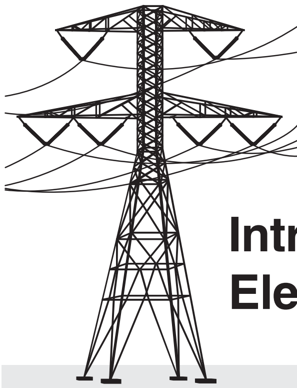


Chapter 1

Introduction to Electric Drives

1.1 PROLOGUE

Every machine that is used in a modern factory, manufacturing unit or transportation unit consists of three parts: (*a*) ***Prime mover i.e., motor or engine,*** (*b*) ***transmission system such as belt, gears etc.,*** and (*c*) ***proper machine***. The prime mover with its system of control and transmission system is called as '*drive*'. Since the most convenient form of power that is available for use in home or industry or farm is electrical, in most places we have electric drive only and is used for converting electric power into mechanical power. Electric drive is therefore defined as: **a form of machine equipment designed to convert electric energy into mechanical energy and provide electric control of this process.** In view of this, fundamental elements of an electric drive are the electric motor, transmission system and electrical control. Since there is a variety of motors, a converting equipment that changes the characteristics of the electric supply, such as form (a.c., d.c. or chopped a.c. or d.c. and frequency and voltage) are changed to match the motor performance to the required load and is also a part of the drive. The main function of the electric drive is to impart motion to the working machine but a modern electric drive with complexity of feedback control can perform several other functions so that the production process is performed in the most efficient manner with high productivity and high quality of the drive.

Historically, the development of different kinds of electric drives used in industry may be divided into three stages: (*a*) ***Group Drives***, (*b*) ***Individual Drives***, and (*c*) ***Multimotor Drives***.

Group Drive

In a group drive a single electric motor drives a line shaft from which an entire group of machines can be operated. This kind of drive is not used in a modern workshop or factory because of its low efficiency and many objectional features.

Individual Drive

An individual electric drive uses a single electric motor to drive each individual machine. Various kinds of electrical hand tools, metal working machine tools, single spindle drilling machines are examples of this kind of drive. Such a drive uses electric motor as an integral part of the machine it drives.

Multimotor Drive

A multimotor drive consist of several individual drives each of which serves to drive one of the many working members of the machine in a production unit. Such a drive is required by complicated metal cutting machine or paper making machinery or rolling mill, industrial robots etc. The use of multimotor drives is continuously increasing due to the complex processes used in production and also due to the use of computers used in control.

1.2 HISTORICAL BACKGROUND

Sometime in the year 3000 B.C. waterwheels were in use for mechanical drive and some of the wind mills still exist and form part in story books. Invention of electric generation was a foundation on which present motor drives are based. However, in the initial stage electricity was generated as d.c. and mostly used for electric lighting. Generation by alternating currents and later development of three phase induction motor started a new age of electric drive. This radically changed the design of machines. The first effect was discarding of line shaft operated drives and their replacement by individual drive. Individual drive reduced the starting time, the most effective speed for machine became possible and reversal of direction became possible with short time. And the most important of all it reduced the distance between driving motor and mechanism to a minimum. It is also important to note that all the electric motors even used today were developed by the end of the nineteenth century with the exception of the special purpose motor used to operate with computers or robots. In other words, the development of electric drive is mostly for development of converters and controllers and controller philosophy and electric drive is subject of interest in general to all concerned and most of the development that we see today is the development that has taken place in the twentieth century. The interesting point to note is, when electric energy is generated at the expense of mechanical energy this is done with the highest efficiency of nearly 33% and when we talk of electric drive, of this one third, two third is converted by electric motors of constant speed type with efficiency of nearly 90% back into mechanical energy but when this energy is actually used by a mechanism nearly 50% of this is wasted by obsolete control methods!

1.3 DRIVE SYSTEMS

Every control process represents a specific association of signal and energy. In connection with signals points to be noted are *(a)* desired value, (*b*) actual value, and (*c*) process of measurement. All mechanical operations are achieved by regulating the flow of mechanical energy. At present there are four different types of drive systems available in the market. These are (1) *Electric Drives*, (2) *Mechanical Drives*, (3) *Electromechanical Drives*, and (4) *Hydraulic Drives*.

Electric Drives

Electric motor drives used in power ranges, from a few watts to several thousands of kilowatts and ranging from very precise high performance position control drive in robotics to variable speed drive for adjusting flow rates in pumps which is not required to be very accurate. Wherever a change in frequency and form (a.c. or d.c.) of the input is needed a power electronic converter is a must.

There exist three main types of electric drive systems today based on (*a*) ***D.C. motors***, *(b)* ***Squirrel-cage induction motors***, and (*c*) ***Slip-ring induction motors***. The choice is influenced by a number of factors such as process requirements, environmental aspects, maintenance, training of personnel and need for low energy consumption. As a result of rapid development that has taken place in control and power electronics there exist a variety of drive systems and for making the choice all the systems have to be weighed against the factors listed above. It is necessary that the person responsible for making the final choice is aware and well informed of all the possible variations.

D.C. motors provide fast and accurate control over a wide range of speed. They are used in the power range of fractional to 10,000 kW and the speed can be controlled with great precision down to 1% of the nominal speed of the motor. The available torque is high in the entire range of speed and multiquadrant operation is usual for drives. When there is a need for high power and high speed a.c. motors have to be chosen. The disadvantage of the d.c. motor is its sensitivity to environment mainly because of the presence of commutator. Usual loads are pumps, fans, machine tools, mine hoists, cranes etc.

Squirrel-cage induction motors are inexpensive, simple in construction, need very little maintenance permit standby duty, are easily adapted to hostile environment, etc. Already installed motors may be upgraded with frequency converters and then run economically. The usual loads are pumps, fans, compressors, machine tools etc.

Slip-ring induction motors have high efficiency over the entire speed range. Due to operation as an induction generator any unutilized power is feedback to the a.c. supply. The starting torque is high (by using the proper starter) and the drive is insensitive to brief supply interruptions. The drive can be adapted to hostile environment. They have highest efficiency among all drives and can be connected directly to high voltage supply. The usual loads are fans, pumps, compressors etc.

Brushless synchronous motors are very reliable in operation and can be used in explosive atmosphere. Since they can generate reactive power by operating at leading power factor, they can supply commutating voltage to the frequency converter and as a result the inverter will be of simple and reliable design. The highest possible speed is 7500 rpm and the power range of available machines is 500 to 50,000 kW. The usual catered loads are large fans, compressors, refineries etc.

As the new ideas are coming forth, many opportunities are available. However, this complicates the selection of the motor and therefore requirement of power semiconductors and converter. The three classical motors as mentioned above operate from pure d.c. or sinewave a.c. electric supply and they can start and run without any kind of electronic controller. All these motors produce almost constant torque with very little torque ripple.

All these motors can also be fed from electronic converters so that they can run at variable speeds. Most of the development that has taken place in power electronics is around these motors.

A squirrel-cage motor is an example of '*Brushless motor*'. To achieve this feature of absence of brushes with classical motors, permanent magnet field may be used. By replacing the field winding on the rotor of a 3-phase synchronous motor it becomes a '*Brushless Synchronous Motor*'. Induction motor in cage form is already '*brushless*'. In case of d.c. motors rotor has to be made from a permanent magnet and the stator has to be made differently. A new class, apart from these varieties are '*Reluctance Motors*' or '*Variable Reluctance Motors*' and '*Switched Reluctance Motors*'. The Stepper Motors are always brushless and almost always operate without shaft position sensing. Their torque is always pulsed but due to large number of teeth and having different number of slots on stator and rotor tends to become smooth. The switched reluctance motor is a derivative of variable reluctance motor with current pulses phased in relation with rotor position. They usually require rotor position transducer. It can produce a continuous ripple free torque and is similar to a brushless d.c. drive. The harmonics caused by switching operation produce parasitic torques, torque ripple and other effects due to which for a given frame size, they have to be derated.

Mechanical Drives

Mechanical drive consist of gas and steam turbines, I.C. engines etc. In general they have lower efficiency than electric drives. The choice is generally dictated by environment particularly the turbine drives as they are suitable for high speed operation.

There are a number of methods of mechanically varying the speed of the driven load when the driving motor is operating at a constant speed. These are typically:

(*a*) Belt Drive

(*b*) Chain Drive

(*c*) Gear Box

(*d*) Idler Wheel Drive

All these methods exhibit similar characteristics where the motor operates at constant speed and the coupling ratio alters the speed of the driven load. As the motor is operating at full voltage and rated frequency it is capable of delivering rated output power. There is some power loss in the coupling device resulting in reduction of overall efficiency. The maximum efficiency depends on design of coupling device and its setting such as belt tension, number of belts etc.

Most of these devices are constant ratio devices and as a result load will be running at a single speed. Some of these methods may allow a variation in speed but are less common and more expensive.

All these methods are constant power (HP) drives obeying the law

$$P = KTN$$

neglecting the losses and the load torque is increased by coupling ratio for reduced speed or reduced by the coupling ratio for increased speed.

Hydraulic Drives

These drives have their own field of application and are suitable for low speed high torque applications. However, process industries are hesitant in their use because of presence of oil.

There are two main methods of hydraulically varying the speed of the driven load when the driving motor is operating at a constant speed. These are:

1. Hydraulic pump and motor
2. Fluid coupling.

In case of a 'Hydraulic Pump' and motor, the induction motor operates at a fixed speed, and drives a hydraulic pump which in turn drives a hydraulic motor. In many respects, this behaves in a manner similar to a gearbox, in that the hydraulic system transfer power to the load. The torque will be higher at the load than at the motor for a load running slower than the motor.

The fluid coupling is a torque coupling where by the input torque is equal to the output torque. This type of coupling suffers from very high slip losses and is used as a torque limited coupling during start with typical slip during run of 5%. The constant power law is applicable but the power in the driven load reduces with speed. The difference between the input power and output power is dissipated in the coupling. In extreme case, when the load is locked and the motor delivering full torque via the coupling, the entire power is dissipated in the coupling. In most applications torque requirement reduces at reduced speed.

Magnetic Drives

There are two main methods of magnetically varying the speed of driven load while the driving motor operates at a fixed speed.

These are:

1. Eddy Current Drive
2. Magnetic Coupling

Both these methods use a coupling method between the motor and the load that operates on induced magnetic forces.

The eddy current coupling is employed with one set of poles coupled to the main motor and the other set coupled to the driven load. The *de bias* on one of the windings is varied and the other set has a shorted winding. When the motor operates, there is a difference in the speed of two rotating magnetic fields and a torque is established. This torque is controlled by d.c. excitation current. Slip power is lost in the coupling.

A magnetic coupling consists of two sets of permanent magnets mounted on driving motor and driven load. It has an advantage of having no mechanical linkage between the two and is most suitable for chemical mixers, stirrers and pumps.

1.4 CHOICE OF DRIVE SYSTEM

Choice of a particular drive system out of the above systems depends upon several performance factors which have to be considered one by one to arrive at the right system of drive.

1. *Shaft power and speed.* By defining shaft power and speed, invariably electric and electromechanical drive remain as competitors but if the cost factor is considered and if the limitations of environment and reliability of the power supply is considered some other solution may emerge.

2. *Speed range.* Speed range remains same within a group or groups.

3. *Power range.* This remains same within a group or groups.

4. *Efficiency.* This remains low for all electromechanical drives.

5. *Starting torque.* More than 100% starting torque is obtainable with more than two groups with some individual difference within group.

6. *Influence on the supply network.* This is minimum for electromechanical drive when compared with electric drives.

7. *Maintenance*. When considered as a group, identical inspection is required for electromechanical and electric drives however, more direct maintenance will be required by an electromechanical drive.

8. *Special competance.* Electromechanical systems are required to have special competance within hydraulics and mechanics.

1.5 SELECTION OF DRIVE FOR INDIVIDUAL APPLICATION

When choice is of variable speed electric drive, there exist today four main types of electric motor drives based on: (1) *D.C. motors*, (2) *Squirrel-cage induction motors*, (3) *Slip-ring induction motors* and (4) *Synchronous motors*. The various aspects and performance figures to be considered are:

(1) Total purchase cost, (2) Cost of energy losses, (3) Influence on power supply such as harmonics in the power supply, power factor, and voltage drop, (4) Environment in which the drive has to function, (5) Availability, (6) Accessibility of the motor for servicing and (7) Service cost during the life time.

The industrial large power electric drives have to be roughly divided into two groups (*a*) Drives with power range below 1000 kW and (*b*) Drives with power range above 1000 kW.

Drives with power range below 1000 kW

General drive for this range is a d.c. motor drive having same performance throughout the entire speed and power range. The speed range available is 1 to 100%. Alternative drive is selected on the following considerations:

(*a*) If the speed range is limited to 50 to 100% such as for pumps and fans, the slip recovery drive is the right choice for power ratings exceeding 300 to 500 kW.

(*b*) If a brushless drive is required, a variable frequency squirrel cage induction motor is selected. In most cases speed below 5 to 10% of maximum speed are not required.

(*c*) Group drives such as roller table drives are best realized with variable frequency motor drives, giving a robust and cheapest solution.

(*d*) The recent changes in technology have made variable frequency drives extremely competitive for small motors in the range 1 to 10 kW compared to d.c. motors.

The slip recovery drive is the given solution for pumps and fans as long as brushes are acceptable on environmental requirements. The converter fed synchronous motor has made possible speeds upto 7500 rpm.

The d.c. motors and synchronous motors are in the competing range for other applications in this range upto 10,000 kW rating. D.C.

motor is still today the motor for rolling mills and mine hoists but the developments of medium voltage converters has given an edge to the synchronous motor for economic advantage.

1.6 CONTROL PANEL REQUIREMENTS

A converter is always mounted in a control panel which receive power input and power output cables from the a.c. supply and the machine that is controlled. Following visual indications may be provided by lamps:

1. Input supply availability
2. All phases in operation
3. Proper phase sequence
4. Controller on and off indication
5. Status of device fuses (if provided)

The measurements of following values may be available by analog or digital meters:

1. Input voltage and current with suitable selector switches
2. Output voltage, current and frequency
3. Reference input (speed)
4. Actual output (speed)
5. Input power factor

Following controls by way of push buttons with indication if necessary may be provided:

1. Controller 'on' and 'off'
2. Motor 'run' and 'stop'
3. Inch 'forward' and 'backward'
4. Emergency stop with (say) dynamic braking

Following reference adjustments by way of potentiometers or thumb wheel switches may be mounted on the panel front:

1. Speed/torque/Horse power reference for output
2. Inch forward/backward speed

Although all these facilities may not be required some of them may be cut short or depending on further requirements additional facilities may be provided.

Control Panel

Electric power is supplied by means of a distribution network but this cannot be continuously connected to the equipment. A switching system must be used, which allows the making and breaking of electric power from the mains to the load. Switchfuses, isolators, circuit breakers and contactors are used to provide this function of *power switching*. In many cases the operator is at a distance from the power switching units and in such cases remote control of power has to be provided. Relays are provided for this purpose and may be controlled by pilot devices and push buttons. Action performed by pilot devices and push buttons is shown by illuminated displays. All such electrical equipment can be mounted quickly and simply in: (*a*) *metal enclosures*, (*b*) *insulated* or (*c*) *one or two door cabinets* designed to resist the severest atmospheric and industrial conditions and serve to work reliably throughout their intended life span. All these enclosures are called *control panels*.

Metal enclosures of welded sheet steel with *V*-channel construction are designed to meet industrial requirements. Insulated enclosures are of fiberglass reinforced polyester especially resistant to the most corrosive atmosphere. Cabinets with single or double door construction are suitable in general for all industrial applications. Removable door-frame provides complete access to the inside of the cabinet for ease of installation and maintenance.The frame is mounted by means of sliding clamps on to channels within the cabinet.

1. Control panel must be manufactured from sheet steel of minimum 2.6 mm (12 SWG) pickled to remove dirt and powder coated for resisting atmospheric effects and rusting. Local reinforcement has to be provided to the rear of the panel for to be relieved of all problems concerning the cycle of operation. (3) In both cases personnel and equipment must be protected. Automatic control is achieved by using float switches, pressure switches, limit switches, proximity detectors, photoelectric detectors etc., interfaced using suitable electronic or electric circuits.

Graphic Representation and Symbols

The active part of an electric system consists of control components (contactors, relays, transformers etc.) and pilot device whose roles are explained on a schematic diagram. After components have been selected, their assembly requires the use of a range of products to aid the mounting, cabling and protection of equipment against ambient conditions which is the role of a control panel.

Graphic symbols and equipment identification is as per international recommendations (IEC, DIN). These recommendations define the rules, graphic symbols and numeric and alphanumeric references which should be used in marking equipment and designing schematics. Observations of these rules leads to standardization, which: (1) promotes internationalization of symbols and references (2) eliminates risks of errors and confusion and (3) simplifies installation and maintenance.

Table 1.1 shows some of the symbols presently in use.

The components of a control panel are identified by following letters followed by numbers:

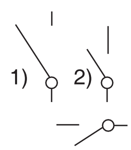
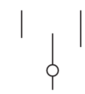
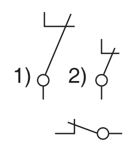
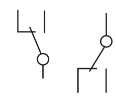
Table 1.1 Symbols for Electrical Terms

Reference	*Equipment*	*Example*
A	Standard assemblies and sub-assemblies	Amplifier, speed and programmable controller
B	Transducers	Thermocouples, thermostat
C	Capacitors	
D	Timers, storage devices	Monostable flipflop
E	Miscellaneous equipment	Lamp
F	Protection devices	Fuses, relays etc.
G	Generators	Battery, alternator
H	Signaling devices	Audio and visual devices

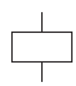
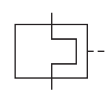
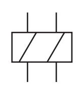
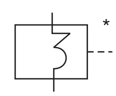
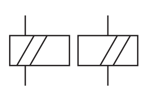
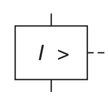
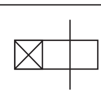
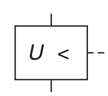
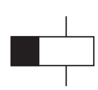
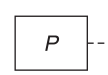
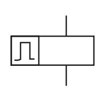
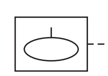
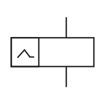
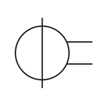
Conductor, main circuit		Tap	
3 conductors	L_1 L_2 L_3	Terminal	
Single line representation		Terminal strip	11 12 13 14
Neutral conductor		Male plug	
Protective conductor	PE	Female socket	
Screened conductors		Plug and socket	
Twisted conductors		Coupled connectors 1. moving part, male 2. fixed part, female	1) 2)
Crossing with no connection			
Crossing with connection (junction)			

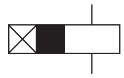
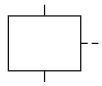
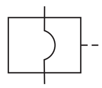
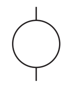
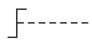
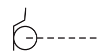
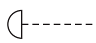
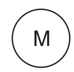
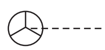
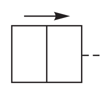
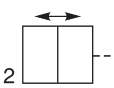
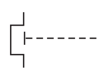
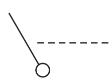
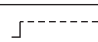
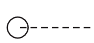
Contacts

Movement of contacts is as follows: from left to right and from bottom to top; the diagram always shows the rest (de-energized) position

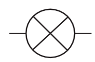
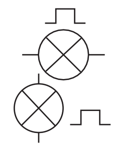
”Make” contact (N/O) (general symbol) 1. main 2. auxiliary		Changeover contact with open neutral position	
”Break” contact (N/C) (general symbol) 1. main 2. auxiliary		Changeover break before make contact	

Control and Measuring Components

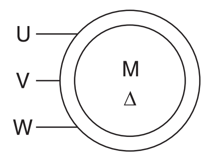
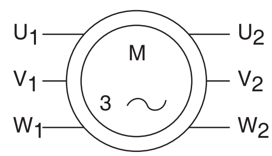
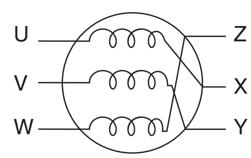
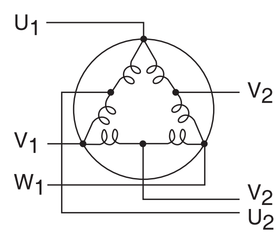
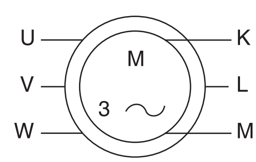
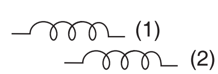
Coil		– thermal overcurrent type	
– with 2 windings (single representation)		– thermal magnetic overcurrent type	
– with 2 windings (comparated representation)		– overcurrent type	
– delayed on energization		– undervoltage type	
– delayed on de-energization		– pressure actuated type	
– of a flasher relay		– actuated by fluid level (float type)	
– of a fleeting relay		Current transformer	

– delay on energization and de-energization		– Lightning conductor	
Measuring relay (general symbol)		Starter	
– magnetic overcurrent type		e.g. star delta starter	
		Indicating device (general symbol)	
– rotary (with latch)		– by cam and roller	
– mushroom head		– by electric motor	
– by hand-wheel		– pneumatic or hydraulic	1 
– by pedal (foot switch)		1. single acting 2. double acting	2 
– with limited access		Operation— to the right	
– by lever		– to the left	
– by lever with handle		– in both directions	
– by key		Rotation – forward direction	
– by crank		– reverse direction	
Latching by push button with automatic unlatching		– in both directions	
Control–by roller		– limited in both directions	

Signalling

Indicator light		Flashing light	

Electric Rotating Machines

Three phase squirrel cage induction motor	
– 2 separate stator windings	
– 6 output terminals (star delta connection)	
– Pole change (2 speed motor)	
Three phase slipring induction motor	
Shunt (1) Series (2) excitation winding	

Main contacts of contactors, isolators, overload relays are referenced by single number, *e.g.,* 1 to 6 for three pole. Odd numbers are placed at the top and numbering progresses from top to bottom and from left to right.

Auxiliary contacts Terminals of auxiliary circuit are referenced by two-digit number. The second digit indicates the function of the auxiliary contact:

1 and 2 normally closed (N/C) contact

3 and 4 normally closed (N/O) contact

5 and 6 normally closed contact (N/C) with special operation (*e.g.,* time delay)

7 and 8 normally open (N/O) contact with special operation (*e.g.,* time delay)

The first digit indicates the physical position of each contact of the component. Number 9 and 0 if required, is reserved for auxiliary contacts of the overload relay followed suitably by 5 and 6 or 7 and 8.

Coil terminals are referenced alphanumerically, with letters followed by numbers *e.g.*, $A1$, $A2$

Control circuit terminals are numbered increasingly from left to right.

Power circuit terminals are referenced as:

Power supply $L1$-$L2$-$L3$-N-PE

To a motor U-V-W; K-L-M

To starting resistances A-B-C etc.

The identification number should be located for components below the symbol and for contacts on the left (vertical representation).

The various parts of the component (*e.g.,* coil, poles, auxiliary contacts etc.) are not shown on the schematic next to each other as they are on the device, but are separated and laid out in an arrangement which gives better understanding of the sequence.

To improve understanding, letters and numbers indicating the device and its type are shown on the left and its terminal marking are shown on the right. The devices are numbered in a logical sequence of their operation. On complex schematics, when it becomes difficult to find all of the contacts of the same device, the diagram of the control circuit will include numerical reference of each vertical line. Written below the coils are the numerical references of the contacts they actuate and the number of the vertical line they are located.

The schematics based on these rules will be seen with reference to 'Induction Motor Starters' in Chapter 4.

Colour Codes for Push Buttons

RED	Stop action or in some case reset action
GREEN	Start after authorization by lighted push button
YELLOW	Start of operation to avoid dangerous condition
BLUE	Any function not covered by other colours
WHITE	Start or preselection of closing of a circuit.

Colour Code for Pilot Lamps

RED	Fault or abnormal conditions, danger
YELLOW	Attention
GREEN	Safe condition
WHITE	Normal condition

1.7 MOTOR CONSTRUCTION AND TRENDS

The materials used for motor construction are the result of technical and commercial development. Due to the commercial pressure of producing the increased output from a given size of frame there has been an increase in the specific output of the machine. A simple step of going to class F temperature levels from class B level will increase the output by about 11%. At present the majority of motors are assigned class B temperature rise while using class F insulation.

Early motor designs had core of large diameter and shaft height above fixing level used to be large. Many a time a motor of one make has to be replaced by another make by adjusting the level by inserting a plate under the new motor and low centre height is a boon in such adjustments. Besides low centre height tends to reduce manufacturing costs. This may be considered by an example. Let us consider two motors of the same active volume. Motor 1 of dia. D and length L. Motor 2 of dia. $2D$ and length $L/4$. For motor 1 the airgap area is double of motor 2. If airgap flux density is same this means motor 1 has twice the flux of motor 2. So, for the same voltage motor the motor turns will have to be doubled leading to increased cost.

Components working in parallel are more conveniently manufactured together to save cost and time and space. This requires that manufacture of frames, cores, coolers and bearings proceed together to produce a single motor with modular construction. Motor cores are assembled separately, so as to occupy minimum space in vacuum impregnating tank.

Steel used to manufacture cores is normally produced in rolls of 1220 mm width. If the lamination can be punched in this width, the core is assembled by single piece laminations. For larger motors, the circle is formed of from a number of steel segments; six segments to form a circle is common. Each segment will be same if the number of slots is divisible by six. It is not essential to have a whole number of slots per segment and on larger machines there may be nine or twelve segments per circle with whole or fractional slots per segment.

The larger motors employ cooling system where cooling air passes radially through ducts of 8 to 12 mm width. These ducts are formed by welding angles or flats to thick punched laminations. These ducts are spaced about 60 mm from each other so that a pack of 1 m core length will consist of about 14 duct spacers.

Low voltage small motors (400 V, 50 kW) use windings formed of enamelled wire. The winding is not formed a rigid mass before winding into slots. Such winding is termed *Random Mush* . The nature of this winding is such that it can be inserted into the semiclosed stator slot wire by wire. For motors of a size capable of being wound by machine, each slot will contain one coil-side and the whole phase group will be wound in a concentric manner. When hand insertion of coil is used, each slot will contain two coil-sides and the winding can be short pitched to save copper and reduce harmonic content of mmf of the winding.

A high voltage winding will have the conductors arranged in a definite relationship to each other and the slot opening will be as large as the slot width, so as to insert the coil sides radially. *Hairpin coil* which was common some years ago, was inserted axially from the slot end into a semi-closed slot. This required each turn being hand connected at the open coil-end resulting into increased costs. The *Pulled diamond* coil was developed and is the most popular coil winding for high voltage motors. Large motors use single turn per coil with each coil side made of transposed bars with *Roebel Transposition* to reduce eddy current and circulating current losses.

All windings have some form of a wedge at the mouth of the slot and this prevents the vibration of the slot portion of the coil during motor operation. The use of semiclosed slots reduce the no-load losses while use of open slots increase the no-load losses. One method that was tried was using magnetic wedges but early magnetic wedges were prone to failure. Some machines were designed with fibre wedges which were continuous in length and having bevel cut in the region of the air-ducts. Magnetic wedges are not easily machined and are confined to core packet length only.

The rotor shaft transmits the output torque to the driven equipment via a coupling. Any shaft must be capable of transmitting the worst torsional stresses and have sufficient stiffness to minimize deflection under conditions of unbalanced magnetic pull. Small motors employ round shafts of adequate steel quality for torsional stresses and good machining property. Large motors have shafts with welded ribs to facilitate airflow and improve shaft stiffness, so weldability of steel is important.

Shaft of a two-pole motor will be circular or have shallow ribs, most probably machined from the shaft material. Further, the shaft will be so designed that it will be at least 15% above or below the critical speed.

Electric motors will use either rolling (ball and roller) or sleeve bearings. Sleeve bearings are white metalled bearings where the journal runs on any oil film against the bearing surface.

Small motors will employ a deep-groove ball-bearing at both the drive and non-drive ends. As the motor size increases, a roller bearing may be used at the drive end to cater for radial thrust of a drive belt, ball bearing being used at the nondrive end to locate the shaft axially. Ideally and on larger motors, two roller bearings are used and an additional ball bearing is used at the drive end, which is free to move in a radial direction. This bearing is solely to locate the rotor axially and can withstand a moderate amount of axial thrust such as produced by a cooling fan. The use of roller bearings is standardized. It is normal to choose bearings which will give life of 50000 to 100000 hours of running.

As per the recommendations of manufacturers, there is a limit to the rolling bearing rotational speed as bearing diameters increase. For this reason and to have extended life large motors with high speed use sleeve bearings. Sleeve bearings will be metalled with either a tin or lead-based white metal. The motors using axial and radial ventilation use a locating bearing at the drive end to take axial fan thrust. Sleeve bearings may have plain or spherical seats between their shells and the bearing housing. This caters for a small degree of misalignment.

Rolling bearings are grease-lubricated, except for a limited use of oil lubrication where high speeds are involved. Sleeve bearings will be oil-lubricated. Cooling of the bearings may be accomplished in 3 ways, (*a*) Natural cooling with heat radiated from the bearing housing surface upto a peripheral speeds of 13 m/s, (*b*) For speeds between 13-15 m/s water cooling by a tube cooler in the bearing sump is satisfactory, and (*c*) Above 15 m/s flood oil will be provided. Main cause of sleeve bearing damage is lack of lubricating oil, for this reason many users prefer to fit a flood oil system if operating conditions make it difficult to see the presence of sufficient oil in the bearing.

When flux carrying path has interruptions, an e.m.f. appears at the two ends of the shaft and if the circuit through frame is not broken current will flow and cause damage to the shaft and bearing which ultimately cause lubrication failure and lead to noisy bearings. Bearing insulation is provided commonly when the core is assembled from segments. Ball and roller bearings can sustain the damage due to shaft currents but sleeve bearings of large motors are prone to damage. Now considerable simplification is achieved by providing insulation on both bearing shells. Usually the drive end insulation is subsequently shorted by an earthing strap of copper to prevent build up of static charge.

Development in the area of power electronic devices is relatively very fast since the SCR was invented in 1959 as a device to replace mercury arc controlled rectifiers. D.C. motor was universally used and thyristor converters were made in various capacities and used with linear controllers. Practically entire range of SCRs is available.

Environmental limitations of d.c. motors have brought forth the variable frequency control of squirrel cage induction motors and due to performance limitations of commutating circuitry power transistors are being used for switching requirements. Power MOSFETS are also in use for lower power requirements and IGBTs and GTOs are in picture for high power PWM type inverters which are more suitable for variable frequency operation of a.c. motors.

As the new ideas are coming, many opportunities are also available. However, this complicates the selection of motors and therefore requirements of power semiconductors and converter. The most important three classical motors are: (1) *D.C. motor with wound field*, (2) *A.C. Synchronous motor*, and (3) *3-phase a.c. induction motor*. All of these produce almost constant torque with very little torque ripple. They operate from pure d.c. or sinewave a.c. electric supply and they can start and run without any electronic controller.

These three types of motors can be coupled to an electronic converter so that they can run at variable speeds. Most of the development that has taken place in power electronics is around these motors. Of these three motors, squirrel cage motor is an example of '*Brushless Motor*'. To achieve this factor of absence of brushes with classical motors, permanent magnet field may be used. By replacing the field winding on the rotor of a 3-phase synchronous motor it immediately becomes a brushless synchronous motor. Induction motor in cage form is already *brushless* but in wound rotor form it cannot be made brushless. In case of a d.c. motor, rotor has to be made a permanent from a permanent magnet but stator has to be made differently. A new class apart from these varieties are reluctance motors and switched reluctance motors or variable reluctance motors. The Stepper motors are always brushless and almost always operate without shaft position sensing. Their torque is always pulsed but due to large number of teeth and having different number of slots on stator and rotor. The switched reluctance motor is a derivative of variable reluctance motor with current pulses phased in relation with rotor position. They usually require a shaft position transducer. It can produce a continuous ripple free torque and is similar to a brushless drive. The harmonics caused by switching operation cause parasitic torques, torque ripple and other effects due to which for a given frame-size they have to be derated.

There are three common reasons for preferring an adjustable/ variable speed drive over a fixed speed drive. These are: (1) *Energy saving to the extent of 50% or more*, (2) *Velocity or position control such as in train, portable tools, washing machines*, and (3) *Reduction of mechanical transients*. The electrical and mechanical stresses caused by '*direct on line*' starters can be eliminated by variable speed drives with controlled acceleration. A soft starter is more economical than a fully adjustable drive.

The factors which are responsible for the progress of variable speed drives are:

1. **Progress in digital electronics.** Control schemes, such as used in steel rolling mills, paper mills etc., require a coordinated control of several shafts by means of a computer or a network of computers. At the other end are drives as used in office machinery and computers. Between these two extremes lie microprocessor controlled systems with all levels of complexity. Initially, microprocessors were used for monitoring and diagnostic functions, which are essentially low speed functions. Recently PWM control of

voltage is becoming standard for a.c. drives. Few microprocessors are fast enough to perform this control. A range of devoted I.Cs. and gate arrays have been also made for this purpose.

2. **Power I.Cs.** Conventional I.Cs. are limited in voltage levels of TTL and CMOS I.Cs. To make them useful for control of power semiconductors, interfacing and level shifting circuitry is required. Recently several power I.Cs. have been designed with voltage ratings 40 to 100 V with sinking and sourcing current capability of 2*A* at 40 to 50 V. This results into saving of a lot of circuitry and design task.

3. **Power Semiconductors.** Power semiconductors used for drives are SCRs, BJTs, MOSFETs, IGBTs. These devices are being constantly improved from their voltage and current ratings, switching speeds, operating frequency and peak current capabilities. Several varieties of SCRs such as GTO, SIT, MCT are produced. The conventional thyristors are used in voltage ratings 500 to 3000 V and switching frequencies of few kHz. The difficulties faced in designing GTO drive circuit are not faced by SIT drive. BJTs are suitable for voltages less than 1000 V. They have low on-state resistance and more or less same operating frequency as a GTO. Power MOSFETs are available upt 750 V and speeds upto 100 kHz. IGBTs have advantages over MOSFETs and BJTs and are more suitable for medium power applications (500 V, 400 A, 50 kHz) and for PWM control.

4. **Advances in magnetic material.** New magnetic materials are responsible for nonconventional motors of brushless types. This has increased number of applications for these motors.

5. **Computer applications in design.** The use of various software for design of motors from various viewpoints such as electromagnetic, material utilization, heat transfer and mechanical design from switch mode supply has made a complicated job easy for multidisciplinary problem.

6. **Progress in Transducer Technology.** It has made possible obtaining of commutation signals for high speed operation for control of motor related quantities.

QUESTIONS

1.1. Explain what you mean by a group drive and individual drive, give examples. What are the merits and demerits of both?

1.2. What are the advantages and disadvantages of electric drive? Which are the other alternatives to electric drive? In what may they are better or worse than electric drive?

1.3. Explain what characteristics of electric motor are required to be considered for selecting an electric motor for industrial application.

1.4. What are the primary types of motor drives?

1.5. What is the colour code used for start and stop push buttons?

1.6. What devices were used for conversion of a.c. to d.c. when semiconductor devices were not available?

1.7. How the frequency of a.c. supply was changed when power electronic converters were not available?

1.8. What are the three important reasons for using Variable Speed Drives?

1.9. Which motors are 'brushless'?

1.10. What is the purpose of a control panel?