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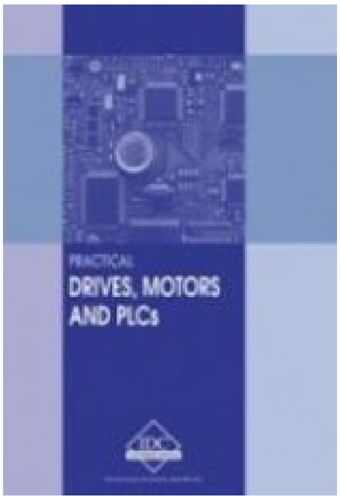
LC-E - Practical Drives, Motors & PLCs for Engineers and Technicians



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Short Description

This manual discusses the technology associated with Drives, Motors and PLCs and their uses in industrial/process plants. It covers the fundamentals of plant layout, the equipment used, design principles and procedures.

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First Chapter

Practical Drives, Motors and PLCs for Engineers and Technicians - The Basic Concepts

1 The Basic Concepts

This chapter introduces the basic engineering concepts of industrial drive and one of its major components – the motors. This chapter also introduces PLCs, which, as the brain of some of the advanced VSD systems, play a significant role in controlling the logical operations of drives of automated machinery.

Learning objectives

In this chapter we will learn the following:

- Variable Speed Drives (VSD) – their utilisation in industry
- Commonly used parameters associated with drives
- VSD for speed control and energy saving
- Basics of electrical machines
- AC power System
- PLC Basics
- PLC and Process Interaction

1.1 Variable speed drives – their utility in industries

There are numerous industrial processes that use variable speed drives (VSD) in one form or other. Chemical industries, power plants, mining, machine shops, food and beverage productions, plastics, textiles and many other processes including HVAC, water treatment plants etc. have been extensively using VSDs for efficient operations and enhanced productivity. Transportation of solid, liquid and gaseous material is another important application area of VSDs. Variable speed drives can be defined as a flexible source of controlled mechanical energy. In general, such mechanisms are used to achieve the following:

- Match the speed of a drive to the process requirements
- Match the torque of a drive to the process requirements
- Save energy and improve efficiency

The variable speed drive mechanism can maintain speed regulation of the driven machine to ±0.1%, independent of load, compared to the conventional fixed speed squirrel cage induction motor, where the regulation would be around ± 3%, from no load to full load.

Likewise, the energy savings , is quite significant, if an adequate torque match is implemented; for example in a centrifugal pump or fan, where the load torque increases as the square of the speed and power consumption,, substantial costs savings can be achieved through proper matching.

The motorcar, an integral part of our daily life, is one such machine which benefits from variable speed control. It is also an excellent example of how variable speed drives are used to improve the speed, torque and energy performance of a machine.

The motorcar has two main controls that are used to control the speed; the accelerator, which controls the driving torque, and the brake, which adjusts the load torque. The driver continuously adjusts the fuel input to the engine (the drive) to maintain a constant speed against resistances such as slope or friction on road or wind flow. He also uses the brake to avoid collisions or to slow the vehicle down to standstill.

A good driver controls fuel input to the engine (as he controls speed) by means of the accelerator. By this method, the energy input to the engine is matched with the load requirement at the driving speed.

Another important issue for most drivers is the cost of fuel or the cost of energy consumption. The fuel consumption would have been exorbitantly high if the driver had used only the brakes to control speed!

1.2 Commonly used parameters associated with VSD

Forward direction - Chosen by designer and designated as positive (+ve); like the forward direction of a car by virtue of its design. Conveyor belts and pumps also usually have a **c**learly identifiable forward direction.

Reverse direction - refers to motion in the opposite direction (to the forward direction and designated as negative (-ve); occasionally used for special situations such as parking or un-parking in the case of a car

Force – it's what causes an object with mass to change its velocity. It has both magnitude and direction and therefore can be +ve (means, applied in forward direction) or –ve (reverse direction). Motion takes place in the direction in which the resultant force is applied. In SI units, force is measured in *Newtons.* Forces acting on 3D objects may also cause them to rotate or deform. The tendency of a force to cause changes in rotational speed about an axis is called torque.

Linear velocity (v) or speed (n) – It is a measure of the linear distance that a moving object covers in a unit of time; velocity imparted is the result of a linear force being applied to the object. In SI units, this is usually measured in *meters per second (m/sec)*. For forward or reverse directions of motion, the velocity is designated Positive (+ve) and Negative (-ve) respectively

Angular velocity (?) or rotational speed (n) - Many industrial applications are based on rotary motion and the rotational force is known as torque. Angular velocity is the result of the application of torque. Angular velocity is the angular rotation that a moving object covers in a unit of time. In SI units, it is radians per second (rad/sec) or revolutions per second (rev/sec) or revolutions per minute (rev/min).

Torque – It's the product of the tangential force *F*, at the circumference of the wheel, and the radius *r* to the center of the wheel and can be +ve or –ve depending, on the direction of application (forward direction of rotation or reverse direction of rotation). In SI units, torque is measured in Newton-meters (Nm).

Figure 1.1 of a motorcar explains how the petrol engine develops rotational torque and transfers this via the transmission and axles to the driving wheels, which converts torque (T) into a tangential force (F). Horizontal motion take place as a resultant force is exerted along the surface of the road to propel the vehicle in the forward direction. Here the acceleration is proportional to the resultant force. As the motorcar moves forward, the torque, speed, and acceleration are therefore, all +ve.

Torque (Nm) = Tangential Force (N) × Radius (m)

Figure 1.1

The relationship between Torque, Force and Radius

Linear acceleration (a) – It's the rate of change of linear velocity, usually in m/sec^2 and may be expressed as **a = (dv/dt) m/sec^2**; also known as deceleration or retardation (**braking**), if the velocity is decreasing (in either direction) with time.

Rotational acceleration (a) – It's the rate of change of rotational velocity, usually in rad/sec^{2}and may be expressed as **a = (d?/dt) rad/sec^2;** also known as deceleration or retardation (**braking**), if the angular velocity is decreasing (in either direction) with time.

Power – It's the rate at which work is being done by a machine. In SI units, it is measured in watts. However, the convention is to measure it in kilowatts (kW) or Megawatts (MW). For rotating machines, power is the product of torque and speed. Output power for a motorcar at rest, is zero. Using SI units, the relationship between power and torque may be written as:

Power (kW) = [(Torque in Nm) X (Speed in rev/min)] / (9550)

Energy is the product of power and time and represents the capacity of doing a work (over a period of time). In SI units it is measured as kilowatt-hours (kWh). It may be formulated as:

Energy (kWh) = *Power* (kW) × *Time* (h)

Moment of Inertia is the property of a rotating object by virtue of which it resists change in rotational speed, whether this be acceleration or deceleration. In SI units, the moment of inertia is measured in kgm^2. Therefore, to accelerate a rotating object from speed $n1$ (rev/min) to speed $n2$ (rev/min), an acceleration torque TA (Nm) must be provided by the prime mover in addition to the mechanical load torque. The time t (sec) required to change from one speed to another will depend on the moment of inertia J (kgm^2) of the rotating system. The rotor comprises of both the drive and the mechanical load. The acceleration torque will be:

The rotational speed (n) can be converted to linear velocity (v) using the diameter (d) of the rotating drum as follows (say for a crane application):

Therefore,

These formulas for power, torque and energy can lead to four possible combinations of acceleration / deceleration (braking) in either the forward or the reverse direction. These are Acceleration Forward / Deceleration Forward / Acceleration Reverse and Deceleration Reverse and can be appropriately expressed in a 4-quadrant torque speed diagram as shown in Figure 1.2.

Figure 1.2

The four quadrants of the torque speed diagram for a motorcar

1.3 Variable speed drives for speed control and energy saving

From the previous discussions, we observed that speed control may be achieved by:

- Controlling the power to the drive (drive control) or
- Varying the load (load control).

Other important observations are:

- Reverse rotation or torque is sometimes required and
- The load, friction and inertia restricts rotation.

Figure 1.3 is a plot of the torque / speed curve of the motor (**upper of the two plots**) and the load (**lower of the two plots**). It is important to note that a motor torque / speed curve is always unique and has to be calculated for every motor type**,** separately. The motor will automatically accelerate until the load torque and motor torque are equal; note the intersection of the two curves. Such curves are often used to illustrate performance of VSD**s**.

Figure 1.3

Torque / speed curves of a motor

Note: The area between the two curves indicates the torque available to accelerate the load

We will now study the drive / load characteristics of two common VSD processes, namely:

- speed control of a motorcar and
- speed control of a centrifugal pump.

From the curves we can find out how speed controls and energy savings can be achieved by using variable speed drive strategy.

1.3.1 Torque – speed characteristics; motorcar

Figure 1.4 indicates the torque – speed curves for a motorcar. It may be noted here that since energy consumption is directly proportional to power, energy also depends on the product of torque and speed. Note: *Power (kW) = [(Torque in Nm) X (Speed in rev/min)] / (9550).* For the motorcar, depressing the accelerator produces more torque that provides acceleration and results in more speed; this consumes but more energy in terms of more fuel consumption.

For the motorcar, the speed control may be achieved through one of the two strategies described below:

Control speed by using drive (engine power) control: adjust fuel supply to the engine, using the accelerator for control, without using the brake.

Control speed by using load (resistance to motion) control: adjust overall torque of the load; keep a fixed accelerator setting and use brakes.

In Figure 1.4, the two solid curves represent the drive torque output of the engine over the speed range for two fuel control conditions:

- High fuel position – accelerator full down (curve D C A) and
- Lower fuel position – accelerator partially down (curve H B G).

The two dashed curves in Figure 1.4 represent the load torque changes over the speed range for two mechanical load conditions. The mechanical load is mainly due to the wind resistance and road friction, with the restraining torque of the brakes added.

- Wind and friction plus brake ON – high load torque (curve J C E) and
- Wind and friction plus brake OFF – low load torque (curve K B A)

Figure 1.4

Torque –speed curves for a motor car plotted for different drive / load conditions

Assuming the motorcar traveling on an open road at a stable speed with the brake off and accelerator fully depressed, the main load is the wind resistance and road friction. The engine torque curve and load torque curve cross at point A, to give a stable speed of, say, 110 km/h. When the car enters the city limits, the speed is reduced to be within, say, 60 km/h limit. This can be achieved in one of the two ways:

- **Reduce Fuel input**; the speed decreases along the load-torque curve A B K. A new stable speed of 60 km/h is reached at a new intersection of the load–torque curve and the engine–torque curve at point B.
- **Apply the brakes**; the speed decreases (with a fixed fuel input setting) along the drive torque curve A C D due to increase in load torque and a new stable speed of 60 km/h is reached.

As mentioned previously, the power is proportional to Torque × Speed; in the graph of Figure 1.4, the drive speed control method is represented by Point B and the brake speed control method is represented by Point C. From the formulas of power and energy computed earlier, the differences in energy consumption between points C and B may be written as:

, or

We can, therefore, conclude that the energy saved by using drive control is directly proportional to the difference in the load torque associated with the two strategies. This illustrates how speed control and energy savings can be achieved by using a variable speed drive, such as a petrol engine, in a motorcar. The variable speed drive strategy would also ensure reduced wear on the transmission, brakes and other components of the motorcar.

1.3.2 Flow - head characteristics; centrifugal pump

Another application of VSD is the control of speed of the prime mover (of, say, a pump) to match the process conditions (in this case, flow requirements). The control can be achieved manually or through automatic control by using a feedback controller. In pumping applications, Q–H curves are commonly used for selecting suitable pumping characteristics and these are similar to torque speed curves. Figure 1.5 shows a typical set of Q–H curves. Q represents the flow, measured in m^3/h and H represents the head, measured in meters.

From the curves, it may be seen that when pressure head increases on a centrifugal pump, the flow decreases and vice versa. In a similar way to the motorcar example, fluid flow through the pump can be controlled either by controlling the speed of the motor driving the pump or by closing an upstream control valve (known as throttling). This increases the effective head on the pump that, from the Q–H curve, reduces the flow.

Figure 1.5

Q-H Curves for a centrifugal pump (Note: such curves are unique to a pump and process)

Similar to the motorcar example, the reduction of flow from $Q2$ to $Q1$ can be achieved by using one of the following two alternative strategies:

Drive speed control, flow decreases along the curve A–B and to a point on another Q– H curve. As the speed falls, the pressure/head reduces mainly due to the reduction of friction in the pipes. A new stable flow of $Q1$ m^3/h is reached at point B and results in a head of $H2$.

Throttle control, an upstream valve is partially closed to restrict the flow. As the pressure/head is increased by the valve, the flow decreases along the curve A–C. The new stable flow of $Q1$ m^3/h is reached at point C and results in a head of $H1$.

From the well-known pump formula, the power consumed by the pump is:

Pump Power (kW) = k × *Flow* (m3/h) × *Head* (m); i.e., *Pump Power* (kW) = $k \times Q \times H$

The Absorbed Energy (kWh) = $k \times Q \times H \times t$

We can compute that the energy difference $EC - EB = K\,(H1 - H2)$

Thus, by using drive speed control instead of throttle control, we save energy which is directly proportional to the difference in the head associated with the two strategies. Such energy savings on large pumps can be quite substantial and these can readily be calculated from the data for the pump used in the application.

Advantages of using Variable Speed Drives for pumps

- Smooth starting, smooth acceleration/deceleration; this reduces mechanical wear and water hammer.
- Current surges in power supply system avoided through feedback controls.
- Substantial energy savings possible; significant with centrifugal loads

such as pumps and fans because power/energy consumption increases/decreases with the cube of the speed.
- Speed controlled in response to the process, leads to very high accuracy for a wide range of process demands.
- Flow, pressure and other parameters (such as batch mixing) can be controlled automatically; the speed control device can be linked to a process control computer such as a PLC.

1.4 Basic principles of motor technology

The majority of machines using variable speed drive technology are commonly driven by electric motors. These motors are prime movers of most of the industrial processes. In the following paragraphs we will take a closer look at the basic engineering principles and technology behind electrical motors – which are the drives for most of the VSD systems.

1.4.1 Basic electrical concepts

Electricity is found in two common forms, namely: - A.C. (Alternating Current) and D.C. (Direct Current).

Electrical equipment can run on either of the two forms of electricity. Each energy source has its own merits and demerits. For commonly used A.C. power sources, it may be L.V. (Low Voltage) or H.V. (High Voltage); frequency may be 50 Hz. or 60 Hz.

Voltage, Current and Resistance

The three basic components of an electrical circuit are:

- Voltage (volts) - electrical potential difference that causes electrons to flow in a circuit
- Ampere (Amps) – parameter which is indicative of flow of electrons in a circuit
- Resistance (Ohms) – it is a measure of opposition to flow of electrons in a circuit.

These parameters are linked together by Ohm’s law which states that:

Electrical power

For a DC circuit, the power (in watts) is the product of voltage and current. It is also the same for a purely resistive AC circuit. However, for inductive and capacitive circuits, it can be further subdivided into real power and apparent power. This is because electrical circuits, comprising of capacitances and inductances, would consume part of the total power supplied to them. This is known as reactive power. The actual power which can be converted to work (real power), is therefore less than the supplied power (apparent power).

Relationship between powers

Apparent Power (VA) =

True Power (Watts) =

Reactive Power (VAR) =

Power factor

It is the ratio between real power and apparent power. Obviously, for a resistance (only) circuit the power factor is 1 (or 100%) maximum value it

% voltage regulation

In terms of power engineering, the voltage regulation is the ability of a system to provide near constant voltage over a wide range of load condition. It is defined as

Where *Vnl* is voltage at no load and *Vfl* is voltage at full load. A low value of *Vr* is desirable.

Electrical energy

Defined as the amount of electrical energy used (consumed) in an hour; can be expressed as **Kilowatt-hour = kW × h;** *h is time in hour.*

Types of electrical circuits

An electrical circuit can be a ***Series circuit***, where all elements of the circuit are in series, i.e., they carry the same electrical current whilst voltage drops may be different. A ***Parallel circuit***may be defined as where the elements are in parallel and therefore have the same voltage drop across them, although the individual currents may be different.

1.4.2 Basic principles of electrical machines

Electromechanical energy conversion

It's the method of energy conversion between electrical and mechanical forms. Eelectromechanical energy conversion devices can be divided into three categories:

- Transducers (for measurement and control); like microphones, speakers etc.
- Force producing devices (linear motion devices); like relays, solenoids, etc. and
- Continuous energy conversion equipment; like motors and generators.

We would study, in brief, the third method of electromechanical energy conversion in its following two forms:

The electromechanical conversion depends on the interrelation between:

- Electric and magnetic fields and
- Mechanical forces and motion.

In rotating machines, power is generated by the relative motion of the coils (commonly known as stator and rotor). For a generator, the winding is rotated mechanically in the magnetic field. This causes the flux linkages with the windings to change, causing induced voltages. In case of a motor, the current carrying conductor is allowed inside a magnetic field. Mechanical force is exerted on a current carrying conductor in a magnetic field and so a resultant torque is produced to act on the rotor. In both the cases, current carrying conductor is in the magnetic field. The conductors and flux travel with respect to each other at a definite speed. In rotating machines, both voltage and torque are produced. Only the direction of power flow determines whether the machine is working as a generator or a motor.

In a generator, the power is supplied by the prime mover. Electrical power is produced by the action of the generator and the resultant power produced due to friction is lost. Whereas in the case of the motor, the power is supplied by the electrical power supply inputs, and there is a slight loss of the resultant mechanical power produced due to friction.

1.4.3 Basic principles of electromagnetism

Every electric charge has its own electric field, called the lines of force. These lines point away from the positive charges and converge towards negative charges. Each charge exerts force on the other charge. These forces are tangential to the lines of force created by the other charge. (See Figure 1.6).

Figure 1.6

Electric force line of a charge

Similarly, the magnetic field lines "flow" away from the N-pole and towards the S-pole. A Magnetic field is created by current due to movement of electric charges. Every orbiting electron forms a current loop that creates its own magnetic field. Magnetic field lines always form circles around the current creating them (see Figure 1.7).

Figure 1.7

Magnetic field lines around a current carrying conductor

Magnetic field produced by a current carrying conductor

The magnetic field produced by a current carrying conductor will surround the conductor. The direction of the current and the direction of the field are decided by **Right-hand rule** (Figure 1.8 below).

Figure 1.8

The right hand rule; note the direction of current and magnetic lines of flux

Flux produced by current carrying coil

Flux can be produced if current flows through a coil, instead of a conductor. The introduction of magnetic material, as the core on which the coil is wound, increases the flux. The direction of the magnetic flux in the coil, is given by the Right-hand rule.

In the case of a motor, the direction of the emf induced is such as to oppose the flow of current. Whereas, in a generator the emf induced is in such a direction as to establish a current.

Fleming’s left-hand rule

Fleming’s left hand rule helps in understanding the relation between the direction of the current, the direction of field, and the direction of the motion. If the forefinger of the left hand points in the direction of the field, the middle finger points in the direction of the current, and the thumb points in the direction of the motion. (See Figure 1.9 below).

Figure 1.9

Demonstration of Fleming’s Left hand rule (image – courtesy magnet lab; Univ. of Florida)

1.4.4 Transformer basics

A transformer transfers electrical energy between two circuits. It usually consists of two wire coils wrapped around a core. These coils are called the primary and secondary windings. Energy is transferred by mutual induction, caused by a changing electromagnetic field. If the coils have different number of turns around the core, the voltage induced in the secondary coil will be different to the voltage on the primary side.

Alternating current in the primary winding creates an electromagnetic field that induces a current in the secondary winding when the field changes. Typically, the coil connected to the source is known as the Primary, and the coil applied to the load is referred to as the Secondary coil.

Small transformers use enameled wire for their windings, whilst large transformers use insulated copper strips. The core of the transformer is used to direct the electromagnetic field through the secondary winding. Silicon steel cores are used for their high magnetic permeability. The insulated laminations work better than solid cores, by confining eddy currents, which reduces their losses.

Figure 1.10

Schematic diagram of a single phase transformer

A single-phase transformer consists mainly of a magnetic core on which two windings, primary and secondary, are wound. The primary winding is supplied with an AC source of supply voltage V1. The current Iflowing in the primary winding produce flux which varies with time. This flux links with both the windings and produces induced emf’s. The emf produced in the primary winding is equal and opposite of the applied voltage (neglecting losses.) The emf is also induced in the secondary winding due to this mutual flux. The magnitude of the induced emf depends on the ratio of the number of turns in the primary and the secondary windings of the transformer.

Potential induced

The potential induced in the secondary depends on the turns ratio between the primary and the secondary. If N1 and N2 are the number of turns in the primary and the secondary respectively then we can write:

For N1 > N2, the voltage induced in the secondary is less than the primary voltage and the transformer is called a *step-down transformer*. For N1 < N2, the voltage induced in the secondary is more than the primary voltage and the transformer is called a *step-up transformer*.

Induced current

Since, in an ideal condition (i.e., without any losses), the power transferred to the secondary is identical to the power input at the primary, we may write the equation for induced current as:

EMF equation of a transformer

R.M.S. value of induced emf in the primary winding is and R.M.S. value of the induced emf in the secondary winding is

Where

N1 Number of turns in primary

N2 Number of turns in secondary

Øm Maximum flux in core

f Frequency of AC input in Hz.

Transformers categorized based on application

Power Transformers – used to change voltage / current levels as per requirements

Potential Transformers – used for precision voltage step-down purpose

Current Transformers – used for current measurement through HV/LV isolation

Isolation Transformers – used for galvanic isolation without changing V/I levels

3-Phase Transformers

Large-scale generation of electric power is generally 3-phasic, with voltages reaching 11 or 32 k volts. For such high 3-phasic voltage transmission, distribution requires the use of 3- phase step-up and step-down transformers.

Transformers used in three-phase systems may consist of a bank of three single-phase transformers, or a single three-phase transformer which is wound on a common magnetic core. A three-phase transformer wound on a common core offers advantages over a bank of single-phase transformers. A three-phase transformer wound on a common core is lighter, smaller and cheaper than the bank of three single-phase transformers. The common core three-phase transformer also requires much less external wiring than the bank of single-phase transformers and can typically achieve a higher efficiency.

Figure 1.11

3-phase transformers (a) 3-wire delta connections and (b) 4-wire star connections

Commonly used 3-phases are 3-phase three wires (Delta) or 3-phase four wires (Star) connected transformers.

Figure 1.11 A and Figure 1.11 B respectively are connections diagrams for a 3 – phase 3 wire delta and 3 – phase 4 – wire star connected transformer.

For Delta connections:

Relationship between line and phase voltage is:

VL = Vph, where VL is the Line voltage and Vph the Phase voltage.

The relationship between the line and phase current is:

IL = ?**3 Iph** where IL is the Line current and Iph the Phase current.

For Star connections:

Relationship between line and phase voltage is:

VL = ?**3 Vph** where VL is the Line voltage and Vph the Phase voltage.

Relationship between the line and phase currents:

IL = Iph where IL is the Line current and Iph the Phase current.

Output power of a 3-phase transformer in kW:

Where Vl Line voltage Il Line current and Cos ? power factor.

Important points about transformers

- Used to transfer energy from one AC circuit to another
- Frequency remains the same in both the circuits
- No ideal transformer exists
- Also used in metering applications (CT and PT)
- Used for isolation of two different circuits (isolation transformers)
- Transformer power is expressed in VA (Volt amperes)
- Transformer polarity is indicated by using dots. If the primary and secondary windings have dots at the top and bottom positions (or vice versa) in diagrams, then it means that the phases are in an inverse relationship.

1.4.5 Basic principle of motors

All motors work on the principle that when "a current carrying conductor is placed in a magnetic field, it experiences a force". For a simple DC motor, there is a current carrying coil supported in between two permanent magnets (opposite pole facing) so the coil can rotate freely inside. When the coil ends are connected to a DC source, current flows through it and the coil behaves like a bar magnet as shown in Figure 1.12.

As the current starts flowing, the magnetic flux lines of the coil will interact with the flux lines of the permanent magnet. This will cause motion of the coil (Figure 1.12, 1, 2, 3, 4) due to force of attraction and repulsion between two fields. The coil will rotate until it achieves the 180 degrees position, whereupon the opposite poles will be in front of each other (Figure 1.12, 5) and the force of attraction or repulsion no longer exists.

Figure 1.12

Motor action

As the current starts flowing, the magnetic flux lines of the coil will interact with the flux lines of the permanent magnet. This will cause motion of the coil (Figure 1.12, 1, 2, 3, 4) due to the force of attraction and repulsion between two fields.

The coil will rotate until it achieves the 180 degrees position, as now the opposite poles will be in front of each other (Figure 1.12, 5) and the force of attraction or repulsion no longer exists.

The role of the commutator in a motor:

The commutator brushes just reverse the polarity of DC supply connected to the coil. This will cause a change in the direction of current of the magnetic field and start rotating the coil by another 180 degrees (Figure 1.12, 6). The brushes will move on like this to achieve continuous coil rotation of the motor. Similarly, the AC motor also functions on the above principle, except here, the commutator contacts remain stationery, because AC current direction continually changes during each half cycle (every 180 degrees).

1.4.6 Basic principle of generator

The action of the generator is similar to that of a motor and can be demonstrated with the motor's diagram itself. In principle, an AC generator's construction is similar to the construction of the motor. Instead of feeding the current in, we draw current out from the coil in an alternator.

A mechanical prime mover rotates the coil in between the poles of a permanent magnet and an AC potential is induced in the coil. As per Faraday's law, when a wire is moved in to cut across magnetic field lines, a force is exerted on the charge (electrons) in the wire by trying to move them along the wire. This is how current will start flowing, if a complete circuit is provided to it. The magnetic field is provided not by magnets, but by field coils. The coil in which the voltage is induced is called armature winding, while the coil that provides the magnetic field is called field winding.

Practically in high voltage generators, it is not good practice to have the armature rotating due to current collecting brushes of high ratings that are required to be installed. Rather, the armature is kept stationary and field rotates.

Alternators of low capacity make use a permanent magnet as a field, while in high capacity alternators, the field winding supply is derived from the exciter assembly, which is a small alternator connected on the same shaft.

1.4.7 Basic principle of electrical machines

An idealized machine

This has a stationary member called a stator and a rotating member called a rotor. The rotor is mounted on bearings fixed to the stationary member. The stator and the rotor have cylindrical iron cores, separated by an air gap. Both stator and rotor have windings on their own core. A common magnetic flux passes across the air gap from one core to another forming a combined magnetic circuit. Two cylindrical iron surfaces with an air gap between them move relative to each other. The cylindrical surface may be divided by an even number of salient poles with spaces in between, or it may be continuous with slot openings uniformly spaced round the circle. This structure may be for either of the stator or the rotor.

Figure 1.13

Common features of an ideal electric machine

The common features of an ideal electrical machine are shown in the Figure 1.13 above. For windings, conductors run parallel to the axis of the cylinders near the surface. The conductors are connected into coils by the end connections outside the core and the coils are connected to form the windings of the machine.

The operation of the machine depends on the distribution of the currents around the core surfaces and the voltages applied to the windings. In various types of electrical machines, the arrangement differs in the distribution of the conductors, windings, and in core constructions depending on whether it is a continuous or a salient pole type. The magnetic flux permeates the iron cores in a complex manner. However, as the iron has a high permeability, the accurate working of a machine can be determined by considering the flux distribution in the air gap. The conductors are actually located in slots formed in the laminations of the core.

Types of electrical machines

There are two main categories; DC machines and AC machines **-** DC machines have an edge over AC when it comes to the speed control of a motor.

DC Shunt motor

This machine has a field winding mounted in the yoke and the armature winding is mounted on the rotor. The shunt motor is used where speed regulation is important.

DC Self-excited motor

The field winding is connected in parallel (shunt) with the armature winding on the same supply. Changing the field current can vary the speed. Torque is proportional to the armature current. This machine can also act as a generator. To limit the high starting current of the motor, the drive releases the voltage in a ramped manner. For this motor, a variable resistor is connected in series with the field circuit to change the flux value and the speed by a small amount.

DC Separately excited motor

The field winding is connected in parallel (shunt) with the armature winding, with separate excitation. Torque is proportional to the armature current. In a separately excited shunt motor, speed can be varied up to a certain limit by changing the armature voltage. After that, using field weakening (reducing field current), it is possible to increase the speed of motor above it’s base speed. Other features remain the same as that of the self excited motor.

DC Series motor

As the name suggests in this type of motors, the field winding is connected in series with the armature winding. Naturally, heavy current will pass through it, so the field winding is of a thicker gauge. The Series motor is used where speed regulation is not important. The main advantage of this motor is that a high torque can be obtained, which makes it useful for applications such as diesel locomotives, cranes, etc. The relationship between Torque and current is expressed as **T** ? $\mathbf{Ia}^{2.}$ It is important to start this motor in a loaded condition, or else it could lead to damage of the motor and its surroundings.

DC Compound motor

If we combine both the series and the shunt motor, then we will have a compound motor. This combines the good features of both types, such as the high torque characteristics of the series motor and the speed regulation of the shunt motor.

AC Squirrel cage induction motor

AC machines are simple and sturdy. A simple definition for an AC induction motor is that it is essentially a rotating transformer. The most common machine of this type is the Squirrel cage induction motor (name was derived from its construction type). Speed of this motor is expressed by the relation **N (RPM) = 120 f / p**, where f is frequency and p is the number of poles.

AC Wound rotor motor

This is similar in construction to the squirrel cage and works similar to the squirrel cage machines except that slip rings are provided. The main feature of the slip ring motor is that the starting current is limited by resistors, which are connected in series with the rotor circuit.
The motor starts with a full resistance bank, but as speed of the motor increases, the resistances are shorted, one by one. As the motor reaches full speed, the whole bank of resistance is shorted out and the motor now runs as a normal induction motor.

AC Synchronous motor

Synchronous motor is a constant speed motor which can be used to correct the power factor of the 3-phase system. Like the Induction motor in terms of the stator, the synchronous machine has either a permanent magnet arrangement or an electromagnet (with current supplied via slip rings) rotor. In simple terms, the rotor will keep locking with the rotating magnetic field in the stator. So, a 2-pole machine will run at exactly 3000 RPM. In many synchronous machines, a squirrel cage is incorporated into the rotor for starting. Therefore, the machine acts as an induction motor when starting and as it approaches synchronous speed, it will suddenly ‘lock in’ to the synchronous speed.

1.5 AC power systems

1.5.1 Single phase power system

The power in a single-phase system is shown in Figure 1.14. In the figure, the current (I) lags the Voltage (V) by an angle ?. The current has two components – the energy component and the watt less component. Only the energy component has a power value. Hence, the power in a single-phase circuit can be written as: **P = V x I x cos,** where P is power (watts), V is voltage (rms), I is current (rms) and Cos ? = power factor.

Figure 1.14

Single Phase power supply

1.5.2 Three phase power system

The three windings of a 3-phase transformer (or an alternator) can be connected in either the Delta or Star mode, as shown in Figure 1.15a and Figure 1.15b respectively

Figure 1.15a

3-phase Delta connection

Figure 1.15b

3-phase Star connection

The relationship between the phase voltages and the currents, and the line voltages and the currents are as follows:

For Delta-connected system

Line Voltage = Phase Voltage, Line Current = ?3 x Phase Current

For Star-connected system

Line Voltage = ?3 x Phase Voltage, Line Current = Phase Current

In a star connection, a neutral point is available. Generators are generally star wound and the neutral point is used for earthing. The 3-phase motors can be either delta or star connected. Usually, delta connections are used for low voltage, small size motors to reduce the size of the windings.

3-phase currents are determined taking each phase separately and calculating the phase currents from the phase voltages and impedances. In practice, the calculations are simple and straightforward as 3-phase systems are usually symmetrical; the loads are therefore balanced load. The calculations for currents, power, etc. can be done using the expression given below. However, for unsymmetrical or unbalanced systems, the calculations and expressions given below do not hold true. In such cases, the calculations are rather complex.

The power in a 3-phase system is the sum of the power of the three phases. Let us consider a balanced delta or star connected system.

The total power, for the 3-phase system, will be:

P = ?3 x V x I x cos ? **(Watts);** V is line voltage, I line Current **and** Cos ? power factor

Power measurement in 3-phase system

3-phase electrical power can be measured with a wattmeter. The true or real power is directly shown in a wattmeter. The wattmeter has two elements which indicate both balanced and unbalanced loads. The measurement process is shown schematically below, in figure 1.16. It is important to note that the reading of one wattmeter should be reversed (by reversing the lead of one wattmeter) if the power factor of the system is less than 0.5. In the case of a power factor less than 0.5, the readings must be subtracted instead of added. The power factor of the 3-phase system, with the two wattmeter method (W1 and W2) can be calculated as:

The summing and subtraction of readings are done to calculate total true power of a 3? system.

Figure 1.16

Measuring power in 3-phase method; 2 wattmeter method for balanced/unbalanced load

Power factor meter

This is similar to a wattmeter. It has two armature coils which are provided with mountings on a single shaft. They are 90 degrees apart from each other. Both armature coils rotate as per their magnetic strengths. One coil moves proportional to the restive component of the power, while the other coil moves proportional to the inductive component of the power.

Energy meter

Energy meters are used to measure the amount of power (electric energy) consumed over a certain period of time. In a watt-hour meter, there are two sets of windings. One is the voltage winding while the other is current winding. The field developed in the voltage windings causes current to be induced in an aluminum disk. The torque produced is proportional to the voltage and current in the system. The disk, in turn, is connected to numeric registers that meters electric energy used, in terms of kilowatt-hours.

1.6 Programmable logic controllers

A Programmable Logic Controller, or PLC for short, is, as the name suggests, a programmable device (that means, a device with a built in processor) which is extensively used in industrial control systems. They are used in many industries including all industries where VSDs are used and provide a flexible way to eliminate hardwired control logics. PLCs are programmed to application's requirement and therefore can surpass the hazard of changing the wiring when requirements changes.

PLCs have a CPU (a computer processor) that is dedicated to run a specific process and for that, it monitors a series of different inputs and logically manipulates the outputs for the desired control. They are meant to be very flexible in how they can be programmed while also providing the advantages of high reliability, compact and economical over traditional control systems.

All PLCs have a programming unit where the actual control logic for the process is first developed, and then transferred to the processor of the PLC itself.

1.6.1 What a PLC can do?

Interestingly, a PLC can do almost all the necessary tasks of an industrial control equipment; a few of them are listed below:

- It can perform relay-switching tasks
- It can conduct counting, calculation and comparison of analog process

values

- It offers flexibility to modify the control logic, whenever required, in the shortest time
- It responds to the changes in process parameters within fraction of seconds
- It improves the overall control system reliability
- It is cost effective for controlling complex systems
- Trouble-shooting becomes simpler and faster
- An operator can easily interact with the process, with the help of the HMI (Human-Machine Interface) computer.

A practical example of one of the highly sophisticated PLC based Drive is Mitsubishi Electric Automation Inc. A700 drive which has a built-in programmable logic controller (PLC) and features other special technologies for Electric servo drive products, such as adaptive auto-tuning which automatically compensates for changes in load inertia..

The torque control obtained through this unit is ultra-fast and suited to all types of variable speed drive requirements$, ranging from high starting torque for heavy industrial machinery, pulse loading for rapid and irregular speed change cycles, to smooth torque delivery requirements for critical speed-based applications. The result is smoother operation, less downtime and ultimately, lower operating costs.
Ref: http://www.mitsubishi-automation.com/products/inverters_fr_a_700.htm

1.6.2 Basic block diagram of a PLC

Figure 1.17 is the basic block diagram of a PLC. As may be seen here, the heart of the "PLC" in the center is the Processor or CPU (Central Processing Unit).

Figure 1.17

The basic block diagram of a PLC

The CPU regulates the PLC program, data storage, and data exchange with I/O modules.

Input / Output Modules are the second important (and basic) components of any PLC system. These are the media for data exchange between field devices and CPU. They provide information to the CPU about the exact status of field devices and also act as a tool to control them.

The programming device is the third significant component. These are typically computers loaded with programming software, which allows a user to create, transfer and make changes to the PLC software.

Memory is the fourth notable component. Memory provides the storage media for PLC program as well as different data.

1.6.3 Components of a PLC system

Figure 1.18

Components of a PLC system in simplified form

CPU or processor

The main processor (Central Processing Unit or CPU) is a microprocessor-based system that executes the control program, after reading the status of the field inputs and then sends commands to the field outputs. It is easy to perform arithmetic functions, manipulate data and calculate Boolean logic.

The PLC’s memory contains the manufacturer’s operating system and housekeeping functions. It also has the program written by the user and data stored by the user related to the process or equipment being controlled. Memory can be volatile (loses information on loss of power) and non-volatile (retains information, even if power is lost). Most PLCs may make use of a combination of both types of memory.

The CPU card is connected to the I/O modules through back-plane connections inside the rack or chassis. Hence, it is possible for the CPU to read the status of all input modules through the data bus. This is called local the I/O chassis.

If the I/Os are located at remote places, the CPU accesses them through a remote I/O chassis. In such a case, the remote chassis will have a remote I/O communication module. It collects the data from I/O modules and sends it to the CPU through an I/O rack communication link. This is particularly useful when the process is divided up, and located in remote parts. The CPU card has ports for communicating with the programming device and operator’s station (or HMI).

I/O section

The I/O section consists of a rack and individual I/O modules, which are plugged into the rack and a DC power supply. A standard approach is to connect to the main processor rack with communication cables to a series of other I/O racks. I/O modules act as “Real Data Interface” between field and PLC CPU. The PLC knows the real status of field devices, and controls the field devices by means of to the relevant I/O cards. Various I/O modules are available. Each one of these will be discussed in more detail in the following sections.

Programming device

A CPU card can be connected with a programming device, through a communication link, via a programming port on the CPU. Thus, it is possible to transfer programs from the programming device to the CPU, monitor the CPU’s program online and make the necessary changes in the CPU’s program.

Operating station

An operating station is commonly used to provide an "Operating Window" to the process. It is usually a separate device (generally a PC), loaded with HMI (Human Machine Interface software). This operating station can change any process set point, observe all process parameters, process alarms, etc.

1.7 PLC and process interaction

The following section gives a glimpse preview of the methods and procedures of interaction between the PLC and the process, through the PLCs input and output ports. This is a brief explanation of role of different I/O modules as a part of PLC and process interaction.

The field devices or field data are broadly classified as follows:

- Digital or discrete or on/off type field devices
- Analog or continuous type field devices.

1.7.1 PLC and digital I/O

Figure 1.19

Digital I/O process interaction

Figure 1.19 above shows how different types of digital or discrete field devices are connected to the PLC through digital I/O modules.

Discrete or digital inputs are the most common types of field inputs. Selector switches, pushbuttons, limit switches, temperature switches, level switches, flow switches, etc., are common examples. All types of switches that permit a digital contact are included in this class. Depending on the field device contacts, they are normally connected to 110V AC, 230V AC and, 24V DC types of digital input cards installed in the PLC rack. It is assumed to be 24V DC in the above figure.

Solenoid valves, relays and auxiliary contactors are discrete or digital output devices commonly used in the field. Depending on the field devices 110V AC, 230V AC and 24V DC types of digital output cards are installed in the PLC rack. It is also assumed to be 24V DC in Figure 1.19 above.

Depending on the state of field devices, i.e., Logic 1 or Logic 0 (True/False) the corresponding voltage signal will be received at a digital input module. The CPU collects the status of Logic 0 or Logic 1 statuses from I/P module for program execution.

At the end of program execution, the CPU will release the On/Off command to the digital output module in form of Logic 0 or Logic 1. The digital output module passes this status on to field devices in the form of a voltage so that they will be turned on/off depending on the state of the output.

1.7.2 PLC and analog I/O

Figure 1.20

Analog I/O process interaction

Analog or continuous devices are generally used for getting feedback of the process parameter control. For example, temperature transducers (RTDs, thermocouples), level, pressure, flow, etc., transmitters.

Basically, all types of transducer devices giving continuous signal are included in this class. Depending on field transducer devices, they are normally connected to 0-20 or 4-20 mA DC, 0-10V DC, RTDs, thermocouples, etc., type of analog input card, installed in the PLC rack.

Analog output actuators, commonly used in the field, include continuous actuators, I/P converter for valves, reference for drives, etc. The corresponding signal received at the analog input module, depends on the value of the field devices (i.e., either 4-20mA or some continuous value), and varies from a minimum to a maximum over the entire calibrated range. This signal is converted by the input module, into a count using an ADC (analog-to-digital converter).

The CPU collects the same count from an analog I/P module, for program execution. At the end of program execution, the CPU will once again release a count proportionate to the control value, to the analog output module.

The analog output module passes the same count (either as a 4-20mA or some continuous signal) using the DAC (digital-to-analog converter) to the field actuating devices. The 4-20mA signal actuator will either open/close the valve, depending on its setup.