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CHAPTER 46

ELECTRONIC CONTROL OF A.C. MOTORS

Learning Objectives

- Classes of Electronic AC Drives
- Variable Frequency Speed Control of a SCIM
- Variable Voltage Speed Control of a SCIM
- Chopper Speed Control of a WRIM
- Electronic Speed Control of Synchronous Motors
- Speed Control by Current-fed D.C. Link
- Synchronous Motor and Cycloconverter

Efficient control of motors becomes critical where high precision, accuracy, flexibility, reliability and faster response are of paramount importance. Electronic and digital controls are employed in such conditions

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46.1. Classes of Electronic A.C. Drives

AC motors, particularly, the squirrel-cage and wound-rotor induction motors as well as synchronous motors lend themselves well to electronic control of their speed and torque. Such a control is usually exercised by varying voltage and frequency. Majority of the electronic a.c. drives can be grouped under the following broad classes :

1. **static frequency changers** like cyclo-converters which convert incoming high line frequency directly into the desired low load frequency. Cyclo-converters are used both for synchronous and squirrel-cage induction motors.
2. **variable-voltage controllers** which control the speed and torque by varying the a.c. voltage with the help of SCRs and gate turn-off thyristors (GTOs).
3. **rectifier-inverter systems** with natural commutation.
4. **rectifier-inverter systems** with self-commutation.

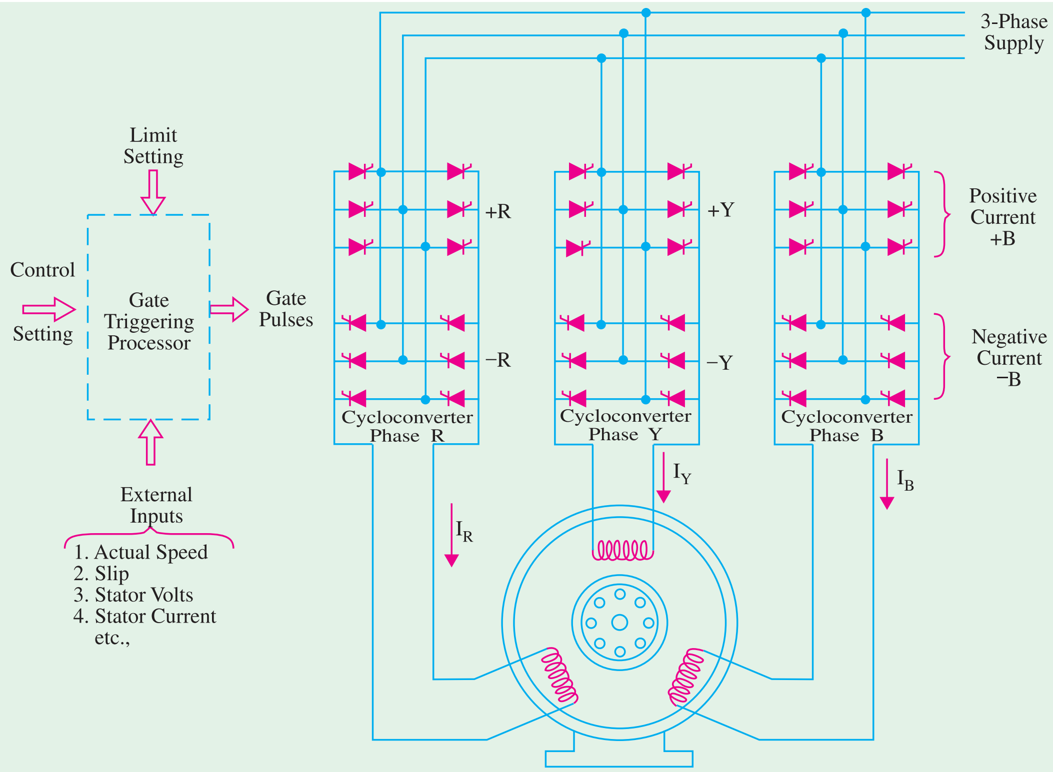


Fig. 46.1

46.2. Variable-frequency Speed Control of a SCIM

Fig. 46.1 shows a 3-phase SCIM connected to the outputs of three 3-phase cycloconverters. As seen, each cyclo-converter consists of two 3-phase thyristor bridges, each fed by the same 3-phase, 50-Hz line. The +*R* bridge generates the positive half-cycle for *R*-phase whereas –*R* generates the negative half. The frequency of the cycloconverter output can be reduced to any value (even upto zero) by controlling the application of firing pulses to the thyristor gates. This low frequency permits excellent speed control. For example, the speed of a 4-pole induction motor can be varied from zero to 1200 rpm on a 50-Hz line by varying the output frequency of the cycloconverter from zero to 40 Hz. The stator voltage is adjusted in proportion to the frequency in order to maintain a constant flux in the motor.

This arrangement provides excellent torque/speed characteristics in all 4-quadrants including regenerative braking. However, such cycloconverter-fed motors run about 10°C hotter than normal and hence require adequate cooling. A small part of the reactive power required by SCIM is provided by the cycloconverter, the rest being supplied by the 3-phase line. Consequently, power factor is poor which makes cycloconverter drives feasible only on small and medium power induction motors.

46.3. Variable Voltage Speed Control of a SCIM

In this method, the speed of a SCIM is varied by varying the stator voltage with the help of three sets of SCRs connected back-to back (Fig. 46.2). The stator voltage is reduced by delaying the firing (or triggering) of the thyristors. If we delay the firing pulses by 100°, the voltage obtained is about 50% of the rated voltage which decreases the motor speed considerably.

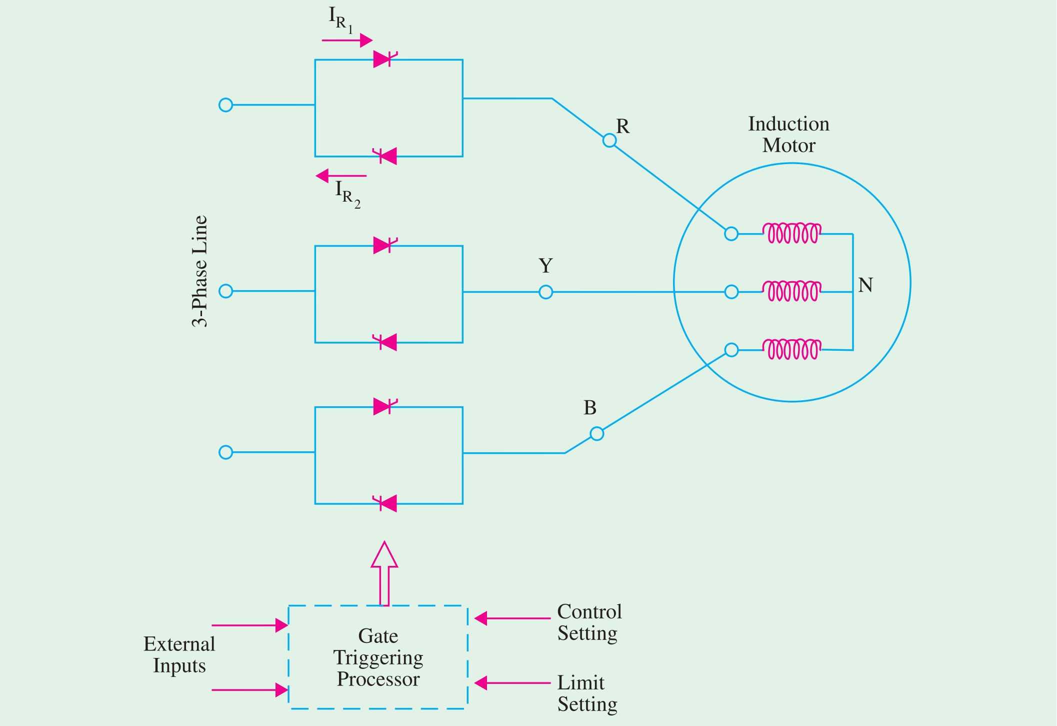
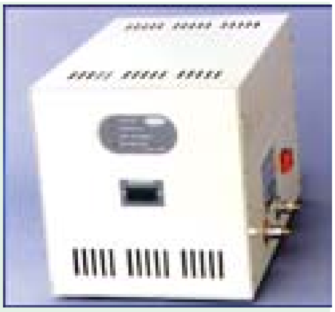


Fig. 46.2

Unfortunately, I^2R losses are considerable due to distortion in voltage. Moreover, p.f. is also low due to large lag between the current and voltage. Hence, this electronic speed control method is feasible for motors rated below 15 kW but is quite suitable for small hoists which get enough time to cool off because of intermittent working. Of course, p.f. can be improved by using special thyristors called gate turn-off thyristors (GTOs) which force the current to flow almost in phase with the voltage (or even lead it).



A commonly used electronic power inverter

46.4. Speed Control of a SCIM with Rectifier-Inverter System

A rectifier-inverter system with a d.c. link is used to control the speed of a SCIM. The inverter used is a self-commuted type (different from a naturally commutated type) which converts d.c. power into a.c. power at a frequency determined by the frequency of the pulses applied to the thyristor gates. The rectifier is connected to the 3-phase supply line whereas the inverter is connected to the stator of the SCIM.

Two types of links are used :

1. constant-current d.c. link —for speed control of *individual* motors.

2. constant-voltage d.c. link —for speed control of several motors.

As shown in Fig. 46.3, the constant-current link supplies constant current to the inverter which then feeds it sequentially (through proper switching sequence) to the three phases of the motor. Similarly, the constant-voltage dc link (Fig. 46.4) provides a constant voltage to the inverter which is switched from one phase of the motor to the next in a proper sequence.

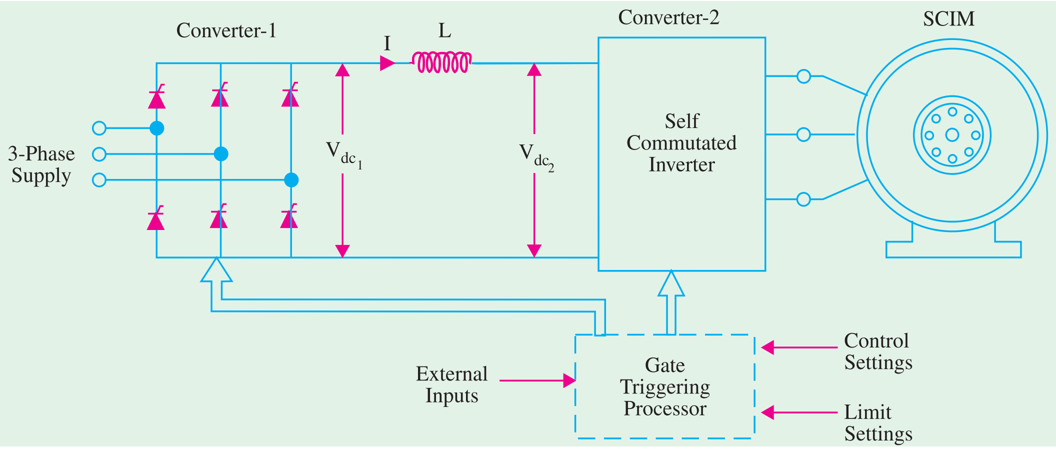


Fig. 46.3

The arrangement of Fig. 46.3 gives speed control with high efficiency in all 4 quadrants in addition to the facility of regenerative braking. Heavy inertia loads can be quickly accelerated because motor develops full break-down torque right from the start. The output frequency of the inverter varies over a range of 20 : 1 with a top frequency of about 1 kHz. The a.c. voltage supplied by the inverter is changed in proportion to the frequency so as to maintain the stator flux constant.

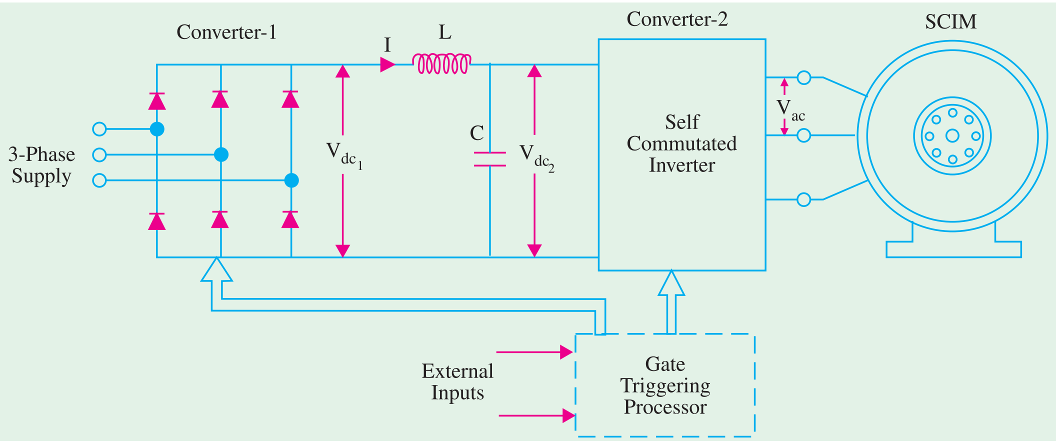


Fig. 46.4

Consequently, d.c. link voltage V_{dc1} has to be reduced as the motor speeds up. This is accomplished by increasing the firing angle of the thyristors in converter 1. Unfortunately, this leads to increase in the reactive power drawn from the 3-phase line which results in poor power factor. To improve the p.f., use of capacitors is necessary. The direction of rotation can be changed by altering the phase sequence of the pulses that trigger the gates of converter 2.

The voltage-fed frequency converter of Fig. 46.4 consists of a rectifier and a self-commutated inverter connected by a d.c. link and is often used for group drives in textile mills. The 3-phase bridge rectifier produces d.c. voltage V_{dc1} which is smoothened up by the *LC* filter before being applied to the inverter. The inverter successively switches its output ac voltage V_{ac} to the three phases of the motor. This voltage is varied in proportion to the frequency so as to maintain constant flux in the motor. Since, V_{ac} depends on V_{dc2} which itself depends on V_{dc1}, it is V_{dc1} which is changed as frequency varies. In this system, motor speed can be controlled from zero to maximum while developing full breakdown torque.

A simple electronic control system

46.5. Chopper Speed Control of a WRIM

As discussed in Art. 30.18 (*d*), the speed of a WRIM can be controlled by inserting three variable resistors in the rotor circuit. The all-electronic control of speed can be achieved by connecting a 3-phase bridge rectifier across the rotor terminals and then feed the rotor output to a single fixed resistor or R_0 via a chopper (Fig. 46.5).

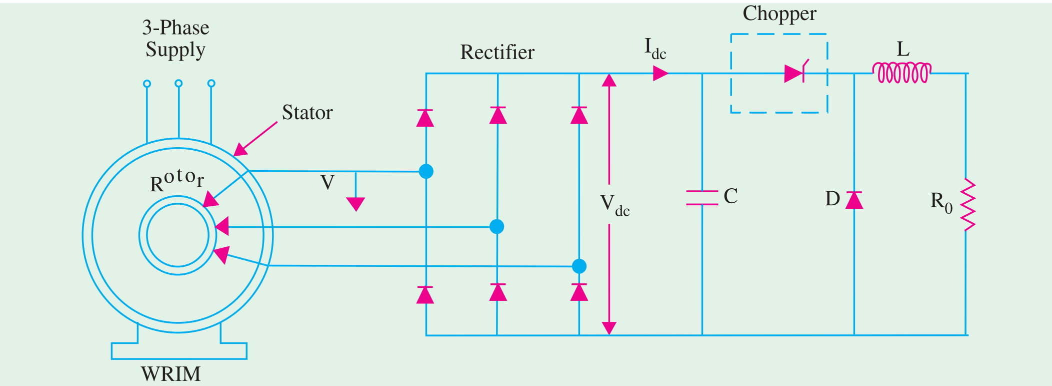


Fig. 46.5

The capacitor *C* supplies the high current pulses drawn by the chopper. The inductor *L* and free-wheeling diode *D* serve the same purpose as discused in Art. 28.14. By varying the chopper on-time TON, the apparent resistance R_a across the bridge rectifier can be made either high or low. The value of apparent resistance is given by $R_a = R_0/f^2\, T_{ON}^2$ where f is the OFF/ON switching frequency of the chopper. The resulting torque/speed characteristic is similar to the one obtained with a 3-phase rheostat.

Example 46.1. *The wound-rotor induction motor of Fig.43.5 is rated at 30-kW, 975 rpm, 440-V, 50 Hz. The open-circuit line voltage is 400 V and the load resistance is 0.5 Ω. If chopper frequency is 200 Hz, calculate* T_{ON} *so that the motor develops a gross torque of 200 N-m at 750 rpm. Also, calculate the magnitude of the current pulses drawn from the capacitor.*

Solution. Obviously, $N_S = 1000$ rpm. Hence, slip at 750 rpm is = (1000 – 750)/1000 = 0.25. The rotor line voltage at 750 rpm is = $sE_2 = 0.25 \times 400 = 100$ V.

The d.c. voltage of 3-phase bridge rectifier is $V_{dc} = 1.35\ V = 1.35 \times 100 = 135$ V.

Now, $T_g = P^2/2\pi\, N_s; P^2 = T_g \times 2\pi\, N_s = 200 \times 2\pi \times (1000/60) = 20{,}950$ W

Part of P^2 dissipated as heat = $sP^2 = 0.25 \times 20{,}950 = 5{,}238$ W

The power is actually dissipated in R_0 and is, obviously, equal to the rectifier output $V_{dc}.I_{dc}$.

$$\therefore \qquad V_{dc} \cdot I_{dc} = 5238 \quad \text{or} \quad I_{dc} = 5238/135 = 38.8 \text{ A}$$

The apparent resistance at the input to the chopper is

$$R_a = V_{dc}/I_{dc} = 135/38.8 = 3.5\ \Omega$$

Now, $R_a = R_0/f^2$ उ$^2_{ह ब}$ or $T_{ON} = \sqrt{R_0/f^2 R_a} = \sqrt{0.5/200^2 \times 3.5} =$ **1.9 ms**

Current in R_0 can be found from the relation

$$I_0^2 R_0 = 5238 \quad \text{or} \quad I_0 = \sqrt{5238/0.5} = \mathbf{102\ A}$$

As seen, capacitor delivers current pulses of magnitude उ$^2_0$ A and a pulse width of 1.9 ms at the rate of 200 pulses/second. However, the rectifier continuously charges C with a current of 38.8 A.

46.6. Electronic Speed Control of Synchronous Motors

The speed of such motors may be controlled efficiently by using ***(i)*** current-fet delink and ***(ii)*** cycloconverter as discussed below :

46.7. Speed Control by Current-fed DC Link

As shown in Fig. 46.6, the typical circuit consists of three converters two of which are connected between the three-phase source and the synchronous motor whereas the third converter (bridge rectifier) supplies dc field excitation for the rotor. Converter-1 (*C*-1) acts as a controlled rectifier and feeds d.c. power to converter-2 (*C*-2). The converter-2 behaves as a naturally commutated inverter whose a.c. voltage and frequency are established by the motor. The function of the smoothing inductor L is to maintain a ripple-free current in the d.c. link between the two converters. Converter-1 acts as a current source and controls I.

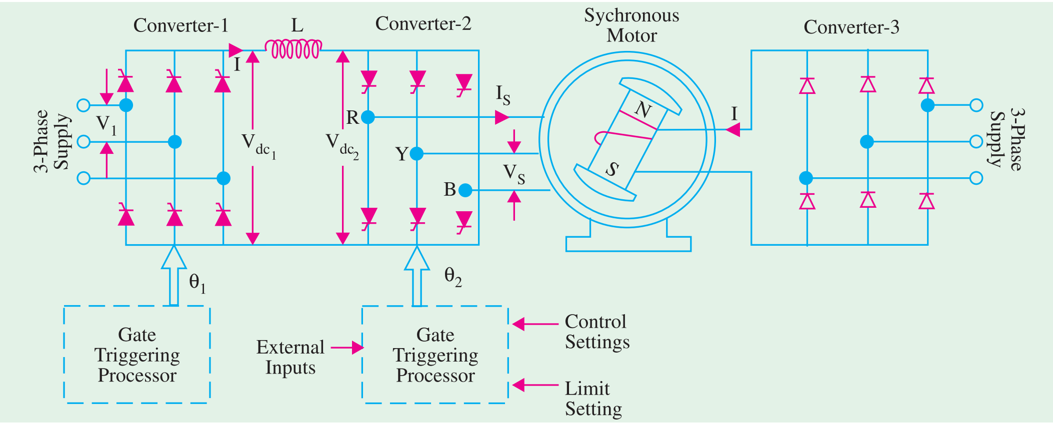


Fig. 46.6

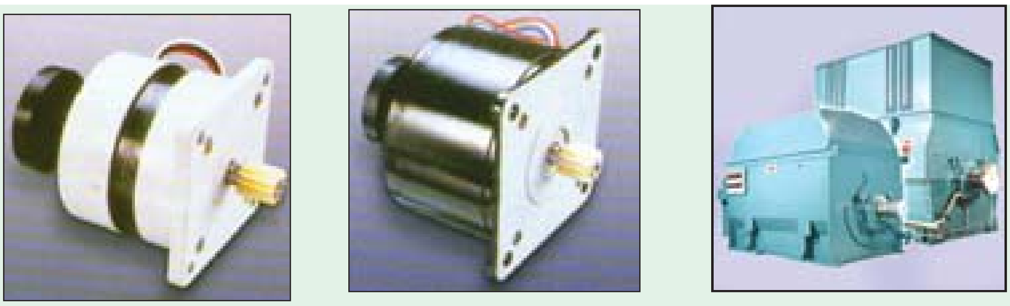
The converter-2 is naturally commutated by voltage V_s induced across motor terminals by its revolving magnetic flux. The revolving flux which depends on the stator currents and the d.c. field exciting current I_{f1} is usually kept constant. Consequently, V_s is proportional to motor speed.

As regards various controls, information picked off from various points is processed in the gate-triggering processors which then send out appropriate gate firing pulses to converters 1 and 2. The processors receive information about the desired rotor speed, its actual speed, instantaneous rotor position, field current, stator voltage and current etc. The processors check whether these inputs represent normal or abnormal conditions and send appropriate gate firing pulses either to correct the situation or meet a specific demand.

Gate triggering of C-1 is done at line frequency (50 Hz) whereas that of C-2 is done at motor frequency. In fact, gate pulses of C-2 are controlled by rotor position which is sensed by position transducers mounted at the end of the shaft. The motor speed can be increased by increasing either d.c. link current I or exciting current I_f.

Now, $V_{dc2} = 1.35\ V_s \cos\alpha_1$ and $V_{dc1} = 1.35\ V_s \cos\alpha_1$

where V_{dc2} = d.c. voltage generated by C-2, V_{dc1} = d.c. voltage supplied by C-1



Special features of A C Synchronous motors: 1. Bi-directional, 2. Instantaneous Start, Stop and Reverse, 3. Identical Starting and Running Currents, 4. Residual Torque always present, 5. No damage due to stalling, 6. Low speed of 60 rpm. Applications of AC Synchronous Motors are found in: 1. Actuators, 2. Remote control of switches 3. Winding machines, 4. Machine tool applications, 6. Valve controls, 6. Printing machines, 7. Automatic welding machines, 8. Medical equipment, 9. Conveyor systems, 10. Paper feeders

α_2 = firing angle of *C*-2 ; α_1 = firing angle of *C*-1

The firing angle α_1 is automatically controlled and supplies *I* which is sufficient to develop the required torque. This method of speed control is applied to motors ranging from 1 kW to several MW. Permanent-magnet synchronous motors used in textile industry and brushless synchronous motors for nuclear reactor pumps are controlled by this method.

46.8. Synchronous Motor and Cycloconverter

As shown in Fig. 46.7, the arrangement consists of three cycloconverters connected to the three

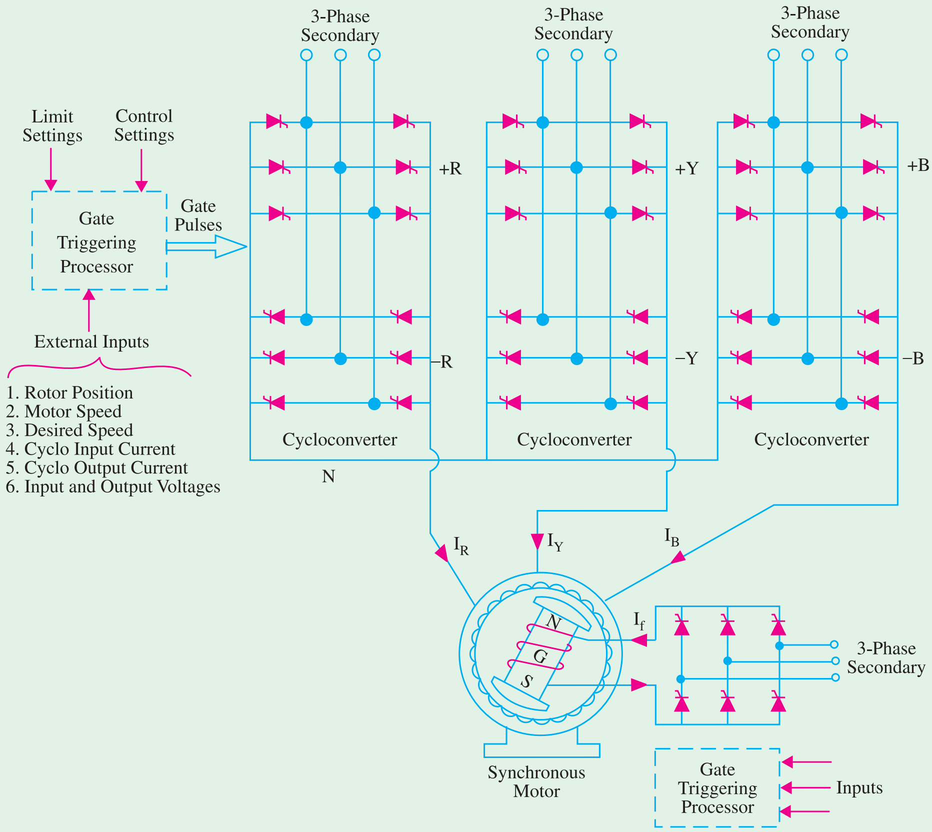


Fig. 46.7

one phases of the synchronous motor and one controlled rectifier for supplying field exciting current I_f to the rotor. Each cycloconverter is composed of two three-phase bridges and supplies a single-phase output. As is well known, a cycloconverter can directly convert a.c. power at higher frequency to one at a lower frequency. With a line frequency of 50 Hz, the cycloconverter output frequency can be varied from zero to 10 Hz.

The cycloconverters and the controlled rectifier function as current sources. The air-gap flux is kept constant by controlling the magnitude of the stator currents and exciting current I_f. By proper timing of gate pulses, motor can be made to operate at unity power factor.

The speed of cycloconverter-driven large slow-speed synchronous motors can be continuously varied from zero to 15 rpm. Such low speeds permit direct drive of the ball mill without using a gear reducer. Such high-power low-speed systems are also being introduced as propeller drives on board the ships.

46.9. Digital Control of Electric Motors

Advantages of Digital Control

1. High precision and accuracy
2. Better speed regulation
3. Faster response
4. Flexibility
5. Better time response
6. Improved performance
7. Economical
8. Easy software control
9. Reliability
10. The greatest advantage of the digital control is that by changing the program, desired control technique can be implemented without any change in the hardware.

The speed information can be fed into microcomputer using a D.C. Tacho (Speed encoder) and A/D converter (Speed *I/P* module). The motor current data is usually fed into the computer through a fast A/D converter. A synchronizing circuit interface (Line synchronizing circuit) is required so that the micro-computer can synchronize the generation of the firing pulse data with the supply line frequency. The gate pulse generator is shown as receiving a firing signal from microcomputer.

A set of instruction (Program) is stored in memory and those are executed by computer for proper functioning of a drive. A typical program flow - chart for this drive system is shown in figure (46.9). The sequence of instructions allows the computer to process data for speed regulation, current regulation and reversal operation.

46.10. Application of Digital Control

The above operations can be clearly understood by considering one of the applications of Digital Control system, such as Digital Control System for Speed Control of D.C. drives using a Micro-computer :

Various components and their operations shown in Fig. 46.8 are discussed below :

(i) Thyristor Converter

PC based control systems can be built where a phase-controlled rectifier supplies a D.C. motor. The main control to be handled is to turn on & off SCRs. Thyristor power converter in this case is a dual converter – one for forward and other for reverse direction.

(ii) Gate Pulse Generator and Amplifier

PC is used for firing angle control of dual converter. It can be programmed using suitable software to perform the function of firing range selection, firing pulse generation, etc. The firing pulses so obtained are amplified, if needed to turn *ON* the SCR reliably. Changeover signal decides whether to

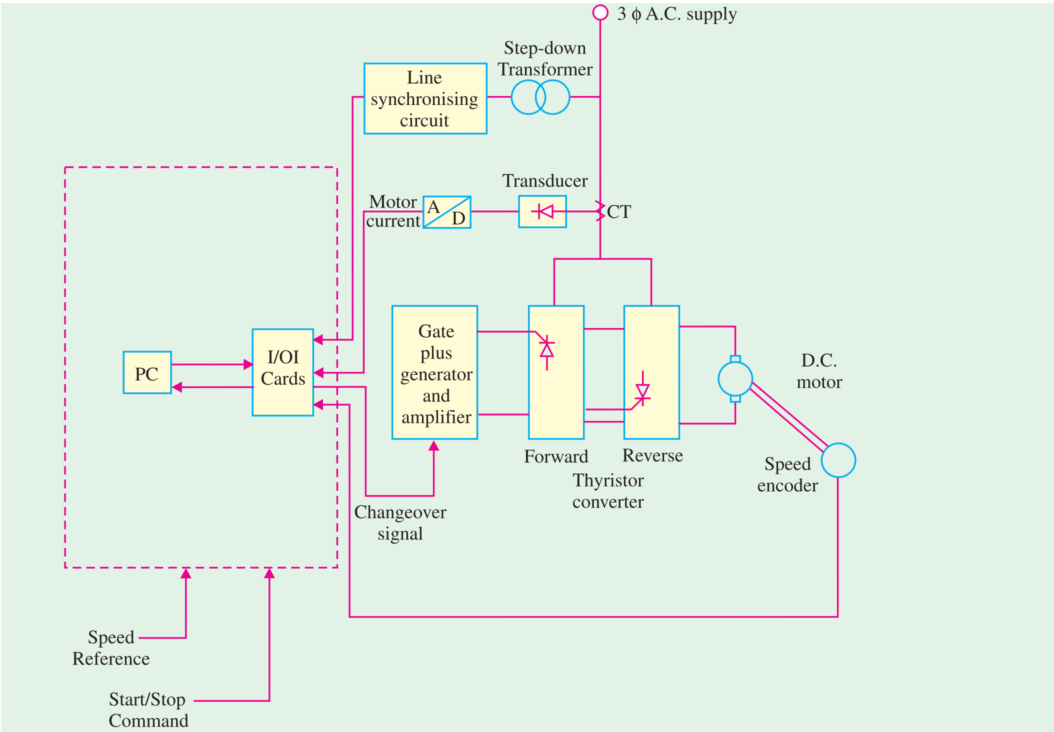


Fig. 46.8

switch *ON* forward or reverse group of SCRs. The gate pulse generator is shown as receiving a firing signal from *PC*.

(iii) Speed Encoder and Input Module

The speed information can be fed to PC through speed input module. The speed measurement is done digitally by means of speed/shaft encoder. It consists of a disc with definite number of holes drilled on it. This disc is fixed on to the shaft. Using a light source and a phototransistor; a series of pulses is obtained, as the shaft rotates. This pulse train is processed and shaped. These optically coded pulses are counted to get actual speed of motor.

(iv) A/D Converter and Transducer

The motor current drawn from supply is stepped down with the help of current transformer. It is converted to D.C. voltage output with the help of current transducer. As PC can't process analog signals, this analog current signal is fed to A/D converter to obtain digital signal which is fed to PC.

(v) Line Synchronizing Circuit

This is required so that PC can synchronize the generation of firing pulse data, with supply line frequency.

(vi) I/O Cards

Input/ Output cards are required to interface PC with the outside world.

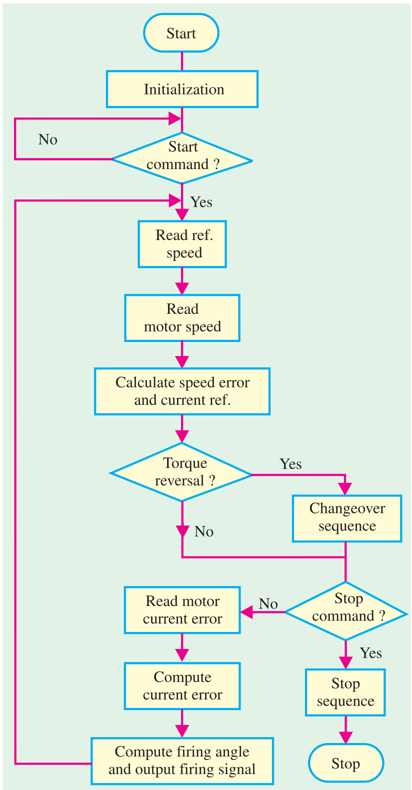


Fig. 46.9. Program flow chart for digital control of motor.

OBJECTIVE TESTS – 46

1. The function of a cycloconverter is to convert
   (*a*) ac power into d.c. power
   (*b*) direct current into alternating current
   (*c*) high ac frequency directly to low ac frequency
   (*d*) a sine wave into a rectangular wave.
2. Major disadvantage of using three sets of SCRs for variable-voltage speed control of a SCIM is the
   (*a*) considerable I^2R loss
   (*b*) poor power factor
   (*c*) long delay of thyristor firing pulses
   (*d*) necessity of using a processor.
3. In the current-fed frequency converter arrangement for controlling the speed of an individual SCIM, the direction of rotation can be reversed by
   (*a*) changing the output frequency of the inverter
   (*b*) altering the phase sequence of pulses that trigger converter-2
   (*c*) interchanging any two line leads
   (*d*) reversing the d.c. link current.
4. In the chopper speed control method for a WRIM, the motor speed inversely depends on
   (*a*) fixed resistor across the rectifier
   (*b*) chopper switching frequency
   (*c*) chopper ON time TON
   (*d*) both (*b*) and (*c*).
5. In the synchronous motor drive using current-fed dc link
   (*a*) converter-2 functions as a self-commutated inverter
   (*b*) converter-1 works as an uncontrolled rectifier
   (*c*) converter-3 is a controlled rectifier
   (*d*) gate triggering of converter-2 is done at motor frequency.
6. In the three cycloconverter drive of a synchronous motor
   (*a*) each cycloconverter produces a 3-phase output
   (*b*) all cycloconverters act as voltage sources
   (*c*) a 3-phase controlled rectifier provides field exciting current.
   (*d*) air-gap flux is kept constant by controlling stator currents only.

ANSWERS

1. (*c*) **2.** (*a*) **3.** (*b*) **4.** (*d*) **5.** (*d*) **6.** (*c*)

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