CHAPTER

1 Basic of Electric Drive

Learning Objectives

- ✓ *To study historical development of electric drive*
- ✓ *To understand concept of electric drive including prominent features and description of basic elements*
- ✓ *To study classifications of electric drive types of*
- ✓ *To understand constant torque and constant power operation of electric drive*
- ✓ *To understand single and multi-quadrant operation of electric drive*
- ✓ *To study performance parameters of electric drive*
- ✓ *To study general overview of closed loop operation of electric drive by using analogue and digital control*
- ✓ *To study various sensing methods of current, speed and position*

1.1 INTRODUCTION

Mechanical machines are extensively used in various production processes to carry out specific jobs in industries. A drive is used to convert one form of power to mechanical power needed for imparting motion to mechanical machines. The drive is designated on the basis of prime mover used for imparting motion. Accordingly, steam drive, hydraulic drive and pneumatic drive had been widely used at early stage of industrial development. The drive incorporating an electric motor as prime mover is designated as electric drive. The electric drive possesses numerous advantages over other form of drives, such as high efficiency, fast dynamic response, wide speed control, smooth acceleration, braking and speed reversal, precise speed regulation, four quadrant operation, flexibility of constant torque and constant power operation and availability in extremely wide range starting from a fraction of a Watt to Mega Watts. The speed-torque characteristics of the electric drive can be easily modified to match the load torque characteristics of mechanical machines, thus, making drive suitable to connect directly or even making integral part of mechanical machines. The electric drive is generally operated in open loop if precise control of speed, position and torque is not required. Modern electric drives are invariably operated in closed loop. In past, analogue closed loop control was exclusively used in electric drives. Presently, the microcomputer based digital closed loop control is gaining popularity because of less dependency on hardware and flexibility in modifying software to meet control requirements. Electric drive is now extensively used at all power level in a variety of industrial, domestic and transport applications.

In this chapter, we will study basic of electric drive, such as configuration, classifications, operating modes, multi-quadrant operation and general over view of closed loop control. Sensing methods of current, speed and position will be reviewed in brief for completeness.

1.2 HISTORICAL DEVELOPMENT OF ELECTRIC DRIVE

A drive is used to provide adequate motion to a mechanical machine. The work horse of the drive is a prime mover whose type and configuration depends on the energy source from which it derives motive power for operation. At early stage of human civilization, hand drive was used for operating mechanical machines. Later on, water wheels and turbines were used. Water wheels were used in China as early as about 3000 BC. Later on, wind mills and after industrial revolution in late 18th century steam engines and internal combustion engines were employed for driving mechanical machines. The group drive in which many mechanical machines were connected to a single drive through shafts, belts and pulleys was the most widely used drive of that era because of restriction imposed by bulky and complex nature of prime mover. The energy conversion efficiency was very poor. The era of electric drive began with the invention of a dc motor in 1840s but it could not make much impact on industrial development till the end of the century because of constructional problems and also major emphasis at that time was to extend use of direct current for electrification. In 1870s single phase and then poly-phase ac motors (induction motor & synchronous motor) were invented. The electric drive employing dc motor was designated as dc drive and with ac motor as ac drive. Owing to easy and low-cost wide speed control ranges dc drive was preferred in industry as an adjustable speed drive. The ac drive, especially having the squirrel cage induction motor has many good features, but the speed control was very complex and costly, therefore, the induction motor drive was generally used as a constant speed drive.

Though speed control of dc drive was easy by applying variable dc voltage to armature but it was troublesome to obtain variable dc voltage from the constant voltage dc supply. Initially, Motor-Generator (MG) set and Synchronous Converter were used to get variable voltage dc supply. Ward Leonard control using induction motor- separately excited dc generator set as a variable dc voltage source for wide and fine speed control of separately excited dc motor is a typical example that had been very popular in pre and post solid state electronics era. Once, three phase ac system was established as the most economical means of power transmission and distribution, efforts were made to obtain variable dc voltage from constant voltage ac supply. The age of power electronics started with the invention of Mercury Pool Rectifiers in the beginning of 20th century. A Mercury Arc Rectifier was the first element in this series. The Mercury Arc Rectifier was widely used in high power field, such as electric traction, steel and mining industries. Gradually Excitron and Ignitron were developed. Thyratron Tube, a gas filled device, was invented in the 1930s. In the meantime technology of Saturable Reactor and Magnetic Amplifier was developed. In addition to these devices, cross field amplifiers, namely, Amplidyne and Metadyne were introduced in the 1940s. They provided two stage amplification. The Metadyne was a constant current amplifier and generally used below 20 KW. The Amplidyne was a voltage amplifier with high amplification factor and extensively used for speed control of high power dc drives in pre and post solid state electronics era. All these devices have become obsolete and do not exist now.

For speed control of three phase induction motor, various methods, such as pole changing method, cascade control, stator voltage control, cycloconverter control, rotor resistance control and slip power recovery control were employed but range of speed control was limited. The supply frequency control with constant voltage to frequency ratio was used for wide speed control but getting variable frequency ac supply had always been a major task. The synchronous generator/ induction generator driven by a dc motor were first employed as variable voltage variable frequency ac source. These schemes provided wide speed control range of 10:1 to 12:1 with high smoothness control but on the expense of very high cost because three machines of higher ratings than the motor rating were needed. The variable voltage variable frequency supply was also obtained by using induction frequency converter and synchronous-induction frequency converter but again needed two additional machines, involving high cost. Based on the concept of EMF injection and commutator frequency conversion, three phase doubly fed motor and Schrage motor were developed. Doubly fed motors were available in wide power ratings from tens of KWs to several MWs and speed control range of the order of 5:1. The power rating of Schrage motor was limited to about 20 kW due to commutation difficulties and had speed control range of the order of 3:1.

The invention of electric motors initiated a new stage of development in the industry. The very first effect was replacement of group drive by an efficient individual drive. It could be possible to place drive near to the mechanical machine and even make its integral part, thus, gained flexibility of operation independent to other machines. In the beginning of the 20th century, various electromechanical components, such as contactors, relays etc, were developed which facilitated implementation of open loop and closed loop automatic control of drive operations, viz. starting, speed control, braking and speed reversal which had been accomplished earlier manually. Consequently, it could be possible to perform various operations of working machines sequentially in a cyclic manner with remote control and bestowed a new horizon to the industrial development.

A modern age of solid state control of electric drive started with the invention of a fast acting controlled semiconductor device, namely, silicon-controlled rectifier (SCR), generally known as thyristor, by Bell Laboratories in 1956 and commercially introduced by General Electric Company in 1958. Since then there has been phenomenal growth in the technology of various aspects of electric drives which can be broadly categorised as (1) advances in power converter topologies, (2) control of electric drives.

Advances in Power Converter Topologies

Following invention of SCR several power semiconductor devices have been invented. Out of them SCR, TRIAC, Gate Turn off Thyristor (GTO), Insulated Gate Commutated Thyristor (IGCT), Power Transistor, Power MOSFET and Insulated Gate Bipolar Transistor (IGBT) are commonly used. Until 1970s, thyristor had been exclusively used in power converters for drive control. Now, its use is limited to ac to dc phase controlled converters, high power cycloconverters and load commutated inverters. TRIAC is widely used in low power ac voltage controllers. GTO and IGCT find wide applications in medium and high power voltage fed and current fed inverters and replaced thyristor in most applications. Power transistor and power MOSFET are used in small power while IGBT in small and medium power dc to dc and dc to ac converters.

Power converters using power semiconductor devices are classified as phase controlled ac to dc converters, ac to ac converters (cycloconverters & ac voltage controllers), dc to ac converters (voltage and current source inverters) and dc to dc converters (choppers). Phase controlled ac to dc converters convert fixed ac voltage supply into variable voltage dc supply. They can also act as a line commutated inverter to transfer load dc power to ac source. AC voltage controllers convert fixed ac voltage into variable ac voltage out at constant frequency. On the other hand, cycloconverters convert fixed ac voltage supply directly into variable frequency (up to half of the supply frequency) variable voltage ac supply. Voltage and current source inverters convert constant voltage dc supply into variable voltage variable frequency ac supply. Since, high dc power is not readily available, ac power supply is generally used and two step power conversion first from ac to dc and second from dc to ac is employed. DC- dc converters convert constant voltage dc supply into variable voltage dc supply. With the advent of high frequency IGBTs, PWM techniques are now very popular in drive control. Out of various PWM techniques, sinusoidal PWM, hysteresis-band instantaneous current control PWM and space vector modulation (SVM) are commonly used. PWM inverters can operate both in rectification and inversion modes and eliminate problem of poor power factor and harmonics in line which occur in phase controlled converters. GTO based large power current-fed inverters operating in PWM mode are also becoming popular.

Advances in microelectronics led passage for the development of application specific ICs (ASICs), dedicated gate/base drive ICs and power integrated circuits (PICs). A standard ASIC provides improved performance and translates "real estate" on the chip. A gate/base drive IC integrates most of the control functions including protection functions against overloads and faults. Gate/Base driver ICs simplified control circuitry of power devices A PIC integrates power device structures with driver and protection circuits on the same chip and loosely defined as "smart power". The main advantages are compactness, reduction in cost and improved reliability. Some prominent PICs are two phase stepper motor driver, one quadrant chopper for dc motor drive, three phase brushless motor driver and three phase diode rectifier-PWM inverter. The advent of microprocessors, microcontrollers and digital signal processors have revolutionized drive control. These processors perform various control functions, such as gate/base drive control, closed loop control of current, speed, position etc. PWM control, sequencing control, on-line parameter and state estimation and many more. Now, it could be possible to realize sophisticated control schemes, such as vector control, sliding mode control, expert, fuzzy and artificial neural network controls and other adaptive and optimal control schemes.

Control of Electric Drives

DC Drives: Single phase converters are used for control of small dc drives and traction drives while three phase converters are used for large dc drives. For one quadrant operation of dc drives, semi-converter is used because it provides smooth voltage control and higher power factor. A full converter is used where two quadrant operation of dc drives is required. A dual converter control, which is the static form of the popular Ward-Leonard control, is used to provide four quadrant operation of dc drives. The chopper control is generally used for small dc drives when input is dc supply, for example, battery supply and photo-voltaic power supply. It can provides one, two and four quadrant operation of dc drive

AC Drives: All speed control methods of induction motors existed in pre thyristor era, such as stator voltage control, rotor resistance control, slip power recovery control and cycloconverter control have been replaced by using thyristor and GTO devices. These methods except cycloconverter control are suitable for limited speed control in neighbourhood of the synchronous speed. The cycloconverter control is used for high power induction and synchronous motor drives operating at low speed, such as in steel mills, cement mills, ship propulsion fans/pumps. With VSI control it is possible to have constant torque operation below the base speed and constant power control above the base speed. VSI fed drives are the most popular drives in low and medium power applications. The CSI control and slip power recovery control (static Kramer and Scherbius control) are used for several hundred kW motors. Vector control drives are generally used for high performance applications. Recently, direct and flux control, generally called DTC control which was proposed in 1980s, is gaining popularity because it gives fast response and easy to implement due to absence of closed loop current control, traditional PWM algorithm and vector transformation. But it has demerits of pulsating torque, pulsating flux and additional motor harmonic losses.

Synchronous Motor Drives: Cycloconverter, VSI, CSI, Vector control and direct torque control techniques used for speed control of induction motor drives are also used for speed control of synchronous motor drives. The cycloconverter controlled synchronous motor drive is preferred to induction motor drive in large power, low speed applications because input power factor can be improved even up to unity by increasing excitation. An over excited synchronous motor can operate in self-controlled mode when it is supplied from a load commutated inverter. The synchronous motor along with load commutated inverter operates similar to a dc motor. It is popularly known as ***commutatorless dc motor***. Similarly, an inverter fed permanent magnet synchronous motor with trapezoidal air gap MMF distribution and rotor position sensor operating in self-controlled mode is popularly called ***brush less dc motor (bldc)***. In 1980s ***switched reluctance motor*** has been developed which has both salient pole stator and rotor similar to a stepper motor. The stator poles carry concentrated coils while rotor is unexcited. The phase windings are excited in sequence by using rotor position sensing. The motor has more rugged construction than a squirrel cage induction motor and finds application where precise speed control is not required.

The VSI control providing wide range of speed control below and above the base speed transformed both induction and synchronous drives as adjustable speed drives and changed the belief that these are constant speed drives.

The most modern electric drive of today is the outcome of successive development of the drive over many centuries.

1.3 CONCEPT OF ELECTRIC DRIVE

Mechanical machines are widely used in various industrial, agriculture, transportation, domestic and other applications. They are required to perform a set of define operations as demanded in a technological process. The motion control is an integral feature of most of the mechanical machines. The driving mechanism used to impart adequate motion to the mechanical machine is called 'drive'. The main element of the drive is a prime mover that imparts motion to the mechanical machine. The drive employing electric motor as a prime mover is called 'electric drive'. It is defined as,

"An electric drive is a set of interconnected elements that converts electrical power into mechanical power and feeds to the mechanical machine and also provides necessary control as demanded in operation". Thus, it can be said that a drive system is a cascade connection of electric drive and mechanical machine in which the drive supplies motive power to the mechanical machine. As the mechanical machine in operation applies torque on the motor shaft or loads the motor, it is usually called a mechanical load or simply a load.

Elementary Electric Drive

The elementary electric drive used to have three elements namely, the power modulator or Power converter, the electric motor and the power transmitting system. Owing to limited speed control range of electric motors, there was a problem of speed mismatch between the motor and the mechanical machine. Therefore, a power transmission system having shaft, belts and pulley or gear arrangement was connected at the motor shaft to match speed of the motor with the mechanical machine. With the development of efficient power converters and speed control techniques it could be possible to operate electric motors over a wide speed range. The power transmitting element is now almost eliminated. This type of drive is not used, now a days, in industry for manufacturing processes.

Open Loop Adjustable Speed Electric Drive

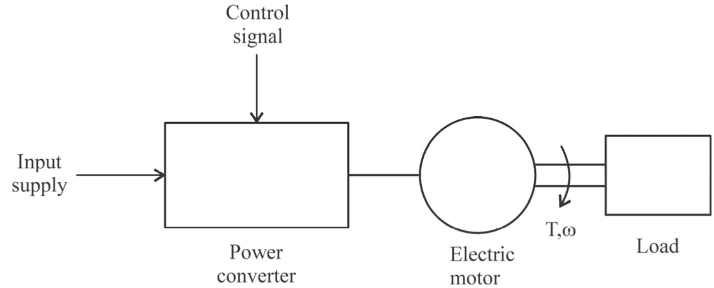

FIGURE 1.1 Block diagram of an open loop adjustable speed electric drive system.

A block diagram of a basic open loop adjustable speed electric drive system is shown in figure 1.1 It consists of a power electronic converter, an adjustable speed electric motor and a mechanical load. Since, the motor speed can be smoothly varied over a wide range, it is directly connected to the shaft of the mechanical machine. The mechanical power transmission system is eliminated. However, in certain applications, such as requirement of the operation of the mechanical machine at extremely low speeds even fraction of an rpm the gear type power transmitting system is still used. The combination of power converter and electric motor constitutes an electric drive. The power converter modulates the input supply as required by the motor to provide speed-torque characteristics suitable to the load. This task is achieved by manually setting a control signal that generates gate/base drive signals which, in turn, controls operation of power semiconductor devices to produce adequate converter output. All operations of the motor, such as starting, braking, speed reversal, inching and jogging are controlled manually. Since, precise control of speed, position and other output variables is not possible, this type of drive is not used in industry for sophisticated machining processes where high quality of finished products is desired. However, this drive is used for general applications.

Modern Electric Drive

In modern industry, automatic control of electric drive is required for precise control of speed, position, and torque and other variables of the mechanical machine to increase productivity and to ensure high quality of finished products. Therefore, closed loop control is an inevitable feature of the modern electric drive. A block diagram of a typical modern electric drive is shown in figure 1.2. The modern drive system consists of a power converter, an electric motor, a mechanical load, a controller and equipment used for sensing output variables, such as speed, position, current etc. to be controlled. The brief description of drive elements is as follows:

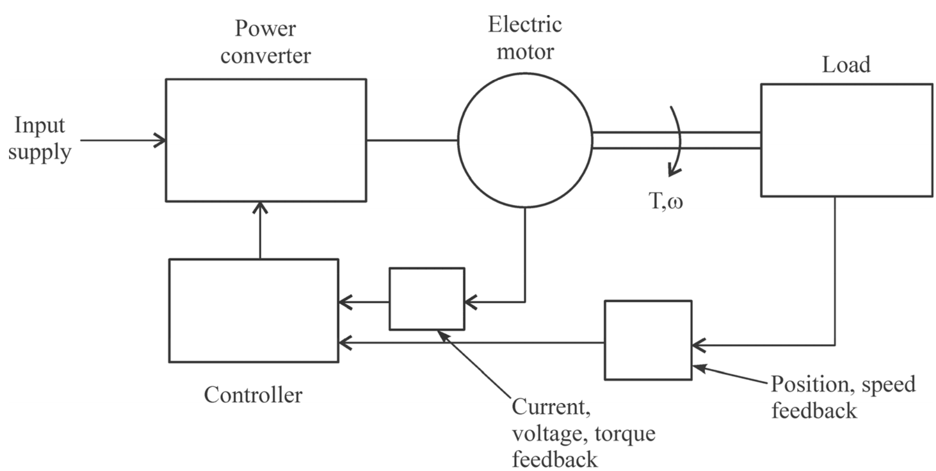

FIGURE 1.2 Block diagram of a modern electric drive.

The electric motor converts electrical power into mechanical power and provides various operations, such as starting, braking, speed control, speed reversal, inching and jogging to the mechanical machine as demanded in operation. DC motors, single and three phase induction motors and three phase synchronous motors are generally used. But for special applications stepper motors, brushless dc motors, two phase ac motors are used.

A power converter is mainly a two port equipment that has one input port and one output port. It receives power at the input port from a source either ac or dc and converts in the form either dc or ac at the output port in the usable form suitable for operation of the motor. For example, it may convert constant voltage ac to variable voltage dc; constant voltage dc to variable voltage dc; constant voltage dc to variable voltage/variable frequency ac; constant voltage ac to variable voltage constant frequency ac or variable voltage variable frequency ac.

The controller controls output power of the power converter by generating adequate control laws and algorithms such that motor matches the load demand. The configuration of controller for a particular drive depends on the type of power converter used and type of control needed. A controller consists of a control unit and gate/base drive unit. The control unit receives feedback signals of variables (speed, current, position, flux, torque) to be controlled from motor and load and also corresponding reference variables. It manipulates these signals and implement suitable control laws to generate a control signal to decide gating strategies for adequate operation of the power converter. It also selects mode of operation of motor, such as starting, braking, speed / position control, speed reversal, inching and jogging etc. It also controls cyclic operation of the mechanical machine. Besides, it provides protection to power converter and motor.

1.4 DESCRIPTION OF ELECTRIC DRIVE ELEMENTS

1.4.1 Power Converter

A power converters is a power electronics based equipment. It consists of one or more power semiconductor devices arranged in a set matrix form that are switched on and off in a sequential manner to produced desired output. Power Diodes, SCRs, GTOs, Power Transistors, Power MOSFETs and IGBTs are commonly used in power converters. The gate/base drive signal controls the switching on and off of power semiconductor devices. A power converter is a generic term used for both rectifier and inverter. When it is used for ac to dc conversion, it is called as a rectifier whereas for dc to ac conversion it is called as an inverter. Presently, power converters are invariably used in industry because they have advantages of fast response, high efficiency, reliability and adaptability to any control strategies. The following power converters are used for driving electric motors.

AC to DC converters

Fully controlled converter: The converter of figure 1.3(a) is a fully controlled (single phase or three phase type) converter. It can provide positive or negative variable dc voltage output with unidirectional current. Therefore, it is widely used for control of dc motors for motoring, braking and speed reversal operations. They can also be act as a line commutated inverter and return mechanical power of the motor to the ac supply. Thus, they are capable to provide two quadrant operation (motoring and regenerative braking) of the motor. By connecting two such converters in anti-parallel configuration four quadrant operation i.e. motoring and braking operations in both directions of rotation of motor is achieved. SCRs are generally used as power switches. The input supply current waveform is distorted and power factor is very poor at low dc output voltage**.** To improve quality of supply current waveform and power factor, GTO/IGBT based PWM converters that are capable to operate as a rectifier and an inverter are gaining popularity.

Half controlled converter: The **c**onverter of figure 1.3(b) is a half controlled (single phase or three phase type) one quadrant converter. It can only provide positive variable voltage dc output and, hence, it is suitable only for motoring operation of dc motors. SCRs are generally used as power switches. It provides smoother voltage control and better input supply power factor than its counterpart fully controlled converter.

DC to DC Converter or Chopper: The **c**hopper of figure 1.3(c) is used to provide variable voltage dc output supply from constant voltage dc supply. It can produce output voltage less than or higher than the input voltage and accordingly it is called step-down or step-up chopper respectively. There are one, two and four quadrant configurations of the chopper. Therefore, they are capable of providing one, two or four quadrant operation of dc motors. Power Transistors and Power MOSFETs are generally used for low power applications, IGBTs and GTOs for medium power applications.

AC to AC fixed frequency converter (AC voltage controller): The ac voltage controller of figure 1.3(d) provides variable voltage ac supply from a fixed ac supply at the same frequency. The fine control of output voltage can be obtained but the output voltage is rich in harmonics when reduced to low values and input supply power factor is poor. AC voltage controllers find applications for voltage control of single and three phase induction motors. SCRs are generally used as power switches in ac voltage controllers for speed control of small three phase squirrel cage induction motors and TRIACs for speed control of single phase induction motors.

DC to AC converter (Inverter): The inverter of figure 1.3(e) provides variable voltage or current single phase or three phase ac output at variable frequency from a dc input supply usually a battery or photo-voltaic generator. The inverter employ power transistor, power MOSFET, GTD and IGBT as power switches. Owing to availability of limited dc power, It finds application for speed control of induction motors in low power applications, such as water pumps, subway cars, trolley buses.

AC to AC two step converter (Dc link inverter): Since, output dc power available from a dc battery or a photovoltaic converter is not sufficient for speed control of medium and large power ac motors, the dc supply is obtained from ac supply by using rectifier The inverter of figure 1.3(f) is a two step -converter. At first step, the ac input supply is converted into constant or variable voltage dc output by using uncontrolled rectifier or controlled converters respectively. At second step, the dc voltage is converted into variable voltage variable frequency ac output. Such converter is designated as dc link inverter. GTO, and IGBTs are used as power switches.

The output frequency of the inverter is limited on the type of power device used. An inverter is designated as voltage source inverter or current source inverter depending on input dc is a constant voltage or constant current. Both types of three phase inverter have six step ac output which is rich in lower order harmonics. As a result, additional heating and torque pulsation occur in the motor. A low pass bulky filter is needed at the motor terminals to suppress these harmonics. Various pulse width modulation (PWM) techniques, such as sinusoidal PWM,, selected harmonic elimination PWM, state vector modulation PWM, hysteresis band current controlled PWM and trapezoidal PWM are generally used to eliminate/ reduce lower order harmonics leading to current waveform nearly sinusoidal but at the cost of increased switching losses.

AC to AC one step converter (Cycloconverter): The cycloconverter of figure 1.3 (g) is one step converter that converts constant voltage constant frequency ac input directly into variable voltage variable frequency ac output. The frequency is usually limited up to 50% of the input frequency. At low frequency operation large distortion occurs in voltage waveform. Cycloconverters employ line commutated SCRs as power switches However, for increasing frequency of operation, self -commutating devices, such as GTO and IGBT are used. Owing to high cost, cycloconverters find applications for operating low speed high capacity three phase induction and synchronous motors where their cost is justified

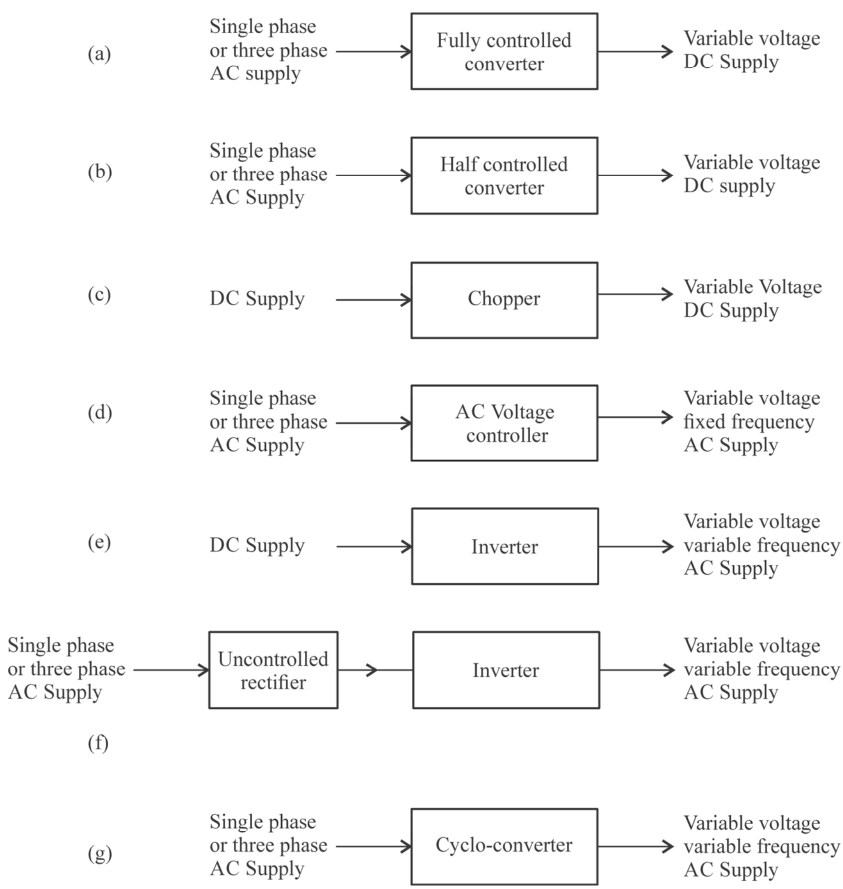

FIGURE 1.3 Block diagram representation of different power converters.

Power converters suffer from problems of distortion of output voltage, generation of harmonic into power supply and interference with communication and signalling circuit. Owing to distorted supply, torque pulsation occurs and additional heat is generated in the motors, resulting in, de-rating capacity of motors to ensure thermal heating within the safe limit.

Low power converters are also available as a single unit or a module consisting of two, four or six power devices in a particular arrangement from application point of view. These modules offer numerous advantages, such as low on-state losses, high speed and high voltage/high current characteristics. Presently, power converters for low power applications are also available in the form of intelligent modules in which power circuit, gating and control circuit integrate into a single unit. The users need only to connect external power source.

1.4.2 Electric Motor

Following electric motors are used in electric drive:

DC Motors: Shunt motor, series motor, compound motor, separately excited and permanent magnet motors, PCB motor.

AC Motors:

Induction Motors: Single phase motor, three phase squirrel cage and slip ring (wound) motors, linear induction motor, universal and series compensated motor, two phase ac servo motor.

Synchronous Motors: Wound rotor motor, salient pole motor, permanent magnet sinusoidal and brushless motors and linear synchronous motor.

Variable reluctance Motors: Reluctance motor, switched reluctance motor, stepper motor.

Dc motors have advantage of easy, low cost smooth wide speed control range. Traditionally, dc motors have been designated as adjustable speed motors because of their wide speed control range. But owing to mechanical commutator and brushes, the highest operating speed is limited due to sparking problem. They also need frequent maintenance.

Induction motors, though rugged in construction and cheaper than their counterpart dc motors, their speed control is complex, less efficient and costly. Traditionally, in past they were mostly used for constant speed applications. Presently, due to advancement of power electronics technology, it could be possible to operate induction motors over wide speed control range. They are replacing dc motors in several applications

Synchronous Motors have advantage of improved power factor by adjusting field current. They have higher full load efficiency but costlier than induction motors for the same rating. From economic point of view their application for small and medium power applications is restricted. They are usually built for low speed and high ratings where they are cheaper than induction motors and also have advantage of power factor improvement.

All conventional dc and ac motors are available from a fraction of kilowatt to megawatt power ratings. The permanent magnet dc and ac synchronous motors, synchronous reluctance and switched reluctance motors are generally available up to 150 kW and higher rating motors are uneconomical. They are used only for specific purposes. Single phase induction motors are available up to 5 kW rating.

The permanent magnet brushless dc (BLDC) motors have special features like wide speed control range, high dynamic performance and simple control and cost effective. Presently, they are becoming more attractive option than induction motors. They have also become more viable option to replace dc or two phase ac servo motor due to their quick response, light weight and large continuous and peak torques.

1.4.3 Controllers

Process controllers are used in closed loop electric drive to improve transient response of speed, position, current etc. They are generally inserted in the forward path of the control system to act on the actuating error and generate control signal to control power converter output such that desired output specifications are met. Out of the various process controllers, proportional (P), proportional-integral (PI) and proportional-integral-derivative (PID) controllers are preferred in drive control. The P- controller provides fast response but steady state error is not zero. The PI controller provides fast response and zero steady state error if parameters are properly selected. Low integral action leads to steady state error and higher integral action increases settling time and even lead to instability. The PI controller works well against small disturbances around the steady state. The PID controller reduces overshoot, improves response and zero steady state error. It works well against large disturbances. The PI controller is generally used for speed control and P controller for current control. Recently, artificial intelligent (AI) techniques, namely, expert system, fuzzy logic, neural network, genetic algorithm are gaining popularity in drive control. All these techniques are realized in the controller block. For sophisticated control and real time control of electric drives, the present trend is to use microprocessor, microcontroller and digital signal processor.

1.5 SALIENT FEATURES OF ELECTRIC DRIVE

Electric drives are widely used because of following advantages in comparison to other type of drives.

- Electric drives are available in extremely wide power range from a fraction of watt for electric watches to hundreds of megawatts for driving pumps in hydro-electric plants. Motor torque and speed are available as high as of the order of 10^6 N-m for rolling mills and 10^5 rpm for centrifuge loads.
- Electric drives provide fast, easy, precise and continuous control of speed, position and torque of loads with good dynamic performance.
- Electric drives have high efficiency usually greater than 70% due to low or no load losses of electric motors.
- Electric drives are capable to operate in all four quadrants of torque-speed plane with a facility of power feedback to source using regenerative braking as desired in electric traction, mine hoist etc. This facility is unique and not available in other types of drive.

- Electric drives provide smooth acceleration, braking and speed control of loads. In fact, any desired sequence of operation can be obtained by employing real time control using computers.
- Electric drives are flexible in operation i.e., they can provide constant torque or constant power operation over wide speed range as per demand of loads.
- Electric drives are also available in linear operational form suitable for propulsion of high speed vehicles.
- Electric drives are made in variety of designs to make compatible with loads. Sometimes, they can even be made an integral part of loads, such as centrifugal pump and drive are made compact in size.
- Electric drives are highly clean and do not produce environmental pollution at the point of application.
- Electric drives are suitable for wide variety of ambient conditions, such as hazardous and radioactive environments, submerged in liquids etc.
- Electric drives produce smooth torque, therefore, vibration and noise are greatly reduced in comparison to other drives.
- Owing to absence of idling and warming time electric drives can be quickly put in the service.
- Electric drives are compact in size require less maintenance and have long life

Though electric drives possess too many salient features but suffer from following limitations:

- Electric drives need continuous electric supply for the operation. Therefore, their use is restricted to only those places where electric supply is available. However, they can be made operative at such places by providing some alternative source of electric energy, such as lead acid batteries for operation of road vehicles, photovoltaic converters for operation of small water pumps and diesel generator set for propulsion of train on non-electrified routes etc.
- Electric drives become immediately inoperative in the event of power failure. This problem is severe in electric traction where electric trains stop as soon as the power failure occurs.
- Electric drives produce limited tangential force per unit surface of the rotor due to magnetic saturation of iron core and cooling condition of electric motors. Therefore, electric drives are less preferable in those applications involving large force and short stroke in comparison to hydraulic drive.

1.6 CLASSIFICATIONS OF ELECTRIC DRIVE

Electric drives can be classified in various ways. Only following types of classification will be discussed.

1.6.1 Inter relationship with Load

This classification is based on historical development of industries. At preliminary stage of industrialization, mechanical machines were required to operate at few discrete constant speeds. Therefore, from economic point of view, a group of loads were operated from a single drive through belts, pulleys and shafts arrangement. Further industrial development necessitated individual drive for each mechanical machine and later on necessity arose to have more than one motor for complex and sophisticated mechanical machines. Electric drives are accordingly classified as group drive, individual drive and multi motor drive which are discussed below:

1.6.1.1 Group drive

It consists of a single motor that operates a group of mechanical machines with the help of shafts, pulleys and belts. In this arrangement, the motor operates a line shaft on which number of pulleys are mounted. Each pulley is connected to a multi stepped pulley mounted on the machine shaft through belt. The multi stepped pulley facilitates the machine to operate at two or three discrete speeds. The drive has following merits and demerits.

Merits

- It is the most economical drive because a motor of smaller rating is needed than the aggregate rating of all mechanical machines connected to the motor due to diversity in their operation time.
- Overload capacity of the drive is high. Even hundred percent overload on one mechanical machine will reflect only small loading on the motor.

Demerits

- Any fault in the motor stops all the mechanical machines connected to it.
- Drive efficiency is low because of appreciable power loss occurring in power transmitting mechanism.
- The speed control of individual mechanical load is troublesome.
- The drive does not have clean appearance because of crowding of shafts, pulleys and belts. The drive occupies more space.
- The layout of mechanical machines depends on the layout of shafts, pulleys and belts, therefore, flexibility is lost.

Owing to these demerits, this drive presently is not used in industry. However, such drives still find applications in small cottage industries where economy factor predominates.

1.6.1.2 Individual Drive

It is a drive in which a single motor is employed to operate various mechanism of a mechanical machine. This drive has numerous applications for driving household equipment, such as fans, washing machines, refrigerators, air-conditioners, driving machine tools/ mechanism, such as lathe, drilling machine, shaper, planer etc., and so many industrial applications. The drive has following merits and demerits:

Merits

- Any trouble in the motor stops operation of only the mechanical machine connected to it.
- The efficiency is high.
- The drive can be placed very close to the mechanical machine even its an integral part. For example, a submerged pump and motor are integrated as a compact unit.
- Precise and efficient speed control of mechanical machine is possible. The closed loop operation can also be easily implemented.

Demerits

- Various mechanisms of the mechanical machine are operated through gear arrangement where power loss occurs, for example, in a lathe, a single motor runs spindle, feed and lubricating pump through gear arrangement.
- Flexibility of speed control of individual mechanism of the mechanical machine is limited.

1.6.1.3 Multi Motor Drive

The drive consists of a number of motors, each motor driving independently one mechanism of the mechanical machine, therefore, independent speed control of all mechanisms can be made. For example, in a travelling crane, three motors are used, one for position, second for forward motion and third for cross motion. This drive is usually used for driving complex mechanical machines and processes, such as rolling mills, paper mills, sophisticated metal cutting machine tools and robotics.

The individual and multi motor drives are backbone of modern industry. They have helped automation of production processes and increased productivity.

1.6.2 Type of Motor Used

Electric drives can also be classified on the basis of type of motor used in the drive. The drive having dc motor is called dc drive and having ac motor as ac drive. The relative advantages and disadvantages of dc and ac drives are given below:

1.6.2.1 DC Drive

Advantages

- Speed control is simple and economical.
- Wide speed control range below and above the rated speed is possible.
- Power converter is simple and inexpensive.
- Starting torque is high, therefore, it is suitable for rapid acceleration and deceleration of heavy load, such as electric traction.
- Implementation of constant torque and constant power operation is simple.
- Technology is well established.
- Drive has fast response.

Disadvantages

- Motors are costly.
- Drive is unsuitable for dusty and explosive environment applications.
- Power to weight ratio is small.
- Motors have mechanical commutator and brushes rubbing on it. At high speed, spark takes place on commutator that restricts the highest operating speed. The operating voltage is usually limited to 600 to 750 volt.
- Frequent maintenance is required.
- If drive is operated on ac supply using controlled converter, the supply current gets distorted and power factor becomes poor.

1.6.2.2 AC Drive

Advantages

- Drives are cheap, though cost of synchronous motor drive for same price is higher than induction motor drive but cheaper than the dc drive.
- Power to weight ratio of ac drive is high. It is 1.5 to 2 times of dc drive for the same rating.
- Squirrel cage induction motor has brushless rotor and robust construction that is best suited for any environmental conditions.
- Owing to absence of mechanical commutator, ac motors can be built for high operating voltages. Squirrel cage induction motor can be built even for more than 15 kV.
- Owing to low inertia, ac motors, particularly induction motors and brushless dc motors, can be built for high-speed operation. Squirrel cage induction motors having speed more than 10^5 rpm are available.
- Reliability is high.

Disadvantages

- Power converter is complex and costly.
- Speed control is complex.

For dc drive the cost of motor is high but the power converter and control system are cheap. Well established design technology is another advantage. On other hand, for ac drive the cost of motor is low but the cost of power converter is high and control system is complex. Presently, the overall cost of motor and power converter along with control system of ac drive is higher than its counterpart dc drive. The decreasing cost of power converter and control circuitry in future may result in cost of ac drive comparable to dc drive. The dynamic performance of ac motors particularly with vector control is comparable to dc motors. Precise and wide speed control is now possible. All these factors are making ac drive preferable to dc drive. As the trend exists, application of ac drives will further increase. However, dc drive will also continue for some more time due to their simple and wide range of speed control till the technology of ac motors matures.

1.6.3 Nature of Speed control

Electric drives are also classified on the basis of inherent speed-torque characteristics of the motor used as adopted by National Electrical Manufacturers Association (NEMA).

Constant speed drive: A drive which operates at any absolutely constant speed regardless of the load or as particularly constant speed where the speed may vary by a very few percentage 20% or less from no load to full load is termed as constant speed drive. Drives having synchronous motor, reluctance motor and plain squirrel cage induction motor are typical example.

Multispeed drive: A drive which can be operated at any one of the two or more definite speeds, each being practically independent of the load is called as multi speed drive. No gradual adjustment of speed is possible between these definite speeds. Drive having pole changing squirrel cage induction motor is a typical example

Adjustable speed drive: A drive in which speed can be varied gradually over a considerable range but when once adjusted remains practically unaffected by the load is called adjustable speed drive. Drives having separately excited motor, dc shunt motor, dc compound motor and induction motors are typical examples.

Varying speed drive: It is a drive in which speed varies with load ordinarily decreasing as the load increases. Drive having single phase ac series compensated motor is a typical example.

Adjustable varying speed drive: It is a drive the speed of which can be adjusted gradually, but once adjusted for a given load will vary in considerable degree with a change in load. Drive having dc series motor is a typical example.

1.6.4 Nature of Speed- Torque Characteristics

In general, all electric drives can be placed in following three groups on the basis of hardness of their speed-torque characteristics:

Absolutely Hard Characteristics Drive: Drive, in which speed does not vary with change in load torque i.e., the speed remains absolutely constant as shown in figure 1.4, is termed absolutely hard characteristics drive. Drives having synchronous motor, synchronous reluctance motor are typical examples.

Hard or Shunt Characteristics Drives: Drive, in which speed drops slightly with increase in load torque as shown in figure 1.4, is termed as hard or shunt characteristics drive. Drives having separately excited dc motor, dc shunt motor and single and three phase induction motors are typical examples.

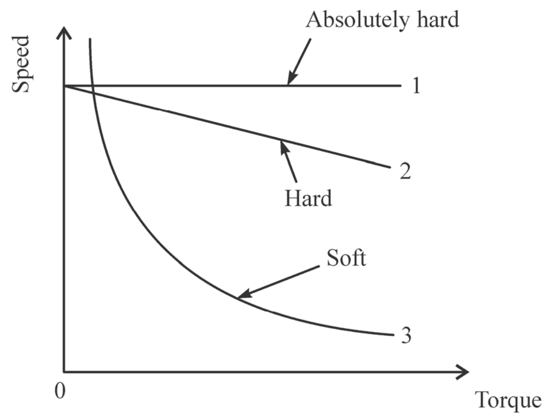

FIGURE 1.4 Speed-torque characteristics of different types of electric motors.

Soft or Series Characteristics Drive: Drive, in which speed drops considerably with increase in load-torque as shown in figure 1.4, is called soft or series characteristics drive. Drive having dc series motor, universal motor and single phase ac series compensated motor drives are typical examples.

Depending on degree of hardness of speed-torque characteristics, a compound dc motor drive may be considered as hard or soft characteristics drive.

1.7 QUADRANT OPERATION OF ELECTRIC DRIVE

1.7.1 Four Quadrant Speed-Torque Diagram

A four quadrant speed-torque diagram on which electric drive operates is shown in figure 1.5. For understanding multi-quadrant operation of drive, it is essential to know sign conventions of motor torque, load torque and speed. In speed-torque diagram, the speed is chosen positive when the motor is rotating in anti-clockwise or forward direction. For up-down motion of load, the speed is chosen positive when the load is moving upward. For reversible speed drives, the positive sign of the speed may be chosen arbitrarily. The motor torque is positive if it helps the motion and the load torque is positive if it opposes the motor torque. All the four quadrants have been numbered in conventional manner from I to IV.

In the IST quadrant, speed and torque are positive, so power drawn is positive. The motor draws power from the source and drives the load in the forward direction. It indicates forward motoring operation. In the IInd quadrant, speed is positive but torque is negative, the power is negative. The motor consumes mechanical power from the load, converts in the form of electrical power which is either returned to the source or dissipated as heat. It indicates generating or braking operation. In IIIrd quadrant, both speed and torque are negative, hence, power is positive. The motor draws power from the source and drives the load in reverse direction. It indicates reverse motoring operation. In IVth quadrant, speed is negative but torque is positive. The motor consumes mechanical power from the load, converts it into electrical power which is either returned to the source or dissipated as heat. It indicates reverse generating or braking operation.

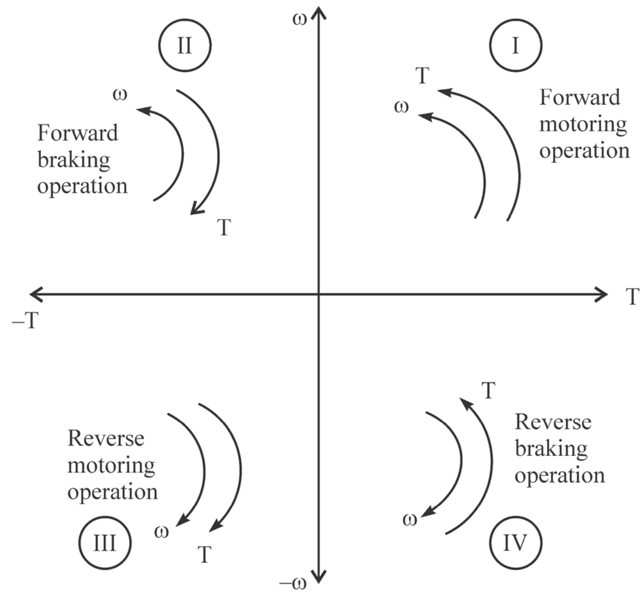

FIGURE 1.5 Multi-quadrant operation of drive in speed-torque plane

Based on quadrant operation, a drive is classified as one, two or four quadrant drive

1.7.2 Quadrant Type Electric Drive

One Quadrant Drive

A drive which is suitable for motoring operation either in I^{ST} or III^{rd} quadrant is called one quadrant drive. Such drive is used to drive small load. For stopping the load, the drive is switched off and the load comes to standstill due to mechanical friction. It is used in metal cutting machines tools, like Lathe, Grinder etc.

Two Quadrant Drive

A drive, capable to perform motoring and braking operations in forward or reverse direction of rotation is called two quadrant drive. Such drive is used to drive heavy loads and applies electric braking for stopping or reducing speed. The regenerative braking returns motor power to the source for stopping the load or holding at the safe speed under overhauling condition. A drive used for vehicle propulsion in up and down gradient of a track is a typical example.

Four Quadrant Drive

A drive capable to perform motoring and braking operations in both forward and reverse directions of rotation is called four quadrant drive. Such drives used in rolling mills, lifts and hoists are some typical examples. The operation of a typical four quadrant drive is explained in the next section.

1.7.3 Operations of a Four Quadrant Drive

The operation of a four quadrant drive is explained considering the drive is hoisting and lowering a load shown in figure 1.6. A rotating drum is attached to the drive motor shaft. A wire rope wound on the drum is connected to a cage at one end and to a counter-weight at the other end. The weight of counter-weight W_C is greater than the weight of empty cage W_0 but less than the weight of load W_L. The drive is required to raise and lower the loaded cage and empty cage. For simplicity, friction resistance is neglected. Since the load is of active nature having gravity effect, the load torque does not change sign on reversing the direction of rotation.

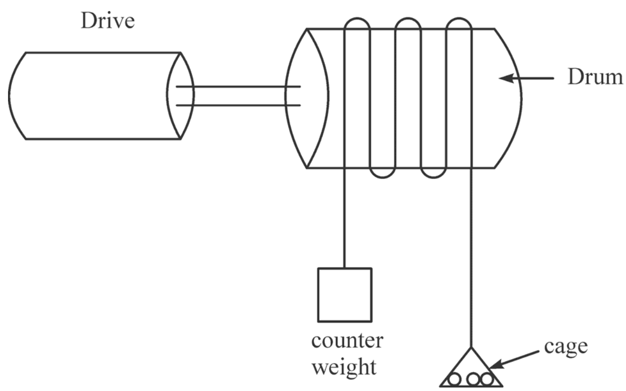

FIGURE 1.6 Drive operating a hoist load.

Load torque during raising and lowering the load

$$T_{L1} = (W_L + W_0 - W_C) \times r_d \tag{1.1}$$

Load torque during raising and lowering the unloaded cage,

$$T_{L2} = (W_C - W_0) \times r_d \tag{1.2}$$

Where r_d is the radius of the rotating drum.

The operation of drive in all the four quadrants as shown in figure 1.7 is explained below:

I[st] Quadrant Operation; Loaded Cage Raised

The load torque T_{L1} is acting downward. The motor torque T greater than T_{L1} is raising the loaded cage i.e. it is acting in the direction of the speed. It is forward motoring operation.

II[nd] Quadrant Operation: Empty Cage Raised

Since $W_C > W_0$, the net load torque T_{L2} is acting upward. It will automatically raise the empty cage with a velocity which may rise to dangerously high value. To have controlled raising of the empty cage, the motor torque must act opposite to the direction of speed i.e., the motor must switch over to braking mode. Since direction of speed is positive but the motor torque negative, the power drawn is negative. Hence, it is a forward braking operation of the drive.

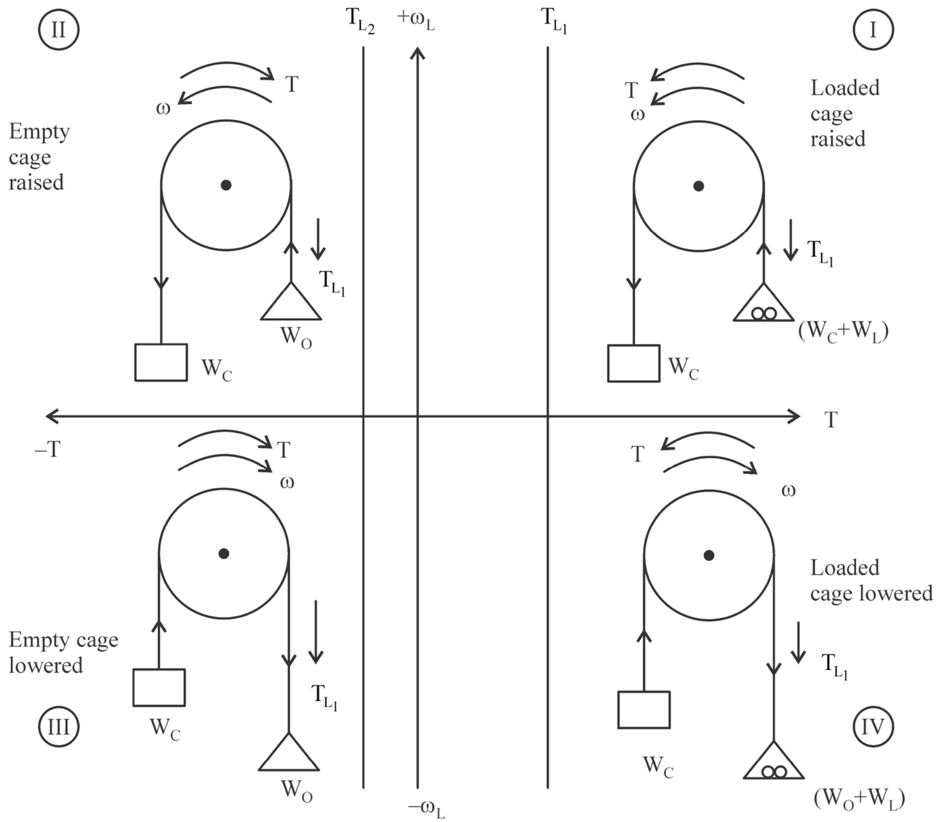

FIGURE 1.7 Four quadrant operation of electric drive driving a hoist load.

IIIrd Quadrant Operation: Empty Cage Lowered

For lowering the empty cage, the motor should rotate in reverse direction i.e., speed is negative. The net torque T_{L2} due to counterweight opposes the motion. Therefore, in order to lower the empty cage, the motor torque must act in the direction of speed. The power drawn is positive. Hence, it is a reverse motoring operation.

IVth Quadrant Operation: Loaded Cage Lowered

The load torque T_{L2} acting downward will automatically lower the loaded cage with a velocity, if not controlled, may reach to dangerously high value. The motor torque now must act opposite to the direction of speed i.e., the motor must switch over to braking mode. The speed is negative and the motor torque positive, the power is now negative. Hence, it is a reverse braking operation.

It is interesting to note that with gravity load, the two quadrant operation of drive takes place either in Ist and IVth quadrants for loaded cage or IInd and IIIrd quadrants for unloaded cage but not in Ist and IInd or IIIrd and IVth quadrants.

1.8 MODES OF OPERATION OF ELECTRIC DRIVES

Some loads need operation in wide speed control range. For wide range of speed control, electric drives are required to operate below and above the base speed

Constant Torque Operation

The constant torque mode of operation is characterised by maximum torque capability of the drive irrespective of variation in speed i.e., the drive should be capable to develop the maximum torque. The rated power of the drive is expressed as

$$P_R = T_R \times \omega_R \tag{1.3}$$

Where T_R and ω_R are rated torque and rated speed respectively. It is obvious from equation (1.3) that the constant torque mode of operation of the drive is possible below the rated speed only above that the motor gets overloaded.

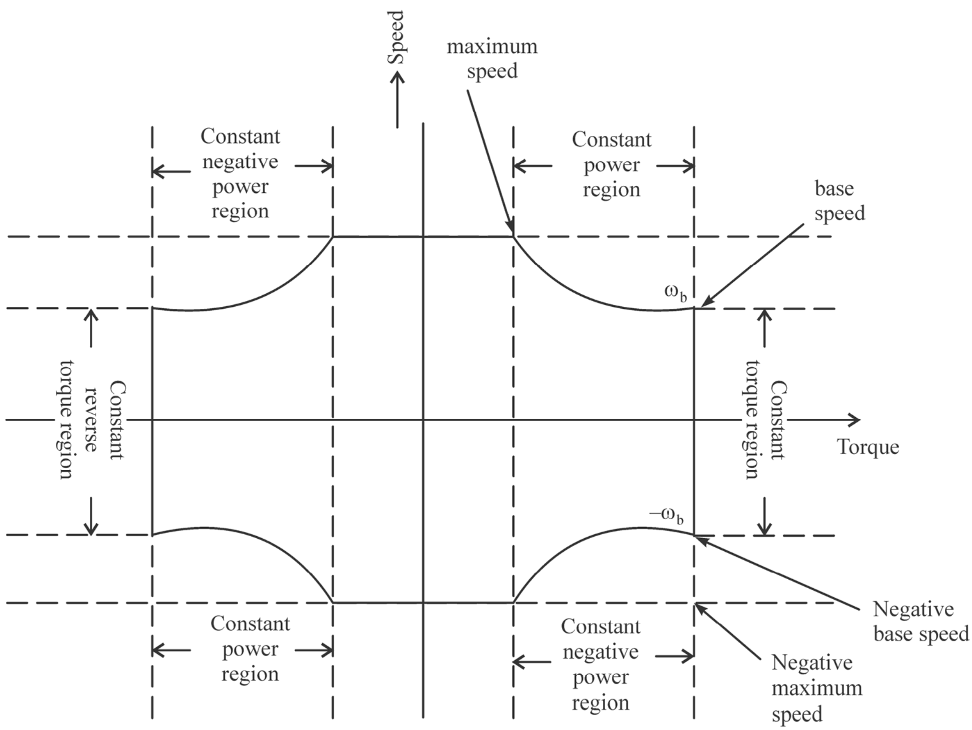

FIGURE 1.8 Speed, torque and power boundaries in constant torque and constant power modes of operation.

Constant Power Operation

The constant power mode of operation is characterized by the constant rated power capability of the drive irrespective of variation of speed. For drive operation above the base speed the developed torque should be reduced such that the rated power remains constant to avoid overloading of the drive.

Note that the terms "constant torque" and "constant power" refer to the maximum torque and maximum power capability of the drive respectively but not the actual torque and actual power which may vary within the capability limits. For reversible speed electric drive operating in constant torque and constant power modes, the speed, torque and power boundaries are shown in figure 1.8

1.8.1 Suitability of Electric Drives

Separately/Shunt Excited DC Motor Drive: In separately/shunt excited dc motors the developed torque is proportional to product of flux and armature current. Below the rated speed, flux is kept constant at the rated value, hence, the drive can produce the rated torque by setting the rated armature current. Thus, the constant torque mode of operation is achieved. The drive can be operated in constant power mode above the rated speed by reducing flux and keeping armature current at the rated value. The developed torque varies inversely proportional to speed, thereby, developed power remains constant. The constant torque and constant power modes of operation of separately/shunt excited motor drives are shown in figure 1.9.

DC Series Motor drive: In dc series motor, torque is high at low speed and decreases on increasing speed such that, the developed power is practically constant at the rated value. Therefore, dc series motor drive is inherently a constant power drive and operates only in constant power mode.

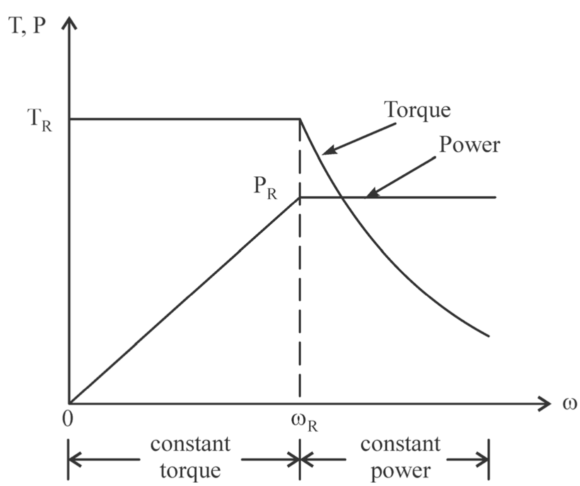

FIGURE 1.9 Constant torque and constant power operation of dc separately excited motor.

Three Phase Induction Motor Drive: Three phase induction motor drive operates slightly less than the synchronous speed. The wide speed control is achieved by varying frequency. Below the base speed, voltage to frequency (V/F) ratio is kept constant. Constant (V/F) operation results in constant air gap flux fairly down to low speed until stator impedance voltage drop becomes comparable to the supply voltage. The maximum torque being propositional to square of the air gap flux is also constant down to low Speed. The drive thus provides constant torque mode of operation. Above the base speed, the terminal voltage is held constant at the rated value and frequency is increased. The V/F ratio decreases that, in turn, decreases air gap flux and, hence, the developed torque. The developed power in the motor remains approximately constant resulting in constant power mode of operation. The constant torque and constant power modes of operation of the drive are shown in figure 1.10.

Three Phase Synchronous Motor Drive: In a three phase synchronous motor, the terminal voltage of the motor is approximately equal to the air gap voltage E_r assuming stator impedance voltage drop negligible. The resultant air gap flux can be held approximately constant down to very low speed. Hence, pull out torque of the motor remains constant from very low frequency to the base frequency, the motor runs in constant torque mode of operation. Above the base speed, speed is increased by increasing frequency keeping rated terminal voltage. For constant field excitation, the pull out torque of the motor falls off inversely with the speed resulting in constant power mode of operation. The constant torque and the constant power modes of operation of the synchronous motor drive are shown in figure 1.11.

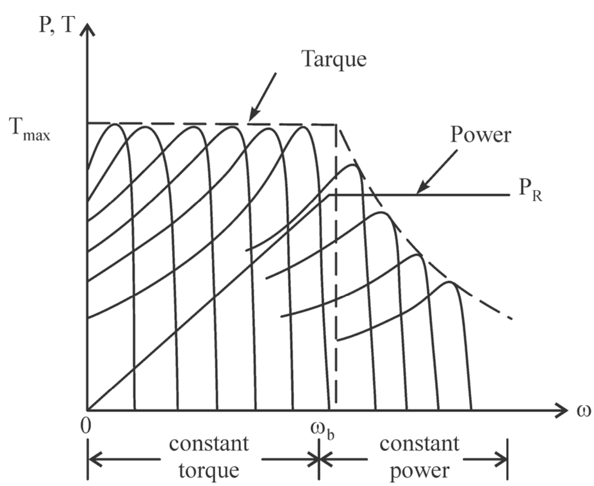

FIGURE 1.10 Constant torque and constant power operation of three phase induction motor.

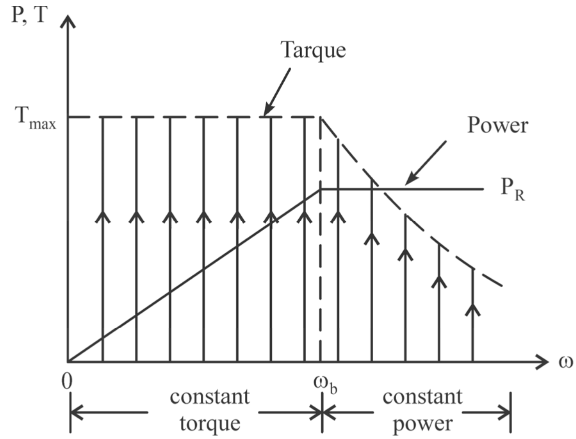

FIGURE 1.11 Constant torque and constant power operation of 3-phase synchronous motor.

1.9 PERFORMANCE PARAMETERS

1.9.1 Motor Performance Parameters

Adjustable speed electric drives are extensively used in modern industry for operation of various types of mechanical loads at variable speed. Prior to invention of power electronic converters, the dc supply was constant and ripple free and ac supply purely sinusoidal. There was no problem of harmonics in motor current and input power supply. Now, various types of versatile and efficient power electronic converters are developed which are widely used for control of electric drives. The performance of electric drives has been greatly improved but power converters impose certain problems in the motor. The motor current contains harmonics which generate additional heating and torque pulsation in motor. If source is ac, the supply current also contains harmonics which results in distortion of waveform and reduction of power factor. Therefore, there should be a set of parameters based on performance of various types of speed control methods could be compared. The following parameters may be used to compare performance of various speed control schemes.

Base speed: Base speed is the speed that the motor develops at nominal rated voltage and full excitation.

Speed Control: Speed control of a drive is an intentional change in speed to a value needed for performing a desired work. It should not be confused with the change in speed due to variation of load. The speed control is needed for following purposes:

1. To increase speed in same direction
2. To decrease speed in same direction
3. To reverse direction of rotation.

Range of speed control

The range of speed control of electric drives depends on type of application. In some applications, speed control below the base speed is required which may be within 20% of the base speed or wide range extending from very low speed to the base speed. In other applications the speed control below and above the base speed in wide range is required.

The range of speed control is defined as a ratio of the maximum speed N_{max} to the minimum speed N_{min}. In general it is expressed as a numerical proportion, such as 4:1, 10:1, 20:1, 100:1 and 200:1 and so forth. This ratio should be as high as possible. For example, metal cutting machine tools depending on their purpose are needed to operate over speed range 100:1 or higher; certain kinds of rolling mills require speed range 20:1 or higher; the high performance closed loop drives may have speed range more than 200:1.

Speed regulation: It is defined as a ratio of fall in speed from no load to full load, i.e.

$$\%\ \text{Speed regulation} = \frac{\text{No load speed} - \text{Full load speed}}{\text{Full load speed}} \times 100 \qquad (1.4)$$

The low value of speed regulation indicates hard speed- torque characteristics. Most mechanical processes need low value of speed regulation.

Smoothness Factor: It is defined as a ratio of the speeds on any two adjacent steps of speed control i.e.

$$\text{Smoothness factor} = \frac{N_n}{N_{n-1}} \qquad (1.5)$$

Where N_n and N_{n-1} are speeds at n^{th} and $(n-1)^{th}$ steps of the speed control respectively.

The low value of smoothness factor indicates smoothness in change of speed from one step to next adjacent step. High smoothness of speed control is often required for production of quality product.

Operational stability

Operational stability at a particular speed is characterized by change in speed produced by a given change in load torque. It depends on hardness of speed-torque characteristics of a motor i.e., harder the characteristics, better is the stability.

Nature of Motor current

The motor current may be discontinuous or continuous. If continuous it may be pure dc or with ripples; pure ac or associated with harmonics. The average and RMS values of motor current are defined as

$$I_{adc} = \frac{1}{T}\int_{t0}^{t_0+T} i_a \ dt \qquad (1.6)$$

$$I_{aac} = \sqrt{\left[\frac{1}{T}\int_{t_0}^{t_0+T} i_a^2 \ dt\right]} \qquad (1.7)$$

1.9.2 Input Supply Parameters

Displacement Factor: It is defined as

$$\text{Displacement Factor} = \frac{\text{Average power}}{\text{RMS fundamental supply voltage} \times \text{RMS fundamental supply current}}$$

$$= \frac{V_1 I_1 \cos\theta}{V_1 I_1} = \cos\theta \qquad (1.8)$$

Where V_1 = RMS value of fundamental voltage

I_1 = RMS value of fundamental current

θ = Angle between fundamental voltage and fundamental current.

Distortion Factor: It is defined as

$$\text{Distortion Factor} = \frac{\text{RMS fundamental supply current}}{\text{RMS supply current}}$$

$$= \frac{I_1}{I} = \frac{I_1}{\sqrt{I_1^2 + \sum_{n=2}^{n} I_n{}^2}} \qquad (1.9)$$

Where I = RMS value of supply current

Power Factor: It is defined as

$$\text{Power Factor (PF)} = \frac{\text{Average fundamental power supplied}}{\text{RMS supply voltage} \times \text{RMs supply current}}$$

$$\text{Power Factor} = \frac{V_1 I_1 \cos\theta}{V_1 I} = \frac{I_1 \cos\theta}{I} = \text{Distortion Factor} \times \text{Displacement Factor} \qquad (1.10)$$

If both the supply voltage and supply current are pure sinusoidal,
Distortion Factor = 1, Hence, Power Factor = Displacement Factor

1.10 OPEN LOOP AND CLOSED LOOP CONTROL OF ELECTRIC DRIVE

The control of electric drive incorporates operation of starting, speed control, braking and speed reversal. In addition, it also maintains drive conditions as required by the mechanical load for operation.

1.10.1 Open Loop Control

At the early stage of electric drive development, all operations of drive were controlled manually. The operator used to control input to the drive manually and starting, speed control, braking and speed reversal operations were accomplished with the aid of rheostats, rotary and plain knife switches. For example, if drive is operating at steady state and the load on the drive is increased, the shaft speed decreases. The operator manually increases input voltage to the motor which, in turn, increases developed torque and the original state is restored. If load on the drive reduces, the shaft speed increases, the operator decreases input voltage accordingly. Such type of control is called open loop control. The design and realization of the system is simple and economical. The system is stable in most of the cases. The system has inherent disadvantages of poor speed regulation, problems in frequent starting and stopping because of manual adjustment, poor quality of finished products, no compensation for the effect of internal and external disturbances and no possibility of remote control.

The necessity for eliminating shortcomings of open loop control led a passage to the development of apparatus for automatic control. Various types of contactors, relays and other accessories were developed. All the manually controlled operations were replaced by relay and contactor based control systems. Such control systems had been very popular in industries and they are still used in some typical applications. However, relay and contactor based control systems alone were unable to meet all the requirements of electric drives needed for modern intensified production. With the development of various types of power converters, such as rotating amplifiers, gas filled tubes, magnetic amplifiers and solid state power converters, it could be possible to employ closed loop control of electric drives.

1.10.2 Closed Loop Control

Closed loop control is widely used in modern electric drives for maintaining operating conditions of mechanical load constant irrespective of disturbances which may arise in operation. The high performance adjustable speed drives are being developed with excellent steady state and dynamic response using closed loop control. The closed loop control in electric drives is used for control of current, voltage, speed, torque, position etc. The variable to be controlled is sensed and compared with the preset or reference value. The error is amplified by controller and used to control operation of power converter in such a way the error reduces to zero.

The closed loop control of electric drive offers following advantages:

- Steady state accuracy is very high. It is as high as ± 0.002% or even better.
- Effects of internal and external disturbances are minimized.
- Dynamic response of the system is greatly improved.
- The sensitivity of the system for parameter variation, noise and environmental changes reduces to a very low value.
- The quality of finished products is improved.
- It reduces running cost, hence, production is economical and productivity is increased.
- It provides better operating conditions and facilitates remote control of drive when it is inaccessible.
- It provides protection of drive against over current, over voltage and excessive thermal heating.

- Drive can be operated in constant torque and constant power modes on demand of mechanical load.
- Quick and smooth starting and braking of drives in controlled manner are possible because motor can produce high and constant torque during starting and braking period.
- The closed loop system operates in real time and is capable of providing very high bandwidth. The controller is effective at all time.

The closed loop system has following disadvantages:

- Devices used for sensing of output variables are not ideal.
- Electronic components are usually hard wired, so their characteristics are fixed, leading to poor flexibility in design changes.
- Electronic components aging and sensitivity to environmental changes can be severe. Moreover, they are susceptible to noise problems.

In most applications, closed loop speed control of drive is invariably used to maintain speed constant against variation of either load or input supply. The current control in the drive is needed to keep the current within the permissible limit under transient conditions and also to protect motor and power converter against short circuit. The current control feature is included by inserting a current control loop within the outer speed control loop. The current can be controlled either by current limit control or continuous current control. In former control, the control action is active when the current exceeds the pre-set current limit which is generally the maximum permissible current and becomes inactive as soon as the current falls below the pre-set limit. Because of such control the current may exceed to a high value above the pre-set current limit in transient conditions before the control action comes in action and cause overheating of the motor. In continuous current control, the control action remains active throughout, therefore, the possibility of current exceeding the maximum permissible limit does not exist. Hence, it greatly reduces starting and braking time of drive because the drive can be operated continuously at the maximum permissible current. The later method of current control is preferred to former method in drive control. Since, position is integral of speed, the closed loop position control can be obtained by incorporating an outer position control loop in the closed loop speed control scheme.

According to method of signal processing, closed loop control may be classified as continuous or analog control and digital control.

1.11 CLOSED LOOP SPEED CONTROL SCHEMES

1.11.1 Analog Control Scheme

A closed loop speed control scheme having outer speed control loop with inner current control loop is shown in figure 1.12. The scheme is widely used for precise speed control of electric drives. It provides fast transient response, less sensitive to variation of power converter gain and no possibility of current overshoot in transient operation.

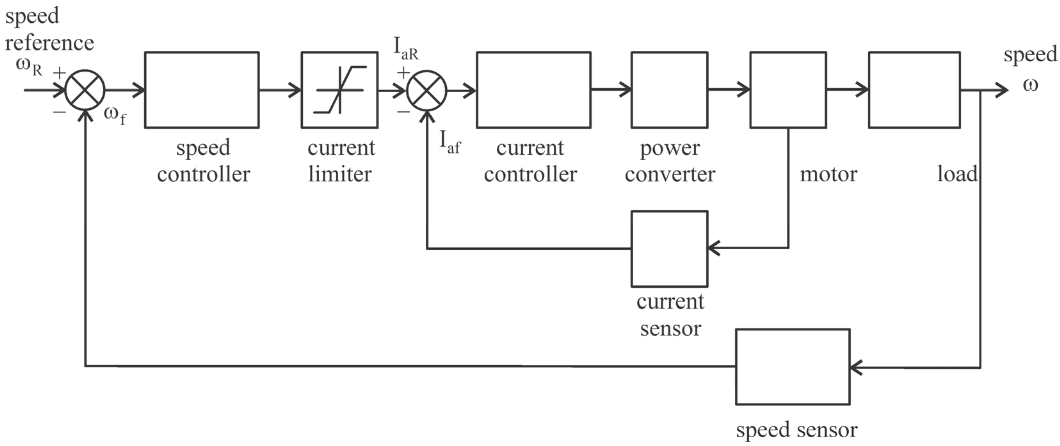

FIGURE 1.12 Closed loop speed control of electric drive with continuous current control.

The operation of the control scheme is explained below:

The speed of the drive is sensed by a speed sensor that provides output voltage proportional to speed. This feedback signal is compared with the preset speed reference signal. The error is fed to the speed controller which is usually a PI controller. However, sometimes, P and PID controllers are used as per requirement of the load. The PI speed controller has advantages of stabilizing the drive, providing fast response by adjusting damping ratio and reducing steady state speed error close to zero by integral action. The speed controller output is passed through a current limiter. The current limiter saturates for a pre-set value of the speed controller output and sets the current reference signal. The motor current is sensed in terms of voltage proportional to current. The feedback current signal is compared with the current reference signal and the error is fed to current controller which may be P or PI type. The current controller output adjusts the control voltage that, in turn, adjusts gate/base signal applied to converter and, hence, input voltage applied to the motor.

The control action takes place in such a way that the actual speed attains the speed set by the speed reference signal. The speed regulation can be obtained as low as ± 0.02%. Let us consider the drive is operating at steady state. A large positive speed error is created either due to sudden increase in speed reference signal or decrease in load torque. The large speed error processed through the speed controller saturates the current limiter and sets the maximum value of the current reference signal. The higher current error after processing through current controller, increases the power converter output. The motor accelerates with maximum permissible current and the speed feedback signal increases. The modified speed error is processed in a similar way. When speed feedback signal reaches very close to the speed reference signal, the current limiter de-saturates. Steady state is obtained when the motor reaches at the pre-set speed and a current at which the motor torque becomes equals to the load torque. When the speed reference signal is reduced or load torque is increased, a negative speed error occurs, the opposite correcting action takes place, and the motor decelerates and finally reaches at the pre-set speed. If current reversal is not required, the negative portion of the current limiter should be omitted, otherwise current response will be delayed.

1.11.2 Digital Control Scheme

In digital control, signals in one or more parts of the system are in the form of either pulse train or numerical codes. In electric drive system, the input and output of electric motor are analog signals. For applying digital control, the output signals are converted into digital form and after processing converted into analog form. This type of control is termed as sampled data control. Digital processors, such as microprocessor, microcontroller, microcomputer and digital signal processor are widely used in industry.

The digital control offers following advantages:

- Digital processors are more compact and light weight and can be made very versatile and powerful for control applications.
- Processing of signals in digital processors is software based, so allow more flexibility in programming. For changing design, alternation of hardware is not required.
- Digital components are less sensitive to aging and environmental changes. Moreover, they are less sensitive to noise.
- Digital control is more reliable and less sensitive to parameter variations.
- Complexity of system is reduced.
- Any complicated control circuitry can be realized.

Digital control suffers from following disadvantages:

- For computing variables, a signal resolution is limited due to finite word length of the digital processor. In contrast, analog controllers operate in real time and the signal resolution is theoretically infinite.
- The closed loop system often leads to instability due to finite word length of the digital processor.
- The limitation on computing speed causes time delay in the control loop which leads to delayed response.

1.11.3 Microprocessor Based Scheme

A microprocessor is a single digital IC chip that consists of an Arithmetic Logic Unit (ALU) and a Control Unit. The ALU performs all logical and arithmetic operations, such as addition, subtraction and bit manipulations. The Control Unit controls and supervises correct execution of instructions. The ALU has some registers for storing data (previously read from memory or result of some operations). Three buses, namely a data bus, an address bus and a control bus are associated with the microprocessor which connect memory and I/O devices. The data bus is bidirectional as the microprocessor accepts and sends data. The address bus is unidirectional. It used to identify a particular memory location or I/O device. Information flows only from the microprocessor to the memory or the I/O device. The control bus is bidirectional to indicate a type of activity in the current process, such as read/write from memory or I/O device, interrupt request, DMA request, Reset, halt etc. The clock is contained in the control unit. The clock frequency determines the basic operating speed of the microprocessor. The microprocessor carries out an operation by executing a sequence of instructions usually called as software program that is stored in a memory connected to the microprocessor. When memory and I/O devices are connected to a microprocessor, it becomes microcomputer. A block diagram of a microcomputer system is shown in figure 1.13.

A microprocessor performs following functions in variable speed drives using power electronic converters:

- Storing and processing of measured signals, such as speed, position, voltage and current.

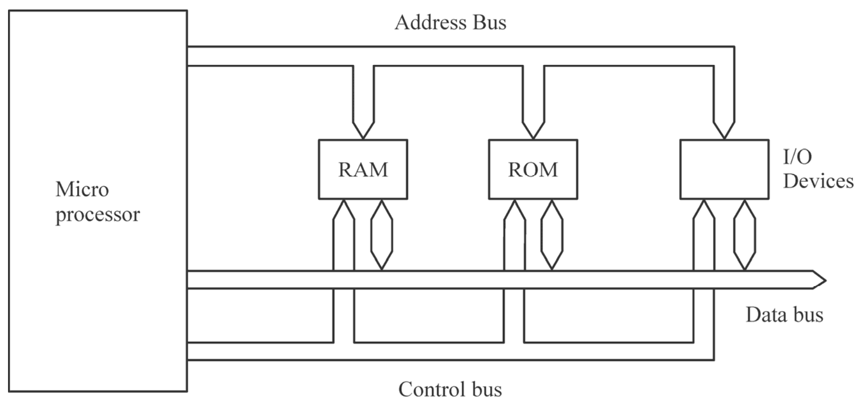

FIGURE 1.13 Block diagram of a microprocessor system.

- Computation of certain signals like torque and flux which cannot be directly measured using measured signals.
- Generation and implementation of nonlinear functions, such as speed controller, current controller etc.
- Generating adequate firing and gate pulses needed for operation of power converters.
- Generating sequence of control.
- Facilitating adaptive and optional control.

In addition, the microprocessor has capability of self-diagnosing, testing and monitoring of operations.

Figure 1.14 shows a typical block diagram of a microprocessor based closed loop speed control of an electric drive.

The speed and current of the motor are sensed by analog devices. These feedback signals are sent to respective samplers and A/D converters. The sampler makes a fast acquisition (sample) of the analog signal and then holds this signal at a constant value until the next acquisition is made. The sampled signal is discretized by the A/D converter and then fed to the microprocessor. If shaft encoder is used for speed sensing, sampler and A/D converter will not be required. However, noise filter will be needed to block noise signal associated with the speed signal. The feedback speed and current signals are compared with the respective reference signals and processed following the desired control. The PI controller is generally implemented by writing assembly language program.

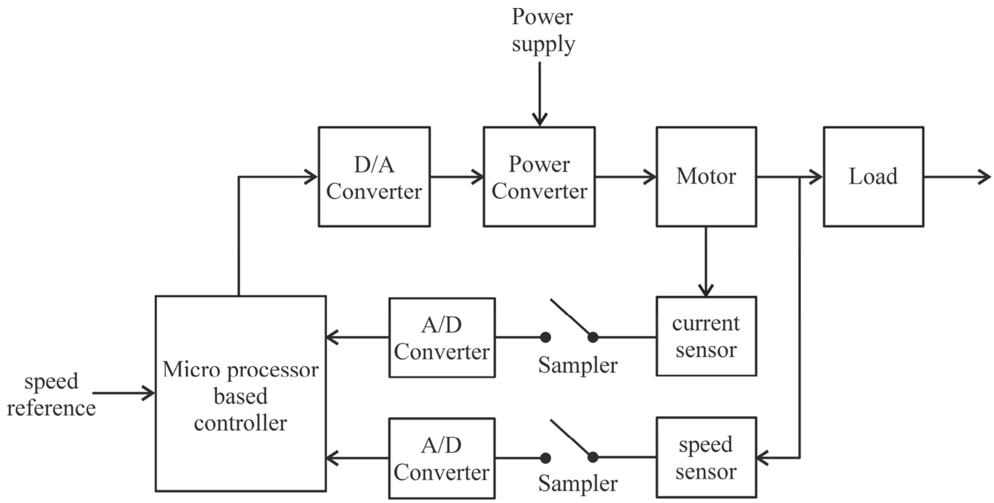

FIGURE 1.14 Block diagram of a microprocessor based closed loop control of an electric drive.

The microprocessor operates on sampling time T second cycle. The control is updated at every T second and is held constant between the sampling intervals. The computational time delay is equal to the sampling time T. The microprocessor generates a pulse at every T second. This pulse performs two functions. The pulse is applied to interrupt line of the microprocessor that causes the microprocessor to stop what it is doing and executes the interrupt routine and generates next value of output. This control signal is sent to the D/A converter that converts the digital signal into the analog signal whose output is fed to gate/drive circuit that generates required gate/base signal, which in turn controls the power converter output. The pulse is also sent to the sample command line of the accumulator where it triggers both samplers whose sample speed and sample current were held for one sample period. The samplers sample the signals and the sample cycle is repeated.

The microprocessor based control has following limitations:

- A microprocessor is designed to perform various functions, such as managing I/O, buses and data manipulation etc.; the speed of execution of these functions is slow.
- Multiplication of two binary numbers takes more time because multiplication is done by repetitive addition.
- Microprocessor has a single bus which has to be shared by program commands and data, so speed is limited.

Recently, digital signal processors (DSPs) have been developed for high speed computing, so they are suitable for high speed control applications. DSP has following special features:

- It contains hardware multipliers which can carry out multiplication and accumulates operations rapidly.
- It has dual bus structure that allows simultaneous processing of program instructions and data.

- It is about 100 times faster than a microprocessor for multiplication of two16 bit numbers. The sampling frequency can be even higher than 20 kHz where as it is limited to 2 kHz in a microprocessor.
- Hardware enhancements improve precision of calculations.
- It is more suitable for adaptive control due to its high speed capability which allows it to perform monitor and control functions simultaneously.

DSPs have drawback that their designing in control system application is difficult unless a dedicated compiler for a specific DSP is available. In that case, the operation codes are to be written in assembly language which needs development tools, such as evaluation modules, assembler/linkages software and hardware simulators.

1.12 CURRENT SENSING

There are two categories of current sensing, namely, direct sensing and indirect sensing. In direct sensing, the sensing element is connected in the power circuit, hence, a separate isolation circuit is needed between power circuit and control circuit. In indirect sensing, the sensing element is isolated from the power circuit, so no additional isolation circuit is required. Several methods are available for sensing dc and ac currents. However, what method should be used depends on magnitude of current, accuracy, response time, bandwidth, size and cost. Only following three widely used methods are discussed below.

1.12.1 Resistor Sensing Method

It is a direct sensing method in which current sensing is done either by connecting a low value resistor or a non-inductive shunt in the power circuit. Because of low value of resistance, the circuit current to be measured is not affected. The sensing resistor is basically a current to voltage converter that develops voltage drop proportional to current passing through it. The sensing resistor may be made in the form of metallic strip, wire wound, metallic film or carbon film. The criteria for selection of type and value of sensing resistor are voltage drop, power dissipation, accuracy, parasitic inductance and cost.

The non-inductive metallic shunts are generally made of Manganin material in strip form. They have four terminals two for attachment of the current carrying leads and other two for measurement of voltage drop across it. They are specified in terms of current, voltage, resistance accuracy and resistance drift. Shunts are, generally, designed for voltage drop of 50 mV, 75 mV or 100 mV when full current passes through them. They have many advantages, such as simple construction, low temperature coefficient, resistance accuracy within ± 0.25%, small thermoelectric EMF and easy measurement. But, they have major drawbacks of large power dissipation at high current and deterioration of performance at high temperature. Owing to these drawbacks, shunts are impractical for sensing high current usually more than 20 ampere.

The sensing resistor is generally placed at low voltage side in the power circuit. It is desirable because the common mode voltage is near to ground potential which allows use of single supply, rail to rail input/output Op-Amp. But, it has drawbacks of inability to detect short circuit taking place through the alternate path and disturbance to ground potential due to other loads.

A typical resistance sensing circuit is shown in figure 1.15. The sensing resistor is connected on low voltage side. The voltage drop across sensing resistor is of the order of millivolt which is filtered out to eliminate noise and then amplified using differential or instrumentation amplifier. Isolation between power circuit and control circuit is provided using an opto-isolator.

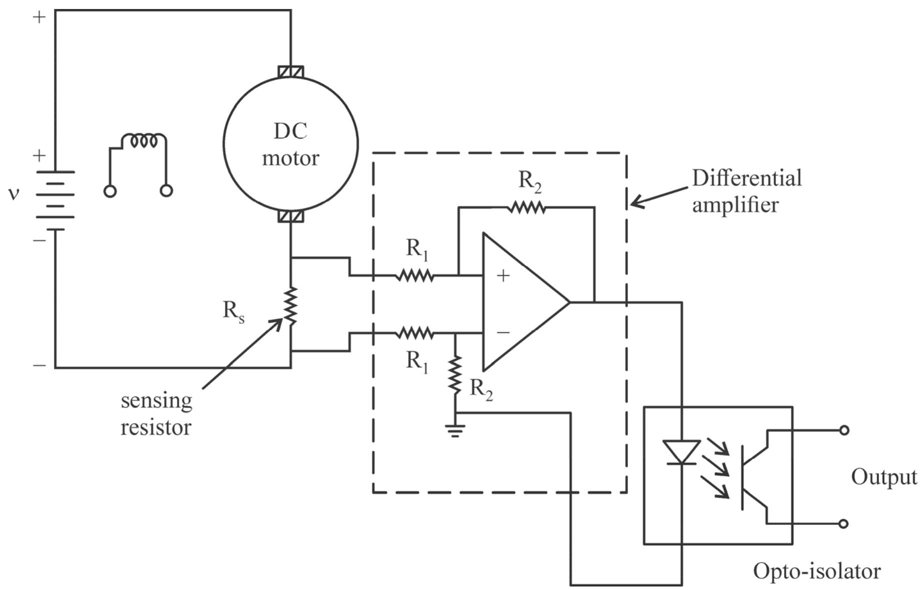

FIGURE 1.15 Current sensing using sensing resistor.

1.12.2 Current Transformer Sensing Method

Current transformer (CT) is used for sensing ac current. The primary winding is connected in power circuit. For sensing high current, the primary of the CT is a power conductor passes through its core. The secondary is generally designed for 5A and terminated through a low resistance. A CT used for current sensing should have low magnetizing current, high linear region of operation, low core losses, small size and low cost. To eliminate drawback of ferromagnetic core, air core coil having large number of turns in secondary is used. This coil is called Rogowski coil and can be used for sensing ac or pulsed dc current. A CT can also be used to measure dc link current indirectly in controlled ac to dc converters and dc to ac converters where dc link current has definite relation with ac current. In such cases, CTs are placed on ac lines and the secondary current is rectified and filtered to smooth out ripples. One such method for sensing ac current in three phase ac lines using three CTs connected in star configuration is shown in figure 1.16. The output of three CTs is rectified and passed through a low pass filter circuit to get ripple free dc voltage proportional to ac line RMS value of current.

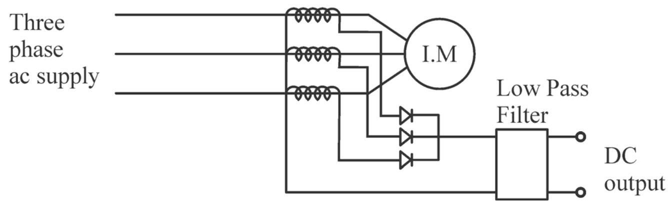

FIGURE 1.16 Current sensing in three phase ac lines by using current transformers.

The CT has various advantages, such as suitability for high current sensing, high bandwidth (50/60 Hz to 20 kHz), isolation between power and control circuits, low power losses, good signal to noise ratio and good common mode rejection. However, major drawbacks are bigger size and higher cost.

1.12.3 Hall Effect Sensing Method

The Hall Effect sensing works on the principle that if a strip of conducting material is placed in a transverse magnetic field, a voltage is produced between the opposite edges of the strip. The output voltage is proportional to current and field strength. It is expressed as

$$V_H = K_H B I/d \tag{1.11}$$

Where K_H = Hall Effect coefficient depends on conductor material

d = Thickness of conducting strip

B, I = flux density and current respectively

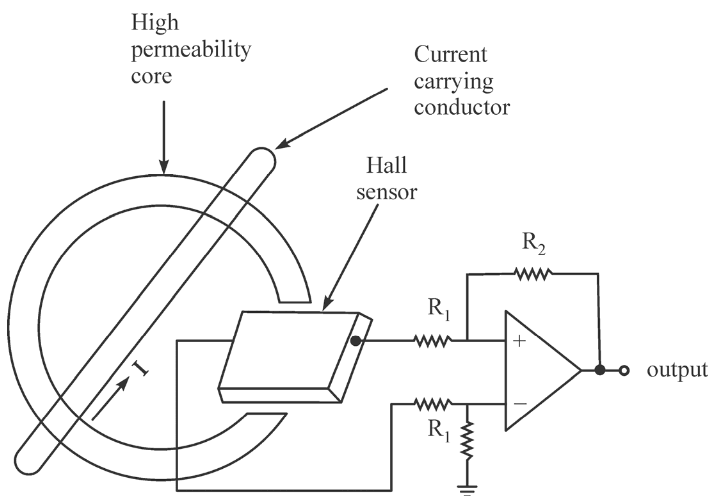

FIGURE 1.17 Hall Effect current sensing method.

A typical Hall Effect current sensing method is shown in figure 1.17. It consists of a slotted high permeability magnetic ring which acts as a field concentrator. A conductor whose current is to be measured is placed inside the ring. A linear Hall Effect sensor is inserted in the slotted portion of the ring as shown in the figure. The current passing through the conductor produces a magnetic field. The output voltage V_H is proportional to magnetic field strength which in turn is proportional to the current. The voltage V_H is amplified which represents current by a scaling factor. It is an indirect method of current sensing suitable for sensing of ac, dc and complex currents.

This method can be used for measurement of currents from fraction of a milli-ampere to thousands of ampere. It has advantages of simple construction, low power consumption, no insertion losses and small size for higher currents. It has drawbacks of limited range of linearity, narrow bandwidth, high offset voltage, sensitivity with temperature, low accuracy and magnetic core heating due to core losses at high frequency current measurement.

1.13 SPEED SENSING

The speed sensing method must have high accuracy, fast response over a wide range of speed control. Following two methods are used for speed sensing:

1.13.1 Analog Speed Sensing

1.13.1.1 Tachogenerator Sensing

DC/AC tachogenerator is coupled to the motor shaft that provides dc/ac output voltage proportional to speed of the motor. The output voltage is generally specified as voltage per 1000 rpm. A typical output voltage is 10 V/1000 rpm.

DC Tachogenerator: It is a permanent magnet type miniature low voltage dc generator whose flux is constant. The armature winding is placed on the rotor and ends of coils are connected to commutator segments. The output voltage is taken across a pair of brushes slide on the commutator. Silver-tip metal brushes are used to reduce voltage drop across brushes. Higher number of poles are used to stabilize the output voltage. The armature core can be iron core type or moving coil type. The iron core type tachogenerator has high inertia, high inductance, low cost and high reliability. In moving coil dc tachogenerator, the armature conductors are placed on the surface of a hollow cylinder made of either epoxy resin or fibre glass. It is placed between permanent magnet structure and stationary flux return path. The one end of the hollow cylinder is connected to the motor shaft. Such type of rotor structure has very low inertia and very low armature inductance. Sometimes, a low pass filter is used to minimize high frequency noise in the output voltage. DC tachogenerator has salient features, such as linear output voltage to speed characteristics, no zero speed voltage error and no undesirable phase shift in output voltage. They have drawbacks of sparking on commutator, wear and tear of brushes and ripples at low speed.

AC Tachogenerator: It is similar to a two phase induction motor. It contains one primary winding and a secondary winding in quadrature with the primary winding. The rotor is in the form of a drag-cup non-magnetic material which provides benefit of low inertia and output voltage free from slot ripples. The primary winding is excited by a sinusoidal voltage supply of 50Hz or 400 Hz. When the motor rotates, the output voltage proportional to speed is induced in the secondary winding. The phase of the output voltage is dependent on the direction of the rotor.

An ac tachogenerator is also designed with permanent magnet rotor with many poles and winding on the stator. It works as a simple ac generator when the motor rotates and generates an ac voltage proportional to speed. Generally, dc voltage is needed in closed loop speed control, therefore, the ac output voltage is rectified and filtered using low pass filter to get smooth dc voltage. The ac tachogenerator has good linearity and accuracy up to 0.1%. It has additional advantage of free from wear and tear and sparking.

1.13.1.2 Back EMF Method

Where high accuracy in speed control is not required, the speed can be sensed with the help of knowing back EMF in dc shunt/separately excited motors. If flux is kept constant, speed is proportional to the back EMF. The back EMF is determined by subtracting armature voltage drop from terminal voltage of the motor. The accuracy is affected due to variation of resistance of field winding and armature reaction. However, speed accuracy up to ± 2% can be obtained. The method is simple and relatively cheaper as no additional sensing device is required.

1.13.2 Digital Speed Sensing

The speed sensing in digital form can be obtained in two ways. One method is to use tachogenerator for speed sensing and convert analog output signal into digital signal by an A/D converter. This method introduces not only time delay in response but also has limited accuracy. The second method is to use a digital transducer that converts linear or rotary displacement directly into digital form and does not require A/D converter. Digital transducers are, generally, called Encoders. Encoders are of three types, namely, tachometer or shaft encoder, incremental encoder and absolute encoder. The tachometer encoder is suitable for speed sensing only in one direction of rotation, whereas the incremental encoder is suitable for speed sensing in both direction of rotation and also for position sensing. The absolute encoder is suitable for position sensing.

1.13.2.1 Tachometer encoder

A tachometer encoder consists of a light source, a circular transparent disk and photo sensor as shown in figure 1.18. The disk, on one side, has a primary circular track divided into a number of equal angular segments which are alternate painted to make them non-transparent. Alternatively, the disk is made of non-transparent material which has equally spaced and identical window (Slot) areas. Each window area is equal to the area of the non-transparent inter-window gap. The former type of disk is preferred. The disk is mechanically coupled to the motor shaft. A light source placed on one side of the disk projects a beam of light on the disk. On the other side of the disk a light sensor which could be a silicon photo diode, phototransistor or photo voltaic cell is placed. The transmitted light from the source is interrupted by the non-transparent area but passes through transparent sector of the primary track and is received by the light sensor. For each transparent sector one pulse is generated, hence, a train of voltage pulses are generated when the motor rotates. Pulse width and pulse to pulse period (encoder cycle) are constant when the motor runs at constant speed. The pulse width decreases continuously during acceleration but increases continuously during deceleration of motor. The pulses generated by the light sensor are not very sharp and a wave shaping circuit is needed.

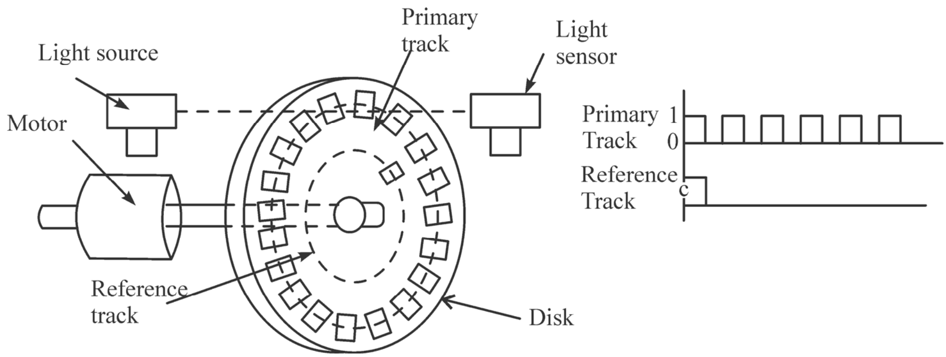

FIGURE 1.18 Speed sensing by using tachometer speed encoder.

Tachometer encoder provides single output signal in pulse form for each increment of displacement. For the motion only in one direction a digital counter can count number of pulses from the reference starting point to determine displacement. In reverse direction of rotation also the same pulses will be obtained, which may cause error. Therefore, this encoder is generally used for sensing of speed where reversible motion is not required.

Speed Measurement: Speed can be measured using following two methods:

Pulse counting method

In this method, number of pulses are counted over a sampling period of the digital processor and used to determine the speed.

Let Number of pulses over a sampling period T = n

Average time of one pulse = T/n (1.12)

Number of windows on the disk = m

Hence, average time for one revolution = mT/n (1.13)

Speed in rpm = 60n/ mT (1.14)

Speed in rad/sec = 2πn/ mT (1.15)

For a given sampling period, there is a lower limit of speed below which this method is not accurate.

Pulse timing method

In this method, the time for one encoder cycle is measured using a high frequency clock signal. This method is suitable for measuring low speed accurately.

Let Clock frequency = f Hz

Number of cycles of clock signal during one encoder period = p

Time of one encoder cycle = p/f (1.16)

The average time for one revolution = mp/f (1.17)

$$\text{Speed in rpm} = \frac{60f}{mp} \tag{1.18}$$

Speed in rad/sec = $2\pi f/mp$

Advantages

- High resolution
- High accuracy due to noise immunity of digital signals
- Easy adoption in digital control system
- Simple in construction and low cost
- Versatile in operation.

Errors

- Quantization error
- Assembly error
- Structural error due to disk or shaft deformation
- Suitable for speed sensing for one direction of rotation. Error is generated if used for reverse rotation.

1.13.2.2 Incremental Encoder

An incremental encoder is similar to a tachometer encoder in construction. It also consists a light source, a circular transparent disk and a light sensor. The disk shown in figure 1.19 has three concentric circular tracks on one side facing the light source. The primary circular track is divided into a number of equal angular segments which are alternate painted to make them non-transparent. The second inner circular track having same number of segments but quadrature offset (90 phase shift) with segments of primary circular track is used to determine direction of rotation. This allows detection of motion based on which one signal rises first. Thus, an up/down counter can be used to subtract pulses when the motion reverses. The third inner most circular reference track is provided to generate one reference pulse in each revolution to initiate pulse counting for the angular position sensing. The incremental encoder is suitable for sensing of speed and position. The displacement is measured with respect to some reference point on the disk as indicated by the reference pulse generated at that location. The speed can be sensed by counting number of pulses over a certain period using any one method discussed at the previous section.

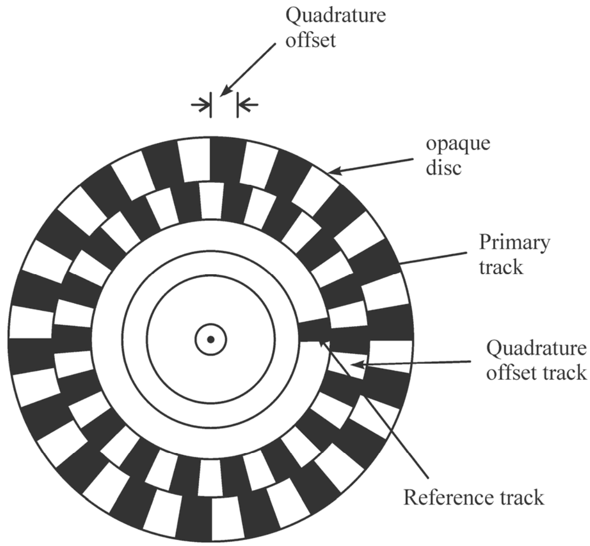

FIGURE 1.19 Incremental encoder disc.

The direction of rotation is determined on the basis of phase shift of pulses obtained from the primary track and the secondary quadrature offset track using a phase detection technique as shown in figure 1.20. Voltage pulses V_1 and V_2 are obtained from the primary track windows and the secondary quadrature offset windows respectively. In figure 1.20(a), V_1 lags V_2, the direction of rotation, say, it is clockwise, while in figure 1.20(b), V_1 leads V_2, the direction is opposite to previous one, hence, counter clockwise.

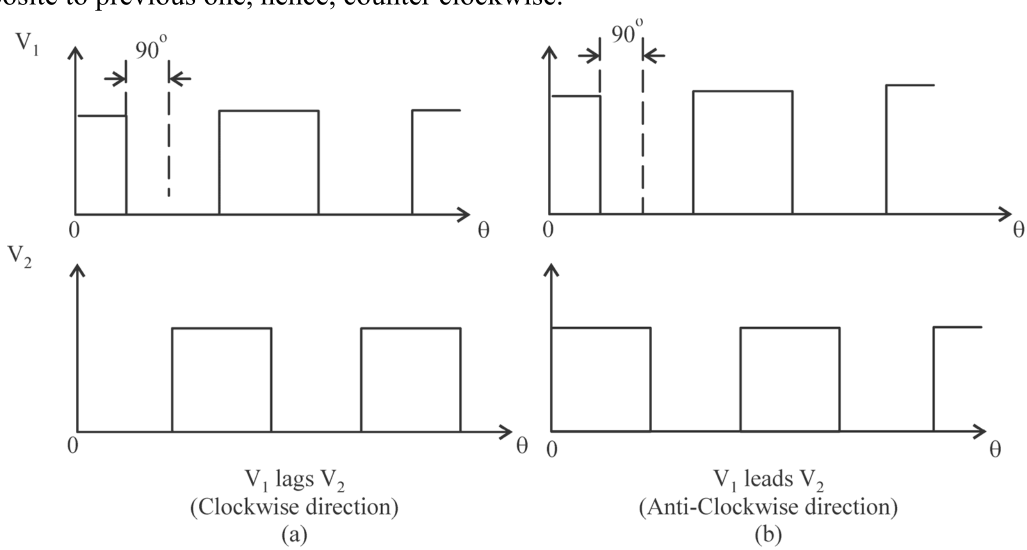

FIGURE 1.20 Determination of direction of rotation (a) clockwise direction (b) anti-clockwise direction.

The incremental encoder has all the advantages as of tachometer encoder. Additionally, it is suitable for sensing of speed and position in both directions of rotation. However, any false pulse generated from electric noise causes error that persists even the noise disappears. Moreover, in the event of power failure the information about position data is lost which cannot be retrieved even after power is restored. An Incremental encoder having only single (primary) track acts as a tachometer encoder.

1.14 POSITION SENSING

Position can be sensed by analog and digital means. There are several methods of position sensing but only following widely used methods are discussed.

1.14.1 Analog Position Sensing

1.14.1.1 Potentiometer Sensing

A potentiometer is an electromechanical device that converts mechanical displacement either linear or rotational into an output voltage. It has two fixed terminals and one movable terminal called wiper. When a voltage is applied across the fixed terminals, the output voltage is measured across the variable terminal and the fixed ground terminal. The output voltage is proportional to the displacement. Potentiometers are generally made with wire of Platinum or Nickel alloy or conductive plastic resistance material. For precision control, the conductive plastic resistance potentiometer is preferred because it has infinite resolution, long life, smooth output and low static noise. Potentiometers may be either linear or rotational type. The rotational potentiometers are either in single or multi revolution form. A typical potentiometer used for measuring displacement is shown in figure 1.21(a). The wiper is operated by the motor shaft.

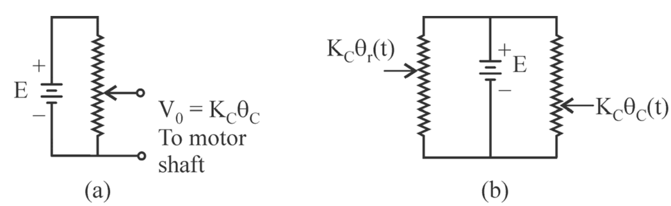

FIGURE 1.21 (a) Position sensing using potentiometer (b) Position error detection using potentiometer.

The output voltage V_o for a shaft position θ_c for rotary motion can be expressed as

$$V_o = E\theta_c/2\pi T = K_c\theta_c \quad (1.19)$$

Where T = Number of turns in the potentiometer

$$K_c = E/2\pi T$$

Two potentiometers connected in parallel as shown in figure 1.21(b) can be used as an error detector in position control system to allow comparison of positions of two remotely located shafts.

The error voltage is given by

$$e(t) = K_c [\theta_r(t) - \theta_c(t)] \quad (1.20)$$

1.14.2 Digital Position Sensing

The position can be sensed digitally by following three methods:

1. Incremental encoder
2. Absolute encoder
3. Resolver

1.14.2.1 Incremental Encoder

The incremental encoder discussed at section 1.13.2.2 is also suitable for sensing position. The position is sensed in the following way:

Let M = Maximum count pulse in θ_{max} which is 2π

K = Number of Pulses in angular displacement $\tilde{\theta}$

Hence, $\theta = K\,\theta_{max}/M$ (1.21)

1.14.2.2 Absolute Encoder

An absolute encoder uses multiple tracks whose outputs are read out in parallel to produce output in binary form which represents rotor position. The absolute encoders use several types of code, such as binary code, Gray code and BCD. A typical Absolute encoder consisting of a circular 4-bit binary coded transparent disk is shown in figure 1.22 which is mechanically coupled to the motor shaft or to the load shaft if speed reduction gear is used. The disk has four concentric circular tracks on one side facing the light source. Each track is divided into a number of equal angular segments with alternate segments painted to make them non-transparent. The black areas in the figure represent transparent or conducting segments while white areas show non-transparent segments. The outer most track is divided into 16 segments with each of 22.5 degrees. The inner tracks in sequence are divided into 8, 4, 2 segments respectively in the binary count (16, 8, 4, 2). Each track has a separate light source that sends a beam of light on the track which is received by the photo sensor placed on the opposite side. Sensors are placed radically facing the corresponding tracks. Sensors produce a voltage pulse when light is received and no output if light blocked. Thus, the sensor output represents 1 or 0 in binary system when light is received or blocked. When the disk rotates, all the sensors produce a bit pattern representing angular position of the shaft. For example, a bit pattern 0110 represents 7th sector in the outer most track is facing the sensor. The shaft position is decoded accordingly. The resolution depends on number of tracks on the disk. For n tracks, the resolution is given by

$$\text{Resolution} = (360/2^n)\ \text{degrees} \quad (1.22)$$

Thus, for a 4-bit binary coding system, the resolution is given by 22.5°. The resolution can be further improved by increasing number of tracks. For example, in a disk having 13 numbers of tracks the resolution would be 0.044º. The encoder provides a noise free and stable output. Since there is one to one correspondence between binary outputs, position data are recovered when power is resumed after interruption. However, binary coding system generates error in output due to small misalignments. This problem can be eliminated by using Gray coded disk in which only one bit changes at each transition. Since, the Gray coded output may not be compatible with the read-out device, conversion from Gray code to binary system is necessary. The Gray code is popular in use. The absolute encoder is generally used for sensing position where the drive has been standstill for a long time or running at very low speed.

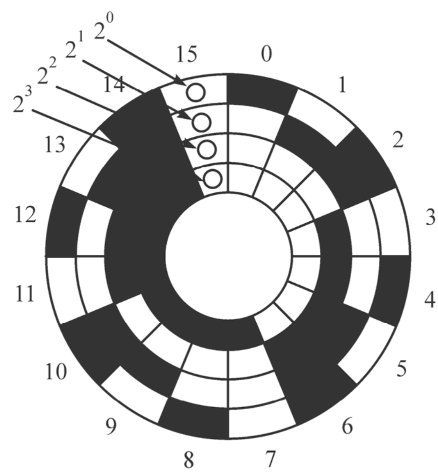

FIGURE 1.22 Binary coded Absolute Position Encoder disc.

1.14.2.3 Resolver

General Description: A resolver is an electromagnetic transducer that can be used for sensing position and speed. It is a rotary transformer that provides output in form of trigonometric function of inputs. The rotor is attached to the load shaft whose position or speed is to be sensed. The stator remains stationary. The rotor may carry one or two primary windings mechanically separated from each other by 90º. One winding is generally short circuited to improve accuracy. The stator consists of two secondary sin and cosine windings mechanically separated from each other by 90º. The function of the resolver is to resolve a vector into its two sine and cosine components through induction coupling. Resolvers are available in 2-pole or multi-pole designs, in other words, number of magnetic poles induced when the primary winding is excited. In two pole resolver, the windings are wound such that the device produces one complete cycle of each sine wave and cosine wave over one rotation of the load shaft. As a result, two pole resolver can provide absolute sensing of position but accuracy is largely affected by mechanical vibrations. A multi-pole resolver produces multiple sine and cosine waves in one rotation of the shaft. For example, a 4-pole resolver produces one sine and cosine wave for each 180º of shaft rotation, thereby, accuracy is better. But increasing number of poles increases design complexity and puts limitation on diameter of the resolver. Sometimes, two poles and multi poles sets of winding are housed in a single package of the resolver. It combines the advantages of absolute position sensing of two pole windings and better accuracy of multi-pole windings. The ac power supply to the primary winding mounted on the rotor can be supplied by slip rings and brushes. This arrangement needs frequent maintenance and may be undesirable in certain applications. Another method is to supply ac power to the primary winding through inductive coupling using transformer action. Such type of resolvers are called brushless resolvers and widely used. Since there is no physical connection of supply to the rotor, the life of the resolver is solely limited by the life of bearings which is several thousand hours. But these resolvers have higher power consumption and higher phase shift.

Operation of Brushless Resolver: A brushless resolver is shown in figure 1.23 and arrangement of stator and rotor windings is shown in figure 1.24. The resolver consists of a primary windings P_1-P_2 mounted on the rotor which is inductively coupled with R_1-R_2 excitation winding to which ac supply $V_m \sin\omega t$ is connected. The stator consists of two windings S_1-S_3 and S_2-S_4 mechanically separated by 90º from each other. The angle θ is measured when axis of the rotor winding is perpendicular to the axis of the stator S_1-S_3 winding i.e., when voltage induced in the S_1-S_3 winding is zero and voltage induced in S_2-S_4 winding maximum. For $\theta = 0$, say, horizontal stator sine winding is decoupled with rotor primary winding while stator vertical cosine winding having maximum coupling produces the maximum output voltage. For any angle θ of the excitation winding the amplitude modulated signals of two windings are given as:

$$V_1 = K\,V_m \sin wt \sin\theta \tag{1.23}$$

$$V_2 = K\,V_m \sin wt \cos\theta \tag{1.24}$$

Where w = Oscillator frequency

V_m = Peak value of oscillator voltage

K = Effective transformation ratio between primary and secondary windings of transformer

θ = Electrical orientation angle of the rotor winding

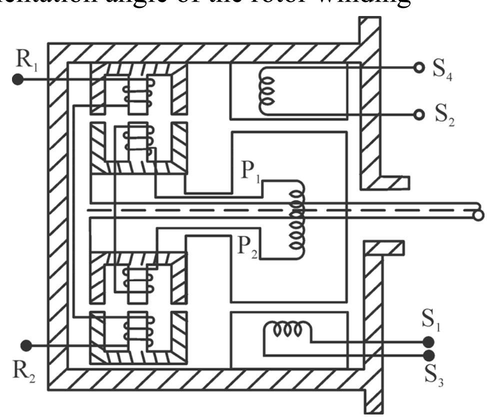

FIGURE 1.23 Brushless Resolver.

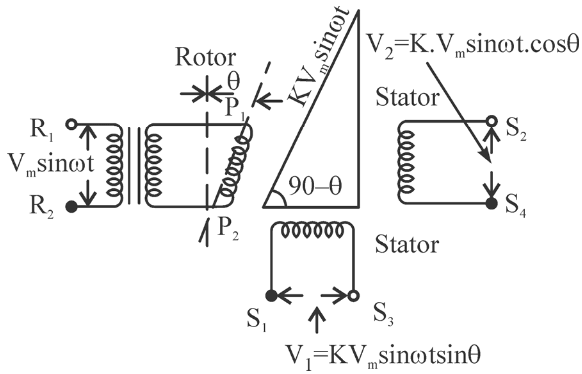

FIGURE 1.24 Arrangement of stator and rotor windings.

From equations (1.24) and (1.25), the angle θ is given by

$$\tan\theta = (V_1/V_2) \quad (1.25)$$

Hence,

$$\theta = \mathrm{Tan}^{-1}(V_1/V_2) \quad (1.26)$$

The spectrum of the amplitude modulated signals V_1 and V_2 is shown in figure 1.25. Most resolvers are specified to work on frequencies from 400 Hz to 10 kHz and voltages from 2 V to 40 V RMS ac supply. Angular accuracy ranges from 0.5 arc minutes to 5 arc minutes.

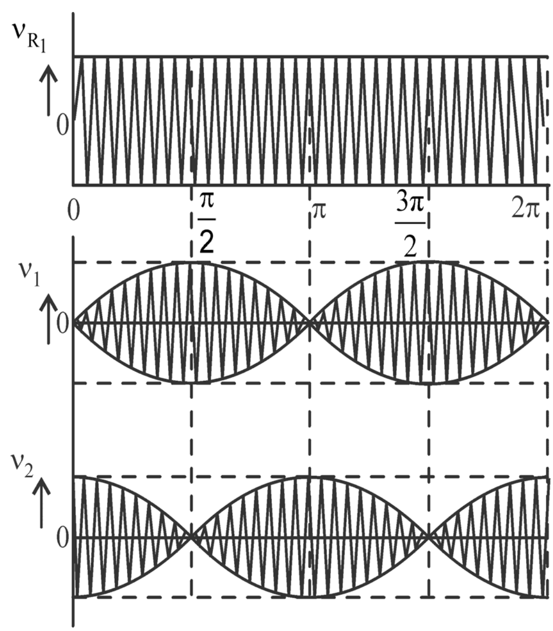

FIGURE 1.25 Voltage profiles of two stator windings with respect to voltage of rotor winding for two-pole resolver.

Advantages

1. Resolver is a simple, elegant and robust in construction.
2. It can provide unlimited resolution and has inherent noise protection.
3. It is highly reliable.

Resolvers have several applications, some of them are in steel mills, aerospace, factory automation, printing presses, machine tools etc.

Resolver to Digital Converter (RDC)

Resolvers are extensively used in applications where accurate and high resolution angular position and/or speed information is demanded. A RDC performs two basic functions, namely, demodulation of amplitude modulated resolver output signals to remove carrier and angle determination in digital form. The most popular method for performing these two functions is called ratio metric tracking conversion. It performs an implicit arc tangent calculation on the ratio of the resolver signals by forcing a counter to track the position of the resolver. The RDC is, therefore, a closed loop tracking technique. A typical RDC is shown in figure1.26. Initially, it is assumed that the present state of the up/down counter is a digital number corresponding to a trial angle α. The RDC looks to adjust the digital angle α continuously to track θ till it becomes equal to θ The estimated digital angle α is applied to the sine/cosine wave generator which incorporates sine and cosine look up tables. The generated sine and cosine waveforms are digital, therefore, these are passed through digital to analogue converters (DAC) to convert in analogue forms. The stator modulated output voltage V_1 and cosine wave are applied to a high precision cosine multiplier where both are multiplied to produce output of the form

$$K\ V_m \sin\omega t \sin\theta \cos\alpha$$

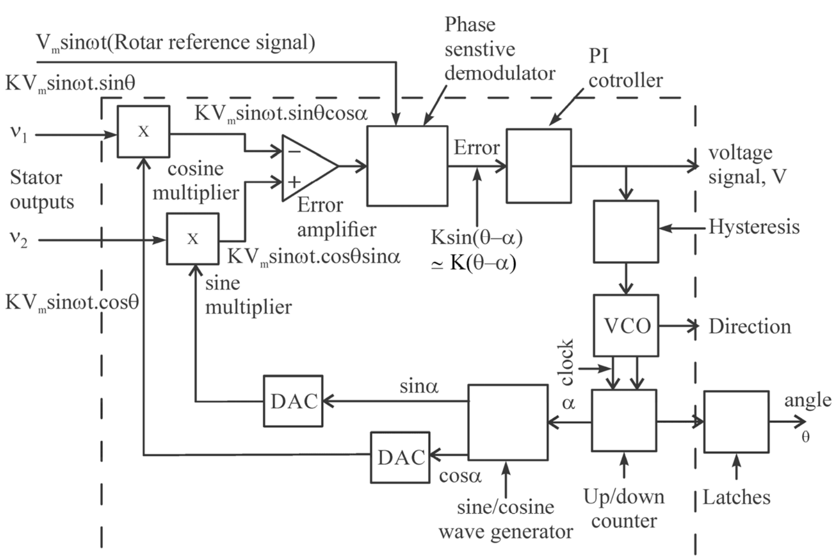

FIGURE 1.26 Resolver to digital converter.

Similarly, the stator modulated output voltage V_2 and sine wave are applied to a high precision sine multiplier to produce output of the form

$$K\, V_m \sin\omega t \cos\theta \sin\alpha$$

The error amplifier subtracts these two signal equations to yield an error signal of the form

$$K\, V_m \sin\omega t\, (\sin\theta \cos\alpha - \cos\theta \sin\alpha)$$

Using trigonometric identity, the above error signal is simplified as

$$K\, V_m \sin\omega t \sin(\theta - \alpha)$$

The simplified error signal is applied to a phase sensitive demodulator to which rotor excitation signal $V_m \sin \omega t$ is also fed. The demodulator synchronously demodulates the error signal using the rotor excitation voltage as a reference. This results in a dc output voltage proportional to Sin $(\theta - \alpha)$. As long as the difference between θ and α is small less than 30°, the following approximation can be used.

$$\sin(\theta - \alpha) \cong (\theta - \alpha) \qquad (1.27)$$

The error signal of equation (1.27) is amplified through a PI controller yielding an analog signal V which in turn drives a voltage controlled oscillator (VCO). The polarity of V gives the direction of signal. Hysteresis is introduced before applying to VCO to prevent dithering and disabling counting when the error is less than $\pm$ 1 LSB. The VCO is an incremental integrator (constant input voltage to position rate output) which together with PI controller forms a type-II tracking loop. The VCO in turn causes the Up/Down counter to generate estimated angle α in proper direction If the angle $(\theta - \alpha)$ is not within $\pm$ 1 LSB, the counter increments or decrements digital output to increase or decrease α. Up counting indicates a positive direction of rotation whereas down counting indicates reverse direction. The tracking finishes when $\alpha = \theta$ within $\pm$ 1 LSB or one count. Hence, the digital output of the counter α represents the angle θ. The latches enable this data and transfer to external circuit without interrupting the tracking loop.

Advantages

1. The error signal is integrated twice in the tracking loop, therefore, a high degree of noise immunity.
2. The conversion system needs only sine and cosine functions instead of division and arc tangent function.
3. The accuracy of RDC ICs is very high. They can provide absolute or incremental output with high resolution.

The use of resolvers was previously limited by the fact that the signal conversion required cumbersome circuitry. Now, low cost and easy to implement monolithic ICs are readily available in the market, therefore, they have wide spread applications in industry. However, the resolver is still more expensive than the optical encoder.

1.15 SUMMARY

In this chapter a comprehensive overview of electric drive has been given. Electric drives have been workhorse in industry for providing adequate motion to mechanical machines for a long time. An electric drive generally consists of a power converter, an electric motor and a controller. With passage of time a lot of advances have taken place in the functioning of electric drive. Therefore, in the beginning, historical development of the electric drive from inception was given. Electric drives are available in wide ranges in terms of power, torque and speed. Electric drives are classified on many ways, but classification on the basis of placement of drive with mechanical load, nature of speed-torque characteristics, type of motor used and quadrant operation have been discussed. Traditionally, dc drives were used as variable speed drives and ac drives as constant speed drives. Now, with the evolution of fast switching, efficient and versatile power electronic converters, ac drives are widely used as variable speed drives. The dc series motor drive is inherently a constant power drive. Other drives, namely, separately excited dc motor drive, induction motor drive and synchronous motor drive are capable of operating in constant torque and constant power modes. The one quadrant drive performs motoring operation in forward or reverse direction of rotation. Two quadrant drive is capable to operate in two quadrants and performs motoring and braking operations. Four quadrant drive is capable to operate in all four quadrants. Next, operation of drive in open loop and closed loop was discussed. Modern electric drives are commonly used in closed loop configuration because of precise control of performance parameters, fast dynamic response, guided acceleration and deceleration and flexibility in implementing any control algorithms. In past, analog closed loop control was only used. But now advances in micro-electronics and evolution of microprocessors and digital signal processors, the application of digital control is progressively increasing mainly because of flexibility in control, less dependency on hardware and realization of complex control algorithms. The digital control replaced analogue control in several applications. General analogue and digital closed loop speed control schemes were discussed. The motor current may exceed the maximum permissible limit during transient conditions which may cause overheating of the motor. To limit the current within the maximum permissible value current control feature is included as a current loop within the speed control loop. Performance parameters were also discussed to understand effectiveness of a particular speed control method to be used. The PI-controller is commonly used for speed or position control to eliminate steady state error. For current control P-controller is generally used if steady state error is not a major issue. The sensing of performance parameters in analog or digital form is an essential requirement for closed loop control. Therefore, commonly used techniques for sensing of current, speed and position were given. The non-inductive shunts are suitable for sensing low current particularly in dc circuits. Current transformer sensing is widely used in ac circuits. The Hall sensing method is suitable for sensing of current from a fraction of milli-ampere to thousands of amperes both in dc, ac and complex circuits. Presently, digital speed and position sensors are widely used in ac circuits. The tachometer encoder is suitable for speed sensing in one direction of rotation only. The incremental encoder and the resolver are suitable for sensing of both speed and position in both directions of rotation. The absolute encoder is used for position sensing only.

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QUESTIONS

1. How does a modern electric drive differ from an elementary electric drive?
2. Draw block diagram of a modern electric drive and discuss function of its elements.
3. State merits and demerits of an electric motor drive.
4. List various functions of a power converter. Discuss different types of power converters in brief.
5. DC drives are not suitable for high power high speed applications. Discuss reasons.
6. Group drive is generally not used in modern industry. What might be reasons?
7. Explain multi-motor drive giving one application.
8. Presently, it is a practice to connect load directly to the motor shaft. Why is it so?
9. Classify electric drives on the basis of speed control.
10. Soft characteristic motors are generally not preferred for industrial applications. Give reasons.
11. Compare dc drives and ac drives giving their merits and demerits.
12. What do you understand by 'one quadrant drive', 'two quadrant drive' and 'four quadrant drive'?
13. What is meant by four quadrant electric drive? Explain four quadrant operation of an electric drive driving a hoist load
14. Why constant torque operation below the base speed and constant power operation above the base speed of electric drive are used?
15. How can separately excited DC motor drive operate in constant torque and constant power modes?
16. Three phase induction motor drive is capable to operate in constant torque and power modes. Justify comment.
17. Is it possible to operate a synchronous motor drive in constant torque and constant power modes? If yes, justify your comment.
18. What do you understand by closed loop control of electric drives? Discuss advantages and disadvantages of closed loop control over open loop control of the drive.
19. What is the role of speed and current sensors in closed loop control of electric drives? Discuss one method each for speed and current sensing.
20. What do you understand by 'continuous current control' and 'current limit control'?
21. A closed loop drive has precise speed regulation. Discuss how it is possible.
22. Explain closed loop speed control of an electric drive with inner continuous current control loop
23. Recently, digital control is replacing analog control in several applications. What might be reasons?
24. Explain microprocessor based closed loop speed control of an electric drive. Mention its limitations.

25. Applications of digital signal processor is increasing in real time control of electric drives. Give your comments.
26. PI controller is generally used for closed loop speed control. Justify comment.
27. Discuss tachometer sensing. Compare dc and ac tachogenerators with reference to accuracy for speed measurement.
28. Explain tachometer encoder with the help of a suitable diagrams. How is speed measurement is done?
29. Compare merits and demerits of tachometer encoder and incremental encoder.
30. Explain resistor sensing method used for current sensing. What are its drawbacks?
31. Explain Hall Effect current sensing method. Mention its merits and demerits.
32. Explain construction and working of incremental shaft encoder. How can it be used for measuring of high and low speeds?
33. How is an incremental encoder suitable for sensing both speed and position in both directions of rotation?
34. What is the problem with an incremental encoder for sensing shaft position? How is this problem eliminated in an absolute encoder?
35. Explain potentiometer based position sensing. How can it be used as position error detector?
36. Explain an absolute position encoder. How is problem of misalignment eliminated?
37. Explain construction and operation of a resolver. Mention its merits and demerits.
38. Describe one method for converting output analogue signal of resolver into digital signal.