motor.

At the end of each comparision cycle the up/down counter is driven either up or down by an amount proportional to the speed difference. The proportionality constant is an adjustable system parameter which has an important effect on system response. The greater the proportionality constant, the more oscillatory is the motor's transient response to a step change. The smaller the constant, the more sluggish is the response. Amplifier gain is another important parameter regarding system transient response.

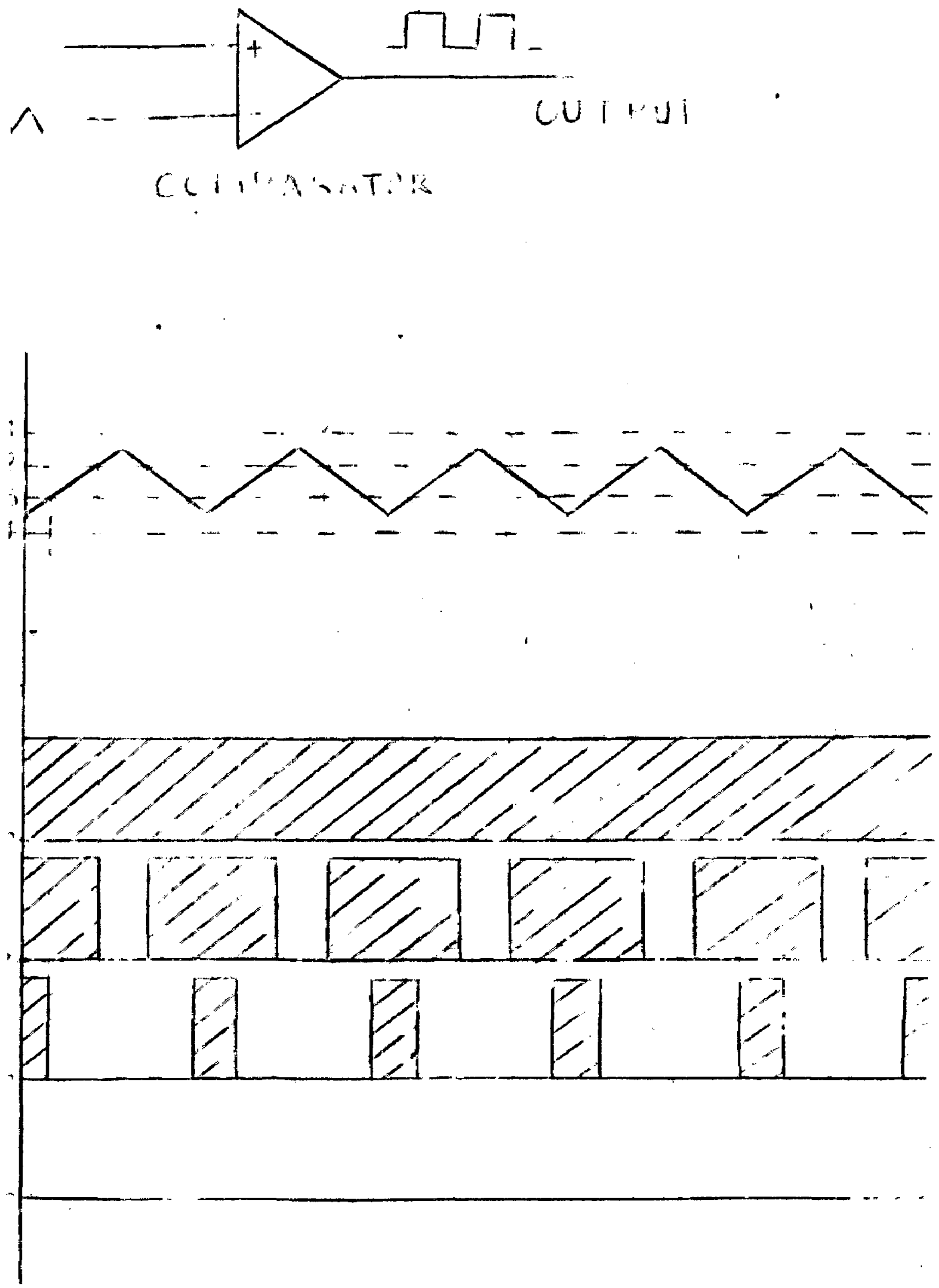
2.1.2 <u>Pulse Width Modulation Motor Control System</u>: [12] The easiest way of speed control of small d.c. motor is with a variable resistor connected in series with the motor and power supply. A d.c. motor runs at a speed proportional to the average applied voltage. Here the average voltage is obtained simply by burning up the unused power. But if a system wanted that taps minimum energy from the power source - while delivering high starting torque even at low speeds - pulse width modulation is worth looking into.

Once fairly complicated and costly, PWM has benefited from advances in solid state electronics. Now most of the electronic hard ware can be reduced to a single IC chip so that power saving and high torque involve very little penality in terms of price or circuit complexity.

In PWM, the motor uses full supply voltage at all speeds, but the power is turned ON and OFF rapidly to do the averaging or stated more explicity, PWM is simply a matter of applying full voltage to the motor in a series of short pulses, and varying the duty cycle (ON/OFF time ratio) to vary the average motor voltage.

Since motor drive torque is a direct function of armature current, it may be better to operate with constant rather pulsed drive currents. In this case, the frequency should be high enough so that the armature current never drops below a predetermined level during the OFF time of the output power transistor (Motor current will then be flowing through the free - wheeling diode). Once speed range and frequency is selected then the type of drive system is choosen.

There are three commonly used methods for obtaining the pulse width modulation. The classical approach uses discrette components in as Astable Multivibrator Circuit.



PULSE WIDTH VARIATION.

FIGURE NO. 2.[illegible]

A similar method uses an integrated operational amplifier, speed variation from 5% to 95% is practical for these circuits. Third approach uses a CMOS integrated - circuit quad NAND gate (complementary metal - oxide semiconductor comprised of four NAND gates). This circuit provides a speed range of approximately 3% to 97% of full speed.

All these circuits are manually controlled with no provisions for any electrical input signal to the control pulse width. For control by an electrical signal, a high gain; operational amplifier comparator with a limited output swing and high slew rate. Two input signals are required ; a triangular wave of fixed frequency and amplitude, and a variable d.c. voltage. This type of cirucit can control pulse widths from full ON to full OFF. It is shown in Fig. No 22. However, there is a slight speed jump in the transition from pulsing control to steady output caused by rounding at the peaks and valleys of the triangular waves. In most case, it is not difficult to limit this jump to less than 1% of the ON or OFF time.

A power output stage is required to apply the pulse width modulated signal to a motor. Using a Darlington transistor is the simplest and most direct means of coupling the pulse energy to the motor. In addition to the transistor ; a free - wheeling diode is required. This diode must be able to carry approximately 40% of the maximum current expected in the motor (which could be easily larger than the normal operating current if the motor is expected to be stalled for periods longer than a second or two).

BLOCK DIAGRAM OF PHASE LOCKED LOOP

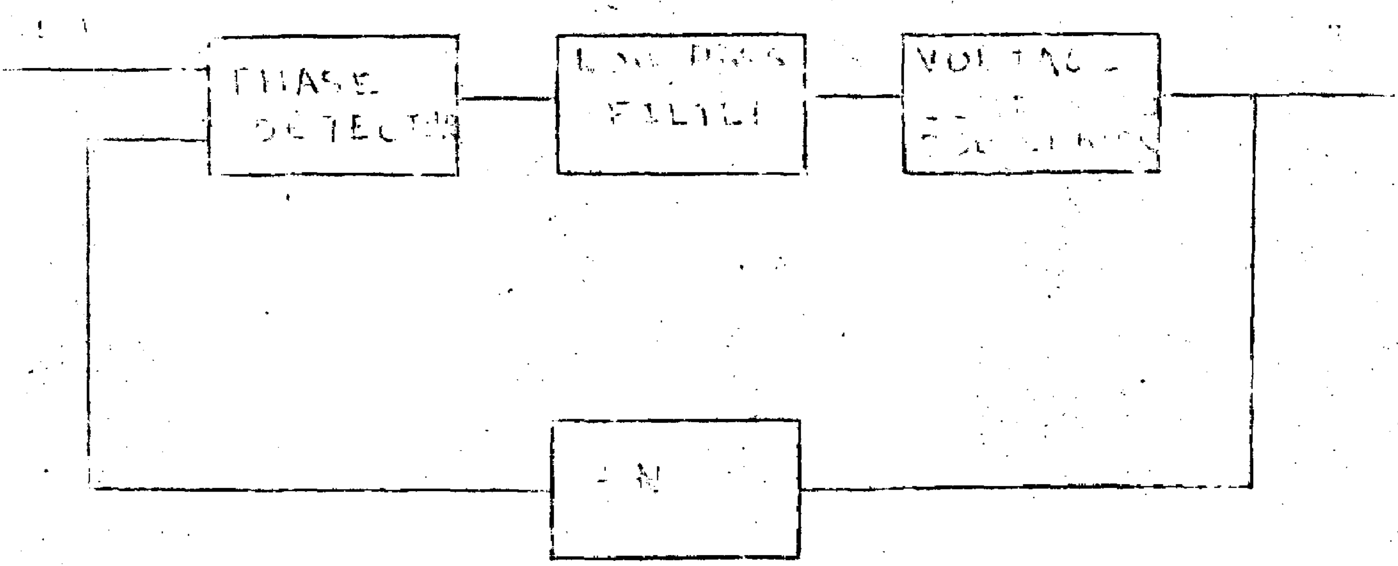


FIGURE No 29

For very - high - current applications, Germanium power devices are the least expensive choice. The input to the germanium device circuit is not from the output buffer of a control circuit, but directly from the output of the any of the operational amplifier or comparator.

2.1.3 <u>Phase Locked Loop Motor Control System</u>[13,14]: Although the primary application for phase locked loops has been in frequency synchronisation of receivers, a lesser known application area may turn out to be almost equally important - the precise control of motor speed. The conventional method of motor - speed control is with analog servos. Phase locked loo motor control systems are becoming more widely used as the cost of digital circuitary is reduced. This type of d.c. motor control has certain advantages over conventional analog sefvos. Among these is the ability to obtain speed accuracies better than 0.01% and possibility approaching 0.002%. Motors of any size can be controlled with this technique once the characteristics of the motor have been incorporated onto the response of the phase - locked loop the only difference is in the motor - drive circuit.

The PLL, in its most elementary form, consists of three components: a phase detector, a low pass filter, and a voltage controlled oscillator (VCO). It is shown in Fig.No.2.3 A frequency divider has been added in the feed back path to provide for variable speed operation. The output of the VCO is a periodic signal whose frequency is controlled by the input voltage. In the case of a PLL motor control, the d.c. motor with an optical tachometer acts as the VCO. The phase detector compares the phase of a periodic input signal against the phase of the VCO output, and the output of the phase detector is a measure of the phase difference between the two inputs. The difference voltage is low pass filtered by the loop filter and applied to the VCO. The control voltage on the VCO changes the frequency in a direction which reduces the phase difference between the input signal and the local oscillator. When the loop is "locked", the control voltage is such that the frequency of the VCO is equal to the frequency of the input signal. When a frequency divider is used in the feed back loop, the frequency of the VCO is an integer multiple of the input frequency. Since the motor shaft speed is proportional to the output signal frequency in the PLL motor control loop, this speed is controlled as acoutrately as the frequency itself.

The use of a d.c. motor as the voltage controlled oscillator in a PLL increases the complexity of the loop design. In electronic PLL design, it is assumed that the VCO responds instantaneously to change in the input voltage. A motor, on the other hand, has a much longer response time due mostly to the mechanical inertia of the system. This response delay effects the stability of the PLL and places much more stringent requirements on the phase detector.

Three types of digital phase detectors are presently in use: the exclusive - OR circuit, the edge - triggered flip - flop, and a logic gate configuration that behaves in a manner similar to that of flip - flop, but has some advantages. All three types are found in phase - locked loop IC's. However, some phase locked loop circuits use analog detectors.

Of the many parameters which are used to describe phase detectors, the parameters which most directly influence motor PLL control are the frequency capture range, the frequency lock range, and the ability of the phase detector to avoid locking on harmonics. The frequency lock range is the range of frequencies over which the PLL can maintain a "locked" condition. This determines the range of motor speeds. The frequency capture range is the range over which "lock" can be acquired if it has been lost. This is important because the motor can not respond instantaneously to rapid changes in the speed set point, and the motor will lose "lock" for a short period of time. With the proper phase detector, "lock" may be required quickly. For the same reason, the ability to "lock" only on the fundamental frequency is also necessary. Large changes in set point could result in incorrect motor speed if the loop locked onto a harmonic of the reference signal.

The basic function of the loop filter is to remove noise and high - frequency components from the error voltage.

It also has a major role in determining the stability and dynamic performance of the loop. Passive filters are suitable for many applications. However, better performance is usually possible with active filters that have the added expense of an amplifier.

Motor drive circuit is used to raise the power level and provide additional control.

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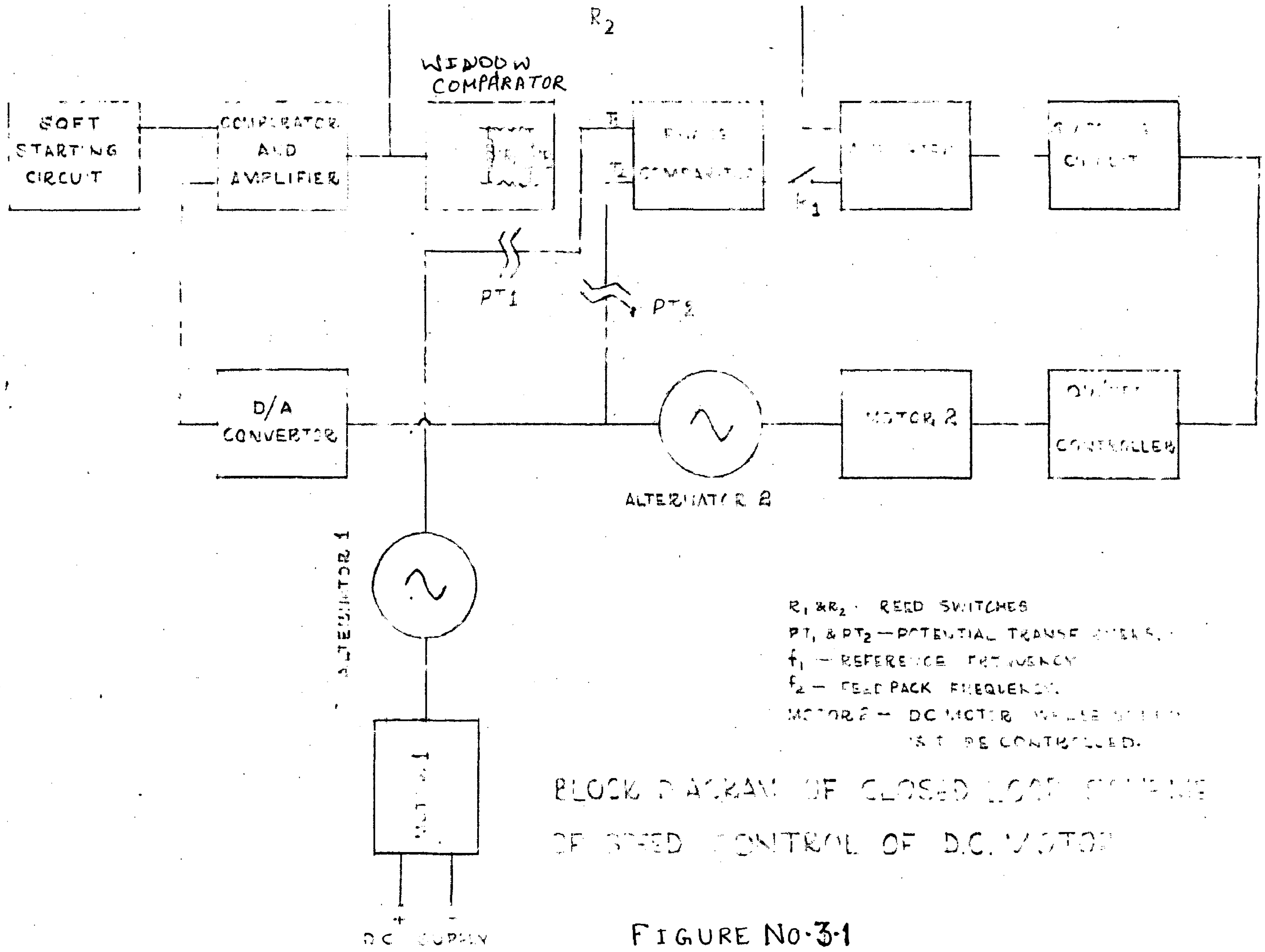
CHAPTER - 3

FUNCTIONAL DESCRIPTION OF A SOLID - STATE D.C. SPEED CONTROLLER USING PWM TYPE FIRING AND PHASE LOCKED COMPARISION TECHNIQUE



BLOCK [illegible] OF CLOSED LOOP [illegible] OF [illegible] CONTROL OF D.C. MOTOR

FIGURE No·3·1

3.1 Introduction :

The developed scheme is essentially a precesion type of d.c. speed controller employing advanced techniques of firing and comparision as well as incorporating some of the latest advances in Micro Electronic circuits like operational amplifier integrated logic circuit and miniaturised techniques.

The scheme essentially utilised two types of closed loops. The first one is with using soft starting circuit which is used for smooth starting of motor from zero speed to the speed near synchronous speed. The other closed loop consists of a newly developed phase comparator of integrator type which will work near synchronism.

Pulse Width Modulation is used for firing circuit. Here a triangular wave and a variable d.c. reference is compared in the voltage comparator. The pulse width is varied by varying the d.c. reference input. According to which the firing instant of the thyristor is changed which will change the controlled d.c. output.

3.2 Functional Description : The functional block diagram of the developed scheme is shown in the figure No.3.1. The functional description of each block is as follows :

3.21 Soft starting Circuit : This circuit replaces the starter of the d.c. motor. It is used to start the d.c. motor smoothly from rest to near synchronous or before the speed range of the phase comparator.

It is essentially a R-C network. A diode is connected in parallel to the capacitor in forward biasing fashion. The voltage across the capacitor is further reduced by utilising a pre-set. Hence a constant voltage V_R is applied to one of the input of the voltage comparator. It is shown in Fig. No. 4.2

3.22 <u>Comparator and Amplifier</u> : The voltage comparator (VC) compares the two input signals and gives an output voltage corresponding to the difference of the two inputs.

Most of the VC's are essentially high-gain differential amplifiers operating in the open-loop manner and driving an output stage conditioned for specific logical voltage level. It is an ordinary type of voltage comparator which [redacted] compares the two input voltages.

A reference voltage V_R from soft starting circuit a and an variable input signal from Digital-Analog (D/A) converter are seperately applied to the voltage comparator inputs. The VC output is at a low voltage level (logic 0). Whenever the input if more negative than the reference voltage; it is a high level (logic 1) whenever the input is more positive than the reference voltage. It is shown in Fig. No. 4.2

The variable output voltage of D/A converter is corresponding to the d.c. motor speed whose speed to be controlled. A RC filter circuit is used to filter the a.c. ripples.

3.23 Window Comparator [5] : Voltage comparators are frequently used in the design of test equipment requiring a circuit that can sense the time instant when the input signal goes outside some preset tolerance range. A circuit that produces such a GO-NO-GO type of output is called a window comparator.

The window comparator is of the type which produces a window that indicates by a logic 1 output the presence of an input signal falling within the range preset by reference voltages V_A and V_B. It is shown in Fig. No. 4.2

This window comparator employs two voltage compartors to produce the window. The same input signal is applied to both comparators. Second comparator compares the input signal with the reference signal V_A in such a way that a high voltage level (logic 1) is produced whenever the input signal exceed V_A. First comparator, being inversely connected, compares the same input signal with a larger voltage V_B. First comparator produces a logic 1 output only when the input signal is less than V_B. The outputs from the two comparators are ANDed, yield a high voltage level whenever both comparators at the logic 1. However this occurs only for input voltages in the range of $V_A \leq V_{in} \leq V_B$. The window comparator range is corresponding to the phase comparator range.

The output of the window comparator is applied to the base of the first transistor. This transistor is adjusted to conduct (ON) for the window comparator range, otherwise it will be OFF. The coil of the reed switch RS_1 is connected between the positive supply and collector resistance of the transistor. And the reed switch is connected to phase comparator and Amplifier.

The second transistor works as an inverter, that is, it will be OFF for window comparator range and above and below this range it will be ON. The coil of Reed Switch RS_2 is connected to the positive supply and collector resistance. The reed switch RS_2 is connected between voltage comparator and Amplifier. The soft starting circuit will work in this range.

3.24 Phase Comparator [15] : Phase comparator compares the phases of two input signals and gives a d.c. output voltage corresponding to the phase difference. The phase difference between the input phases is correspond to the difference in the speed of the d.c. motor whose speed to be controlled to the reference signal. The output d.c. voltage is linearly proportional to the phase difference between the two input phases.

It is a newly developed type of phase comparator The basic circuit of phase comparator depicts two parallel connected integrators of same characterstics, cascaded with a differential amplifier which subtracts the two output signals of the integrators and generates its, output signal in the form of d.c. voltage. Field effect transistor (FET) with differentiating circuit is used for resetting. It is shown in Fig 4.3

Phase-1 which is corresponding to the reference signal is applied to an OP Amp which is acting as saturated amplifier and gives square-wave output. This output is fed to the two integrators. Starting point of integration of first integrator is fixed. For resetting of I integrator as upper differentiating circuit is used, using FET as switch. Starting point of integration of II integrator is adjusted by pulses corresponding to phase-2. Phase-2 is corresponding to the feedback signal. For resetting of it lower differentiating circuit with FET as switch is used.

The outputs of the two integrators are fed to the differential amplifier which subtracts the two and gives a output signal in the form of d.c. voltage. The inputs of the phase comparator are applied at low voltage.

3.25 Amplifier : It is an ordinary op Amp used to amplify the soft starting circuit output and phase comparator output. The gain for two inputs may differ according to the requirements of the switching circuit.

[56]

3.26 Switching circuit : It is the firing circuit for triggering the thyristors of the 3-Ø half controlled full wave rectifier. The d.c. output voltage of the converter is changed if the firing instant of the thyristors are changed. It is shown in Fig. No 4.5

This circuit utilized the PWM firing technique. The firing instant of the thyristor is changed if the d.c. reference voltage at the comparator of this circuit is changed.

The first Op Amp of the switching circuit works as the square-wave generator. A square-wave generator acts as a self-triggered switch to continuously alternate back and forth between twod.c. voltages levels without utilising any outside triggering signal.

If this square-wave output is applied as the input to the integrator circuit. It results in a triangular-wave generator. The circuit consists of a low-pass R.C. Filter.

Consider the waveforms starting at t=0, the area under the input curve increases linearly until t_1 this produces the amp output during this time. From t_1 to t_2 V_O drops linearly in response to the negative area generated under the input curve. The output should therefore stay constant when there is no input (since no area is generated) rise linearly for a constant positive input and drop linearly for a constant negative input.

The triangular - wave and a d.c. voltage reference are the inputs of an Op Amp comparator, the comparator output switches from full ON to full OFF when (and so for as long as) the triangular wave amplitude exceeds that of the d.c. reference voltage. Thus to vary pulse width, we must vary the d.c. reference voltage amplitude.

The output of the comparator is fed to the Uni Junction Transistor (UJT) equivalent circuit. This device is used to apply a sudden pulse of power to fire a thyristor. The last transistor works in pulse amplifier. The output of it is applied to the pulse transformers of the 3-Ø half-controlled thyristor bridge.

3.27 Half-Controlled, Full-Wave 3-Ø Bridge Thyristor Converter Arrangement :

3.271 Pulse Transformer [4] : Switching circuit output is fed to the primary side of the pulse transformer. Pulse transformers has primary to secondary ratio 1:1. It is used for isolation purposes. A diode is connected to the secondary side to rectify the input pulses to positive side only.

3.272 Thyristor Convertor [1,2,3] : The introduction of thyristors has brought into use a number of controlled rectifier circuits which are a mixture of thyristors and diodes. If the inverter operation is not required the 3-Ø bridge circuit is simplified by replacing three thyristors by the regular diodes.

In this scheme of solid state speed controller for d.c. motor, inverter operation is not required. Therefore 3-Ø half-controlled, full-wave thyristor converter is used for rectification purpose. It is shown in Fig. No. 4.6

The working of the half-controlled 3-Ø bridge can be explained by considering it as a phase-controlled half-wave circuit in series with an uncontrolled half-wave rectifier. The output voltage of the uncontrolled rectifier is constant, but the controlled rectifier delivers a variable output voltage which is added to that of the uncontrolled section. By delaying the thyristor firing beyond 90°, the controlled section operates as an inverter, and power delivered by the diodes is returned to the a.c. supply by thyristors.

The invertor back e.m.f. opposes the rectifier voltage and reduces the resultant output voltage of the bridge. Theoretically zero output voltage is obtained when the firing angle is 180°, but in practice, the circuit may malfunction at large delay angles due to the failure of a thyristor to commutate in the limited time available. This is known as "Half Waving" Effect.

The output voltage ripple gradually changes its character from a 6-Ø ripple when the firing angle α is zero, to a 3-Ø ripple when α is large. The input p.f. is also higher than that of a fully controlled bridge rectifier without a free-wheeling diode.

The 3-Ø a.c. voltage is applied to the bridge through a 3-Ø Auto transformer and an isolation transformer. Scott-Transformer is used for isolation purpose.

3.273 <u>Over Voltage Protection of Thyristors</u> : Voltage transients may be generated in the circuit owing to inrush current to transformer primary, stray capacitance between primary and secondary of the transformer and interruption of the current into the primary of the transformer.

Voltage transients, if they exceed the peak forward rating of the thyristor, could destroy the device. Even if this rating is not exceeded faulty firing could occur, which in many cases would lead to over current and operation of current limiting fuses. In the reverse direction a transient will cause relatively large currents to flow in a small area of the thyristor junction, causing localising heating and device failure.

It is necessary to ensure that as many sources of voltage transients are eliminated from a thyristor circuit as possible. The most commonly used method of elimination of voltage transient is by connecting RC Circuit known as SNUBER Circuit across the individual devices. It is shown in Fig.No.4.7

The controlled d.c. output voltage of the 3-Ø half controlled bridge is applied across the armature of the d.c. motor whose speed to be controlled. The d.c. output voltage vary according to the difference between the reference signal and feedback signal. A choke is connected in series with the armature of the d.c. motor to reduce the a.c. ripples and against hunting. The choke in series of armature of the motor absorbs energy during ON period from the supply and fed to the motor during OFF period for smooth control of motor.

CHAPTER - 4

DESIGN CONSIDERATIONS OF DEVELOPED SCHEME

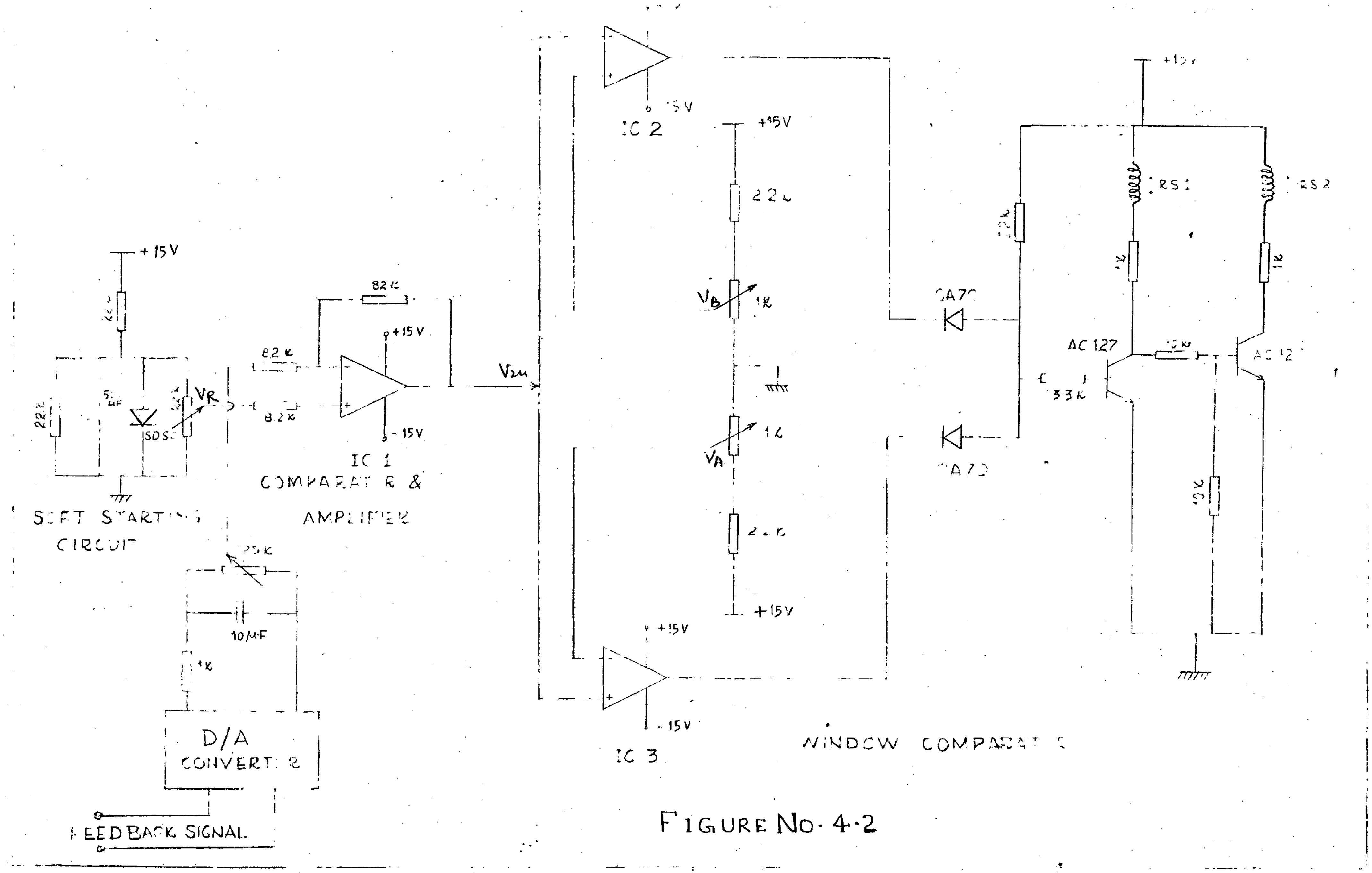

+ 15V
22K
5µF
SDS
VR
SOFT STARTING
CIRCUIT
25K
10MF
1K
D/A
CONVERTER
FEEDBACK SIGNAL
82K
8.2K
+15V
-15V
IC 1
COMPARATOR &
AMPLIFIER
V2u
IC 2
IC 3
+15V
22K
VB
1K
VA
WINDOW COMPARATOR
AC 127
3.3K
RS1
RS2
1K
10K

FIGURE No. 4·2

4.1 General Considerations :

The schematic diagram of the solid state d.c. speed controller is shown in the Figure No.4.1. The basic design considerations of the scheme are accuracy, reliability, economy, space requirements and operational requirements.

This scheme provide very accurate speed control, reliability and synchronisation capability, by locking onto a reference frequency, speed accuracies of 0.002% are possible, which represents almost a hundredfold improvement over earlier methods of speed regulation. But this regulation reduces to 0.01% at the low end of the range.

The reliability of solid state devices used in the comparators and switching circuit has been good. The thyristors and power diodes used in the 3-Ø converter are excellent from reliability point. Therefore the over all reliability of the scheme is good.

The cost of thyristors is decreasing day by day and can be said tolerable with respect to their power handling capability. And the Op Amps used in the switching circuit and comparators are quite cheap now a days. Hence the over all scheme is cheap comparative to the conventional Ward Leonard method of speed control. But is is expensive for higher power requirements.

The space required by this scheme is very less and can be called as package control of the d.c. motor.

The facility of variations in the basic design of the unit is provided according to the different operation requirements. Necessary modifications can be done in the scheme if remote control is needed.

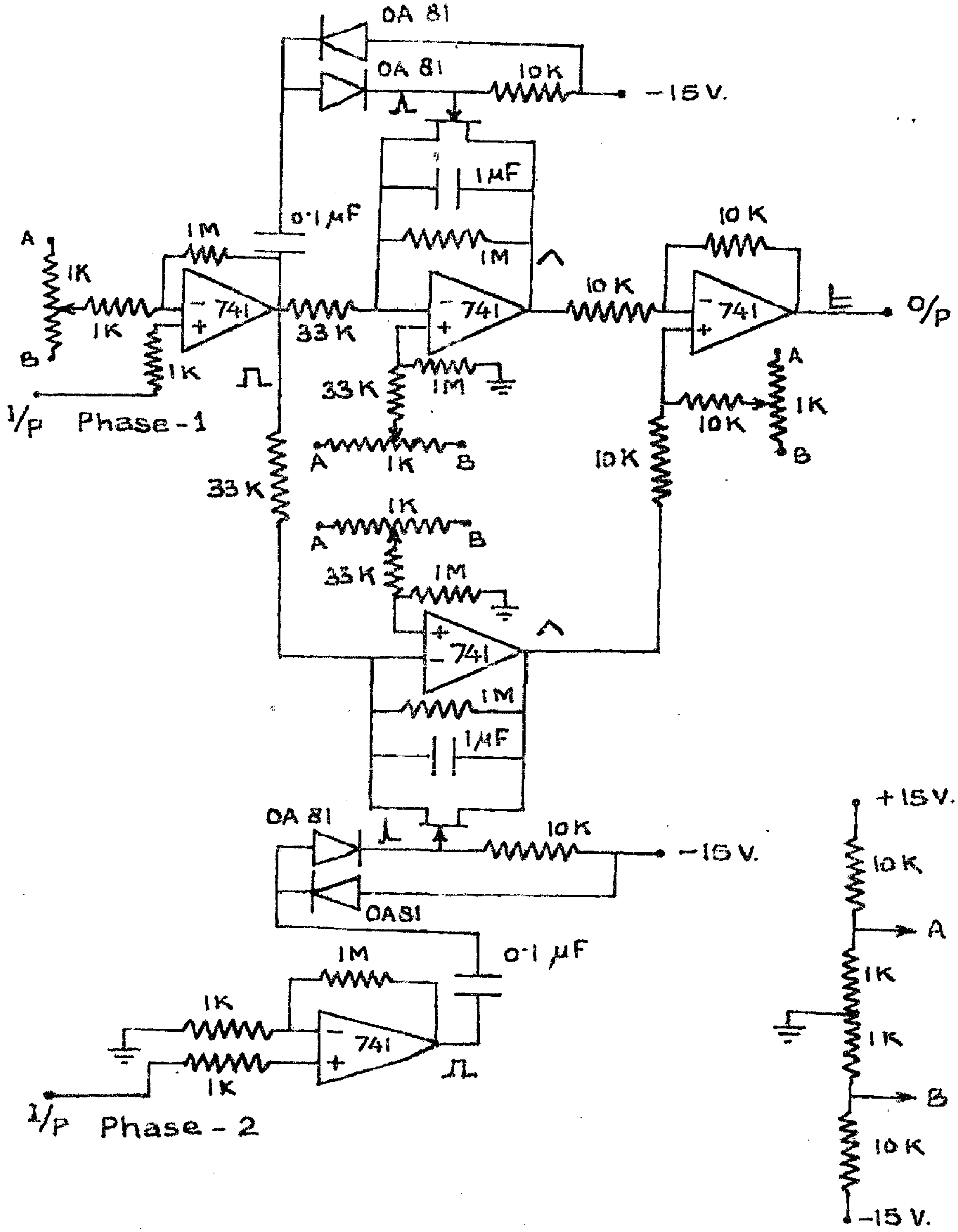
4.21 Soft Starting Circuit : The soft starting circuit is shown in the Figure No. 4.2. Time period of the circuit must be more than the motor time period. Time period of the circuit is adjusted by the values of the resistance R_1 and Capacitor C_1.

As the d.c. motor has large inertia so it will take time to speed up near to synchronism. If the soft starting circuit is not used then the phase comparator will give maximum output voltage corresponding to zero speed. This large voltage will generate current of large peak value which will burn the thyristors used in the 3-Ø half controlled bridge.

The output voltage of the soft starting circuit is reduced to match the D/A Convertor voltage according to the reference frequency or speed.

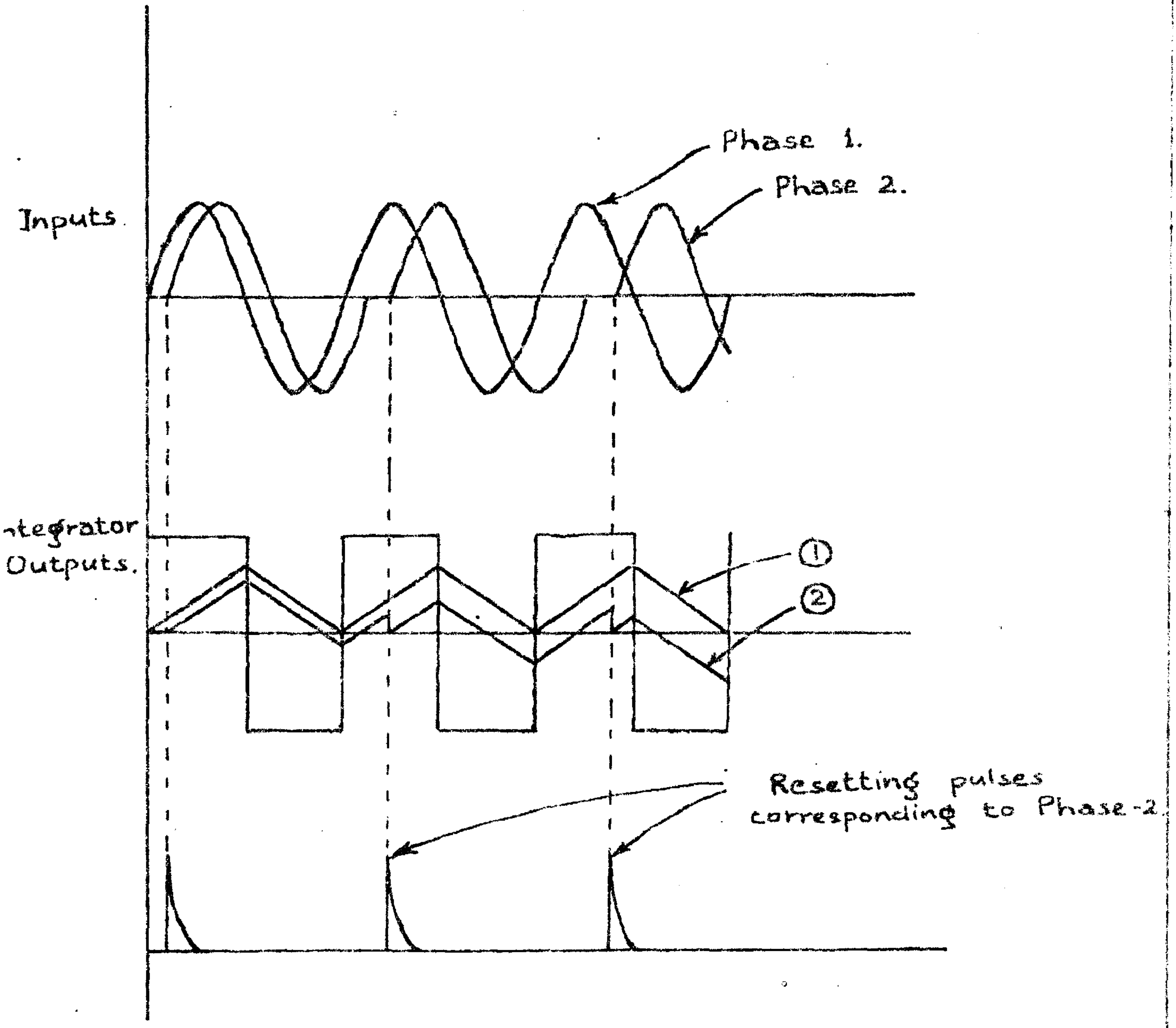
4.22 Comparator & Amplifier : It is shown in Fig. No. 4.2. As ther is no intention of reproducing any part of the original input singnal wave shape. Therefore it is a high gain differential amplifier operating in the open loop manner.

4.23 Window Comparator : It is shown in the Fig.No.4.2. The window comparator range should be correspond to the working range of the phase comparator. Its range is adjusted by using two



PHASE COMPARATOR.

FIGURE NO·4·3



Phase Comparator Waveforms.

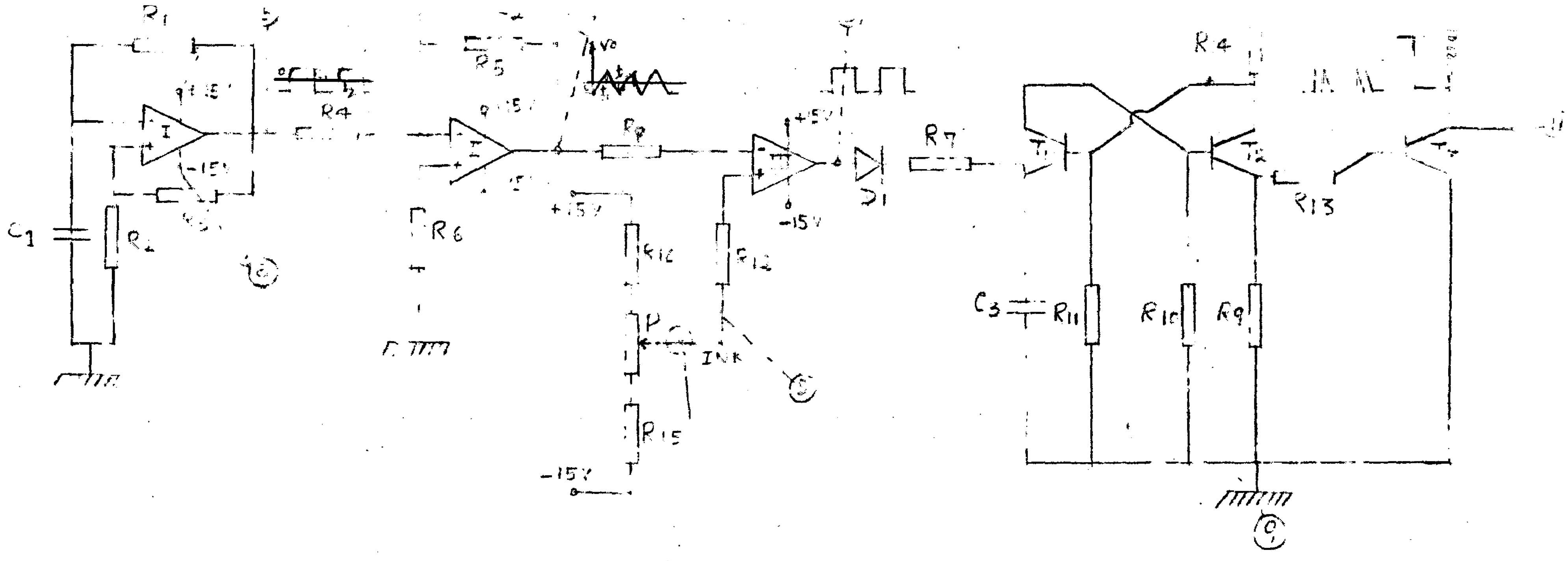
FIGURE No. 4.4

positive reference voltages as one of the inputs of the two Op Amps. These voltages are compared with the reference voltage V_{in} from previous comparator output. Thus the range of the window comparator is V_A to V_B.

Invertor circuit is used when the output of the window comparator is out of the range of phase comparator. For this ranges soft starting circuit will work.

4.24 Phase Comparator : The circuit diagram of the phase comparator and the wave forms of the phase comparator are shown in Fig.No.4.3 and Fig.No.4.4 respectively. Operating frequency is fixed to the reference signal frequency for Zero Crossing Detector. Integrator time period must be greater than the time period of the supply so that the integration should not complete before. A-B reference shown in the Fig.No. 4.3 is used for nullifying the off set of each integrated circuit. FET switches are used as channel resistance between source and drain is low. Therefor the capacitor of differentiating circuit is discharged quickly.

This type of phase comparator is a fast response detection method. It is stable against the random noises included in the input signal. The holding characterstics in the output signal of d.c. form is automatically guaranteed despite of the fact that it has no holding circuit of high input impedance type. Each part of the device can easily be constructed, with the popular IC components. [15]



MULTIVIBRATOR INTEGRATOR COMPARATOR FIRING CIRCUIT

COMPONENT LIST

R_1 = [illegible]K	R_{13} = 100K	C_1 = [illegible]
R_2 = 10K	R_{14} = 10K	C_2 = [illegible]
R_3 = [illegible]	R_{15} = 10K	C_3 = [illegible] // 0.47MF
R_4 = [illegible]K	R_{16} = [illegible]	T_1 = B[illegible]7
R_5 = [illegible]K	IC_1 = [illegible]1 (14 PIN)	T_2 = B[illegible]
R_6 = [illegible]	IC_2 = 741 (14 PIN)	T_3 = [illegible]
[illegible]	IC_3 = [illegible]	
R_8 = [illegible]	D_1 = ANY SI. DIODE	
R_9 = 1K	P = [illegible]K	
R_{10} = 10K		
R_{11} = 7.5K		
R_{12} = 10[illegible]		

PIN CONNEXIONS

1 → N.C.
2 → VARIABLE POINT OF PRESET
3 → O/P OF IC_3 (COMPARATOR)
4 → SUPPLY (+15)
5 → O/P OF IC_1 (MULTIVIBRATOR)
6 → SUPPLY (-15V)
7 → O/P OF IC_2 (INTEGRATOR)
8 → N.C.
9 → [illegible]
10 → N.C.
11 → FINAL OUTPUT
12 → N.C.

FIGURE No. 4.5

4.25 Amplifier : It is shown in the Fig.No. 4.1 of closed loop scheme. It is used to increase the amplitudes of the soft starting circuit output and phase comparator output so that the d.c. level at the switching circuit's comparator changes sufficiently. There is only one input at a time to the amplifier as the soft starting circuit and phase comparator can not work simultaneously. If the soft starting circuit output voltage is low the gain of the amplifier for it can be increased.

4.26 Switching Circuit : It is shown in the Fig.No. 4.5. First IC works as square-wave generator. The elements R_1 and C_1 provide the integrating or timing function. The required regenerative action comes from feeding the non inverting input of the Op Amp 1 with a fraction of the output voltage impedance across the amplifier inputs will be very low under the conditions imposed by this circuit.

The amplitude of the output voltage are controlled by the positive and negative power supplies. The output voltage waveforms has sharp leading and trailing edges, typically making the transition from one saturation level to the other in few micro seconds. The transition time is determined by the slew-rate of the Op Amp.

The 2nd Op Amp works as integrator. Because one end of the capacitor is tied to the virtual ground point, the output voltage of the amplifier equals the capacitor charging voltage. The frequency is controlled by the ramp rate of the triangular wave.

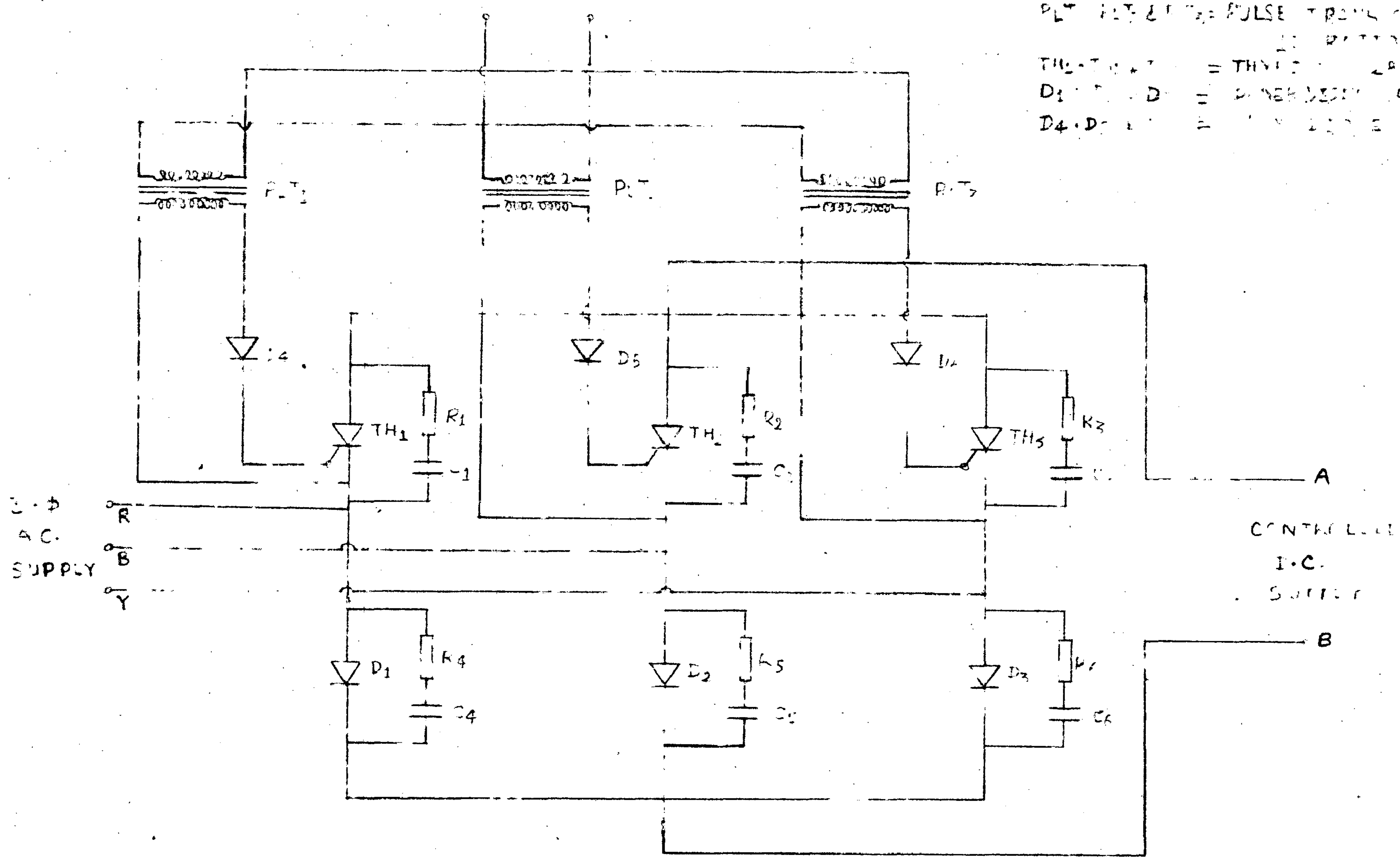


FIGURE NO. 4·6

It is a low-pass RC filter whose time constant is much larger than the square-wave period. In effect, the larger the time constant, the more linear the ramp output, although the amplitude is also reduced.

Third Op Amp works as comparator. The pulse width is varied by varying the d.c. reference voltage amplitude. As the d.c. reference voltage is the output of the amplifier it will vary until the d.c. motor attains the required speed.

Since a thyristor usually is fired by a short-time pulse of gate current, a circuit is needed that can delay and control the instant that such a pulse occurs within each half cycle. So the output of the comparator is fed to the UJT equivalent circuit. It is used as an oscillator.

The last transistor in the figure No. 4.5 is used as the pulse amplifier. Its gain must be enough to give the sufficient amplitude of the pulses to fire the thyristors.

4.27 <u>Half-Controlled, Full-Wave 3-Ø Bridge Thyristor Converter Arrangement</u> :

4.271 <u>Pulse Transformer</u> : Pulse transformer provides isolation arrangement for the transmission of pulses from the pulse circuits to the gate - cathode terminals of the thyristor. It is shown in the Fig. No. 4.6.

The cost of these pulse transformers has to be taken into account, although considering the insignificant power

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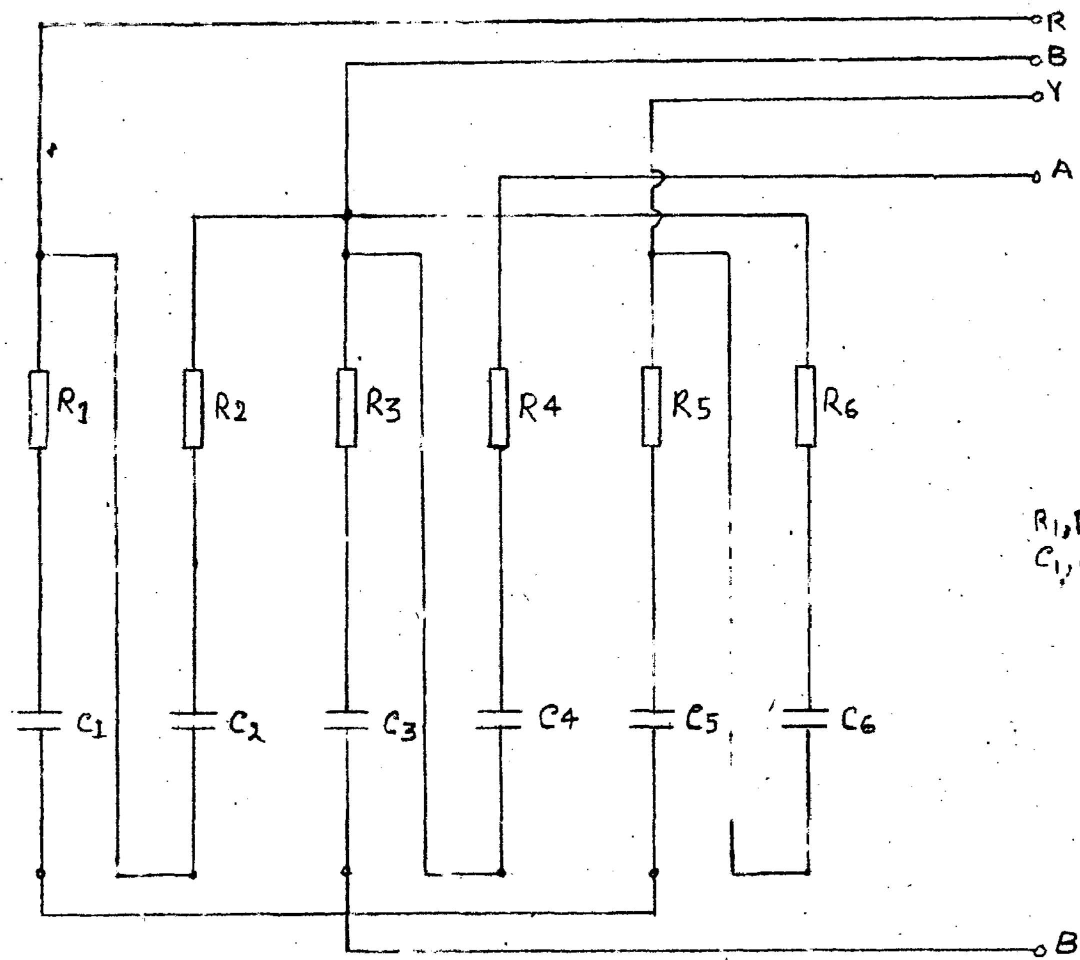

R1, R2 R3, R4, R5 & R6 = 50Ω, 5 WATTS
C1, C2, C3, C4, C5 & C6 = 0·05 μF or 0·01 μF
1500V

SNUBER CIRCUIT

FIGURE NO·4·7

requirement for firing a thyristor the extra cost is small compared to the cost of pulse circuits.

4.272 Thyristor Convertor : The 3-Ø bridge half controlled full-wave thyristor converter is shown in Fig.No. 4.6. As the recti-fication operation is only required so it is economic to replace some of the thyristors by power diodes owing to the high cost of thyristors compared to the diodes.

Thyristors and power diodes have an excellent record of reliability, the only failure has occured as a result of over heating. The cost of thyristors has fallen substantially over the past years. In addition their power handling capacility has increased. The maintenance required in very less.[9]

4.273 Over Voltage Protection of Thyristors : The snuber circuit used for the protection of thyristors against voltage transients is shown in the Fig.No. 4.7. The electrolytic type of capacitors are physically small, can be used. The capacitor can discharge through the resistor when the circuit is de-energized.

This type of arrangement of protection of thyristors requires less space and less maintenance. This circuit is economic also.

CHAPTER - 5

TEST RESULTS AND CONCLUSIONS

5.1 <u>Test Results</u>: Connections shown in Figure No. 4.1 being made. First, the reference motor - alternator is started. D.C. supply is applied to the motor armature and field and motor is started with the help of a starter. When d.c. supply is fed to the alternator field it starts generating the voltage. A reference signal proportional to it is applied to the phase comparator input. Then d.c. supply is fed to field of the motorwhose speed to be controlled and a separate d.c. supply is fed to the alternator field coupled to it. Now a 3 - Φ a.c. supply is switched on and a.c. voltage is applied through scott transformer (isolation transformer) to the converter bridge while simultaneously power supplies of the different printing plates are made ON.

In the beginning motor will start by soft starting circuit and motor will speed up to near synchronous speed. The synchroneus speed is taken as 1500 r.p.m. of the referance motor alternator set corresponding to 50 c/s.

Near synchronism i.e. speed between 1400 r.p.m. and 1600 r.p.m. phase comparator will work and synchronise the motor whose speed to be controlled to synchronous speed i.e. 1500 r.p.m.

If due to some oscillations occurred the motor falls out of synchronism and even out of the range of the phase comparator. Soft starting circuit starts working and makes the speed of the motor in the range of phase comparator and then phase comparator will again synchronise the speed of the motor to the reference speed.

5.2 Conclusions:

a) Motor will take nearly 10 seconds to reach the speed near synchronous speed. In this range soft starting circuit will work.

b) Phase comparator working range is 1400 r.p.m. to 1600 r.p.m.

c) Accuracy is very high in this system. The motor whose speed to be controlled will run on the speed as that of the reference speed.

d) A slight sustained oscillations are there due to instability.

5.3 Scope for Further Work:

This scheme can be modified to provide a provision of better locking when the synchronisation of the d.c. motor is done with respect to the reference signal and the motor is loaded.

A facility of multiple speed of the reference speed can be provided if a divide by N counter is added in the feed back path of the closed loop scheme.

Facility of regeneration can be provided if the 3 - Φ bridge half controlled full wave converter is replaced by 3 - Φ bridge full controlled full wave converter. Similarly the facilities of regnerative backing and dynamic bracking can be provided by making necessary modifications in the design of the scheme of d.c. speed controller.

5.4 Recommended Areas of Industrial Application:

The low cost of integrated circuits and thyristors makes this scheme of d.c. speed controller economical. Motors of any size can be controlled with this technique once the characteristics of the motor have been incorporated onto the response of the scheme.

Especially suitable for this scheme are systems in which motors must be synchronized to each other or to an existing clocking signal. An example of the former is conveyor for materials handling, of the latter, a drive for a computer peripheral such as a disk unit.

REFERENCES

1. MAZDA F.F., "Thyristor Control", Pub - Newnes - Butterworths.

2. MURPHY J.M.D., "Thyristor Control of A.C.Motors", Pub - Pergamon Press.

3. RAMSHAW R.S., "Power Electronics - Thyristor Controlled Power for Electric Motors", Pub - Chapman and Hall Ltd., London.

4. SEYMOUR J., "Semiconductor Design in Power Engg.", Pub - Sir Isaac Pitman and Sons Ltd.

5. GRAME J.G., TOBEY G.E., HUELSMAN L.P.," Operational Amplifiers Design and Applications", Pub - McGraw Hill Book Co.

6. MANERA A.S., "Solid State Electronic Circuits; for Engineering Technology", Pub - McGraw Hill Book Co.

7. SCHIEMAN R.G., WILKES E.A., JORDAN H.E., " IEEE Proceedings, Dec. 1974, "Solid State Control of Electric Drives".

8. KUSKO A., Control Engineering, July 1966, Vol. 13, No. 7, "Package SCR D.C. Drives Part II - Surveying the makers".

9. SCHOFIELD J.R.G., SMITH G.A., WHITMORE M.G., Power Semiconductors applications, Vol. I, General Considerations (IEEE Press), "The Application of Thyristors to the Control of D.C. Machines".

10. DAVIES J.A., KIDD A.C., BEABLE R.E. and TILSTONE G., Power Semiconductors Applications, Vol. I, General Considerations (IEEE Press), "Thyristor Convertor for D.C. Motor Drives".

11. MALONEY T.J. and ALVARADO F.L., IEEE Transactions on Industrial Electronics and Control Instrumentation, Feb. 1976, "A Digital Method for D.C. Motor Speed Control."

12. ZINDER D.A., Machine Design, April 4, 1974, Vol. 46, No. 8,"Energy Saving Route to Motor Control".

13. MOORE A.W., IEEE Spectrum, Vol. 10, No. 4, April 1973, "Phase Locked Loops for Motor Speed Control".

14. SMITHGALL D.H., IEEE Transactions on Industrial Electronics and Control Instrumentation, Vol. IEC I-22, No. 4, Nov. 1975, "A Phase Locked Loop Motor Control System".

15. TAKATA S., VEDA R., OHETA E. and NAKASHIMA H., IEEE Transaction on Power Apparatus and System, Vol. PAS - 94, No. 6, Nov./Dec. 1975 "Fast Response Detection of Mean Value of Power System Quantities".

APPENDIX

Pin connections of printing circuits plates are as follows:

Switching Circuit

1. N.C.
2. Variable point of pre-set (Amplifier output)
3. O/P of IC_3
4. Supply + ive
5. O/P of IC_1
6. Supply - ive
7. O/P of IC_2
8. N.C.
9. Ground
10. N.C.
11. Final output
12. N.C.

Phase Comparator

1. Output
2. Supply + ive
3. Supply - ive
4. N.C.
5. Reference signal (input)
6. Other signal input (Feed back signal)
7. N.C.
8. N.C.
9. N.C.
10. Ground
11. N.C.
12. N.C.

Window comparator

1. N.C.
2. Supply + ive
3. N.C.
4. Supply - ive
5. Input from D.A. Converter
6. To amplifier input (Phase comparater side)
7. From phase comparator output
8. N.C.
9. N.C.
10. To amplifier input (Soft starting circuit)
11. Ground
12. N.C.

Amplifier

1. Supply - ive
2. N.C.
3. N.C.
4. Non inverting input
5. N.C.
6. N.C.
7. N.C.
8. N.C.
9. Output
10. Inverting input
11. N.C.
12. Supply + ive