Speed control of 3 phase induction motor by VVVF/AC drive

Objectives: At the end of this lesson you shall be able to
- **state about AC drives (VFD/VVFD) and changing of speed of AC motor by AC drive**
- **explain the operation of AC drive with block diagram**
- **list out the advantages and disadvantages of AC drive**
- **explain the components / parts and power and control terminals of AC drive**
- **state the parameter setting - speed control changes of direction of AC & DC drives / VFD/VVVFD (variable frequency drive/ variable voltage variable frequency drive)**
- **state the speed control of universal motor.**

Variable Voltage Variable Frequency Drive (VVVFD)

The AC drive industry is growing rapidly and it is now more important than ever for technicians and maintenance personnel to keep AC drive installations running smoothly. AC drives change the speed of AC motor by changing voltage and frequency of the power supplied to the AC motor. In order to maintain proper power factor and reduce excessive heating of the motor, the name plate volts / hertz ratio must be maintained. This is the main task of VFD (Variable frequency drive).

Applications of AC drives

1 AC drives are used to stepless speed control of squirrel cage induction motors mostly used in process plants due to its ruggedness and maintenance free long life.

2 AC drives control the speed of AC motor by varying output voltage and frequency through sophisticated microprocessor controlled electronics device.

3 AC drive consists of rectifier and inverter units. Rectifier converts AC to DC voltage and inverter converts DC voltage back to AC voltage.

Changing of speed of AC motors by using AC drive

From the AC motor working principle, that the synchronous speed of motor N_s in rpm, is dependent upon frequency. Therefore by varying the frequency of the power supply through AC drive, it can control the synchronous speed.

Speed (rpm) = Frequency (Hertz) x 120 / No. of poles.

Where

Frequency = Electrical frequency of the power supply in Hz., No. of poles = Number of electrical poles in the motor stator. Thus the speed of AC motor can conveniently be adjusted by changing the frequency applied to the motor. There is also another way to make the AC motor work on different speed by changing the no. of poles, but this change would be a physical change of the motor. The VFD provides the controls over frequency and voltage of motor input to change the speed of a motor. Since the frequency is easily variable as compared with the poles variation of the motor. AC drives are frequently used.

Constant V/F ratio operation

If the same voltage is applied at the reduced frequency, the magnetic flux would increase and saturate the magnetic core, significantly distorting the motor performance. The magnetic saturation can be avoided by keeping the ϕ_m constant.

All AC drives maintain the voltage -to- frequency (V/F) ratio constant at all speeds for the reason that follows. The phase voltage V, frequency F and the magnetic flux ϕ of motor are related by the equation.

$V=4.444 f N \phi_m$

or

$V/f = 4.444x N \phi_m$

Where N = number of turns per phase

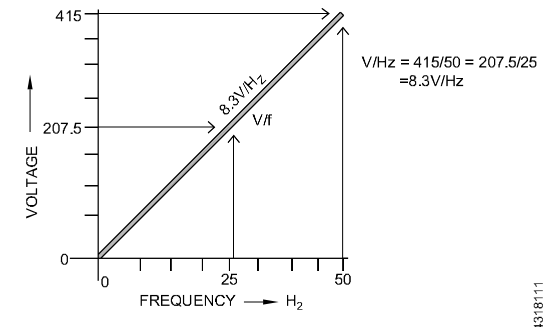
ϕ_m = magnetic flux

Moreover, the AC motor torque is the product of stator flux and rotor current. For maintaining the rated torque at all speeds the constant flux must be maintained at its rated value, which is basically done by keeping the voltage - to - frequency (V/f) ratio constant.

An AC drive is capable of operating a motor with constant flux (Φ) from approximately zero (0) to the motor's rated nameplate frequency (typically 50Hz). This is the constant torque range. As long as a constant volts per hertz ratio is maintained the motor will have constant torque characteristics. AC drives change frequency to vary the speed of a motor and voltage proportionately to maintain constant flux. The Fig1 is the graph illustrates the volts per hertz ratio of a 415 volt, 50 hertz motor. To operate the 415 volt motor at 50% speed with the correct ratio, the applied voltage and frequency would be 207.5V volts, 25 Hz. The voltage and frequency ratio can be maintained for any speed up to 50Hz. This usually defines the upper limits of the constant torque range.

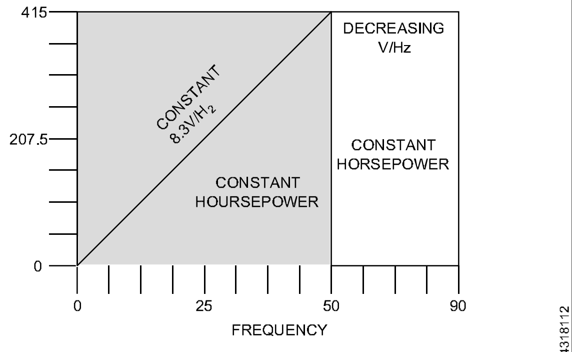
Some applications require the motor to be operated above base speed. The nature of these applications requires less torque at higher speeds. Voltage, however, cannot be higher than the available supply voltage. This can be illustrated as in Fig 2. Voltage will remain as 415 volts for any speed above 50Hz. A motor operated above its rated frequency is operating in a region known as a constant horsepower. Constant volts per hertz and torque is maintained up to 50Hz. Above 50Hz the volts per hertz ratio decreases. The V/Hz ratio at 25 Hz is 8.3, at 50Hz is 8.3, at 70Hz is 5.93 and at 90Hz is 4.61. Flux (Φ) and torque (T) decrease. Operation of the motors above rated nameplate speed (base speed) is possible, but is limited to conditions that do not require more power than the nameplate rating of the motor. This is sometimes called "field weakening" and, for AC motors, means operating at less than rated V/Hz and above rated nameplate speed.

Fig 1



V/F RATIO CHART

Fig 2



V/F CHART

Block diagram of AC drive

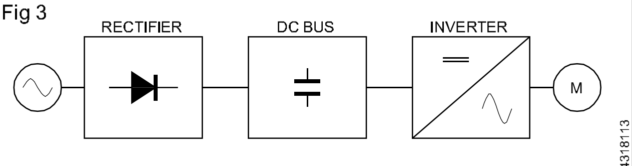
The Insulated - Gate - Bipolar- Transistor (IGBT) is in the past two decades come to dominate VFD as an inverter switching device.

IGBTs (insulated gate bipolar transistor) provide a high switching speed necessary for PWM (Pulse width Modulation) inverter operation. IGBTs are capable of switching ON and OFF several thousand times a second. An IGBT can turn on in less than 400 nanoseconds and off in approximately 500 nanoseconds. An IGBT consists of a gate, collector and an emitter. When a positive voltage (typically +15 VDC) is applied to the gate the IGBT will turn on. This is similar to closing a switch. Current will flow between the collector and emitter.

An IGBT is turned off by removing the positive voltage from the gate. During the off state the IGBT gate voltage is normally held at a small negative voltage (-15 VDC) to prevent the device from turning on. So the gate can control the switching on/off operation of an IGBT.

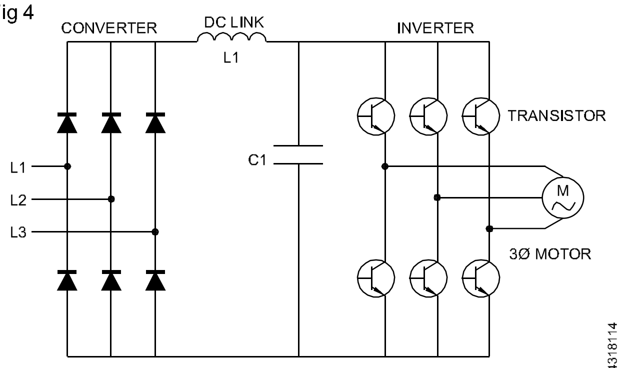
Fig 3 shows the block diagram of AC drive and Fig 4 shows the internal connection diagram. There are three basic sections of the AC drive; the rectifier, DC bus, and inverter.

Fig 3



BLOCK DIAGRAM OF AC DRIVE

Fig 4



INTERNAL CONNECTION OF AC DRIVE

The rectifier in an AC drive is used to convert incoming AC power into direct current (DC) power. Rectifiers may utilize diodes, silicon controlled rectifiers (SCR), or transistors to rectify power . An AC drive using transistors in the rectifier section is said to have an "active front end.

After the power flows through the rectifiers it is stored on a DC bus. The DC bus contains capacitors to accept power from the rectifier, store it, and later deliver that power through the inverter section. The DC bus may also contain inductors, DC links, chokes, or similar items that add inductance, thereby smoothing the incoming power supply to the DC bus.

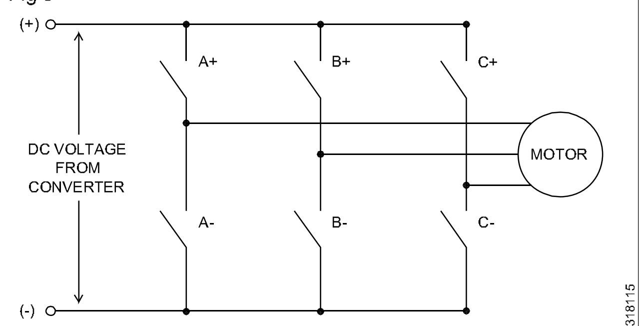
Inverter : An inverter is a device which converts DC into AC. The inverter contains transistors that deliver power to the motor. The "Insulated Gate Bipolar Transistor" (IGBT) is a common selection in modern AC drives. The IGBT can switch on and off several thousand times per second and precisely control the power delivered to the motor. The IGBT uses a method named "Pulse Width Modulation" (PWM) to simulate a current sine wave at the desired frequency to the motor.

The following example, explains how one phase of a three-phase output is developed and controlled. Switches replace the IGBTs for convenience. A voltage that alternates between positive and negative is developed by opening and closing switches in a specific sequence. For example, during steps one and two A+ and B- are closed. The output voltage between and A and B is positive. During step three A+ and B+ are closed. The difference of potential from A to B is zero. The output voltage is zero.

During step four and five A- and B+ are closed. The output voltage from A to B is negative. During step 6. A- and B- closed. The difference of potential A to B is again zero.

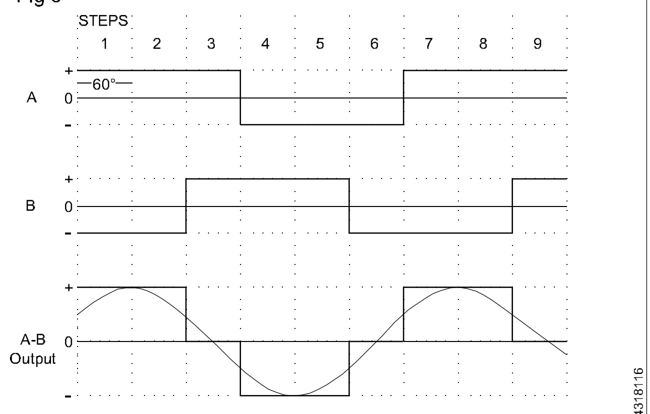
The same action from step 1 to 6 is repeated from step 7 onwards. This will continue. The Fig 5 shows the internal connection of inverter which converts DC into AC. The Fig 6 shows the output wave form of inverter. Only one single waveform due to switching action between A and B is shown. There are other two waveforms between B & C and A & C together which form a 3 phase AC supply. The magnitude and frequency of output voltage is dependent on the speed of the switching action of IGBTs.

Fig 5



INVERTER CONNECTION

Fig 6



OUTPUT WAVE FORM OF INVERTER

Advantages and disadvantages of AC drive

Advantages

- They use conventional low cost 3 phase AC induction motors for most applications
- AC motors require virtually no maintenance and are preferred for application where the motor is mounted in an area not easily reached for servicing or replacement.
- AC motors are smaller, lighter, more commonly available and less expensive than DC motors.
- AC motors are better suited for high speed operation (over 2500 rpm) since there are no brushes, and commutation is not a problem.
- Whenever the operating environment is wet, corrosive or explosive, special motor enclosures are required. Special AC motor enclosure types are more readily available at lower prices.
- Multiple motors in a system must operate simultaneously at a common frequency/speed.

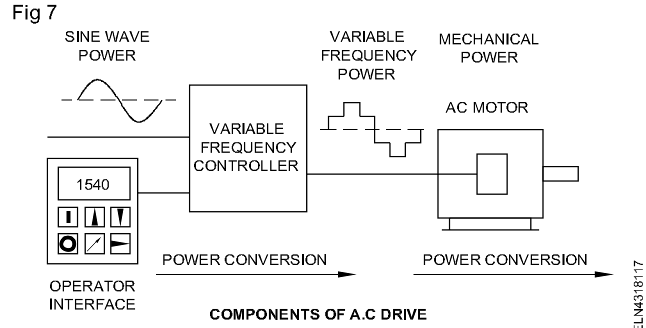
Disadvantages

- A standard motor can not adequately cool its winding at slow speed or handle the irregular electrical waveform from the AC drive.
- An AC drive requires installation of motor with heavier windings.
- AC drive has complicated electronics circuit, so fault rectification is costly.
- AC drives produce a simulated waveform, not a perfect sine wave. That degrade the power equality.

Components of AC drive

A variable frequency drive is a device used in a drive system consisting of the following three main sub-systems. AC motor, main drive controller assembly, and drive / operator interface as in Fig 7.

Fig 7



COMPONENTS OF A.C DRIVE

AC motor

The AC electric motor used in a VFD system is usually three - phase induction motor. Some types of single - phase motors can be used, but three - phase motors are usually preferred. Various types of synchronous motors offer advantages in some situations, but three - phase induction motors are suitable for most purposes and are generally the most economical motor choice. Motors that are designed for fixed - speed operation are often used. Elevated - voltage stresses imposed on induction motors that are supplied by VFDs require that such motors are designed for definite - purpose inverter-fed duty.

Controller

The VFD controller is a solid - state power electronics conversion, system consisting of three distinct sub-systems, a rectifier bridge converter, a direct current (DC) link, and an inverter. Voltage - source inverter (VSI) drives are the most common type of drives. Most drives are AC to AC drives in that they convert AC line input to AC inverter output. However, in some applications such as common DC bus or solar applications, drives are configured as DC-AC drives. The most basic rectifier converter for the VSI drive is configured as a three -phase, six -pulse, full-wave diode bridge.

In a VSI drive, the DC link consists of a capacitor which smooths out the converter's DC output ripple and provides a stiff input to the inverter. This filtered DC voltage is converted to quasi-sinusoidal AC voltage output using the inverter's active switching elements. VSI drives provide higher power factor and lower harmonic distortion than phase- controlled current - source inverter (CSI) and load - commutated inverter (LCI) drives.

In variable -torque applications suited for volts - per- Hertz (V/Hz) drive control. AC motor characteristics require that the voltage magnitude of the inverter's output to the motor be adjusted to match the required load torque in a linear V/Hz relationship. For example, 415V, 50Hz motors, this linear V/Hz relationship is 415/50=8.3V/Hz.

Although space vector pulse- width modulation (SVPWM) is becoming increasingly popular, sinusoidal PWM (SPWM) is the most straight forward method used to vary drives motor voltage (or current) and frequency. With SPWM control quasi- sinusoidal, variable - pulse-width output is constructed from intersections of a saw-toothed carrier signal with a modulating sinusoidal signal which is variable in operating frequency as well as in voltage (or current).

An embedded microprocessor governs the overall operation of the VFD controller. Basic programming of the microprocessor is provided as user - inaccessible firmware. User programming of display, variable, and function block parameters is provided to control, protect, and monitor the VFD, motor, and driven equipment.

Operator interface

The operator interface provides a means for an operator to start and stop the motor and adjust the operating speed. Additional operator control functions might include reversing, and switching between manual speed adjustment and automatic control from an external process control signal. The operator interface often includes an alphanumeric display and /or indication lights and meters to provide information about the operation of the drive.

An operator interface keypad and display unit is often provided on the front of the VFD controller shown in the Fig 7. The keypad display unit can often be cable - connected and mounted a short distance from the VFD controller. They are also provided with input and output (I/O) terminals for connecting push buttons, switches, and other operator interface devices or control signals. A serial communications port is also often available to allow the VFD to be configured, adjusted, monitored, and controlled using a computer.

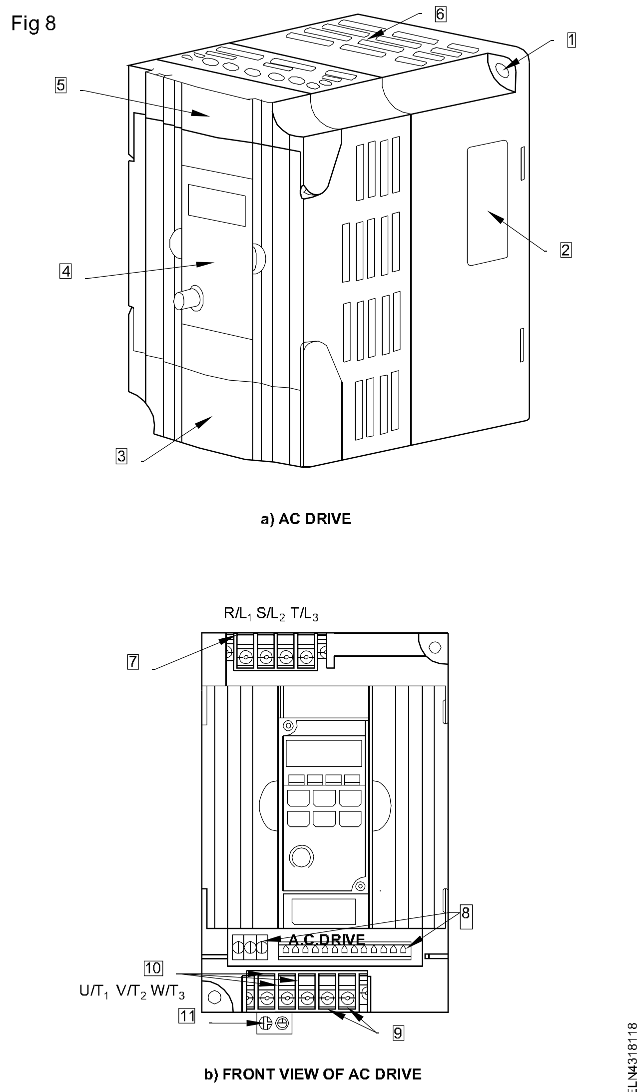
Operation of AC drive

When the VFD is started the applied frequency and voltage are increased at a controlled rate or ramped up to accelerate the load. This starting method typically allows a motor to develop 150% of its rated torque while the VFD is drawing less than 50% of its rated current from the mains in the low - speed range. A VFD can be adjusted to produce a steady 150% starting torque from standstill right up to full speed. However, motor cooling deteriorates and can result in overheating as speed decreases such that prolonged low -speed operation with significant torque is not usually possible without separately motorized fan ventilation.

With a VFD, the stopping sequence is just the opposite as the starting sequence. The frequency and voltage applied to the motor are ramped down at a controlled rate. When the frequency approaches zero, the motor is shut off. Additional braking torque can be obtained by adding a braking circuit (resistor controlled by a transistor) to dissipate the braking energy.

Part of AC drive (Fig 8a & 8b)

Fig 8



a) AC DRIVE

b) FRONT VIEW OF AC DRIVE

AC drives of various brand with different ratings are available in the market. It is generally assembled in a metallic enclosure. The front panel has the power input and output terminals, control terminals, keypad (operator interface) for controlling the drive etc. It has provision for connecting to PC for programming the drive.

The main parts are given below and shown in Fig 8a and 8b.

1 Mounting screw holes

2 Name plate label

3 Bottom cover

4 Digital keypad

5 Upper cover

6 Ventilation hole

7 Input terminals

8 Control Input/Output terminals

9 External brake resistor terminal

10 Output terminals

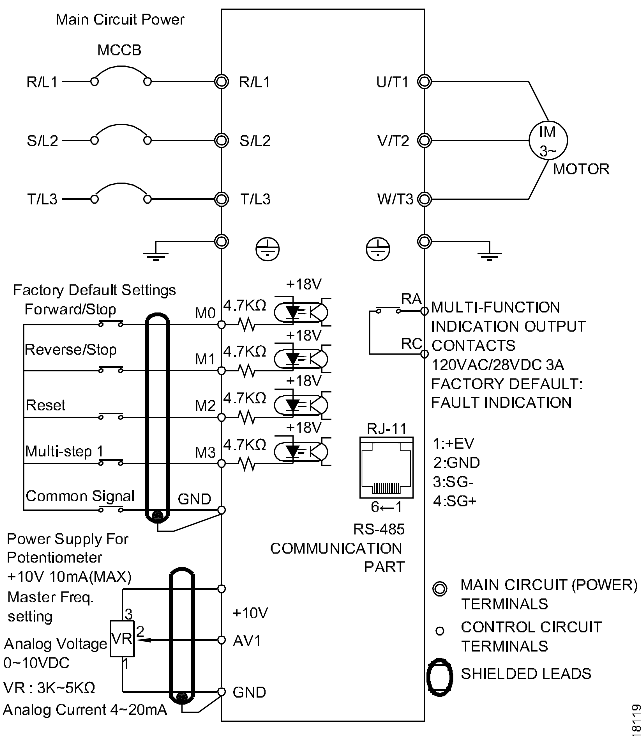
11 Grounding

Power and control terminals

In AC drive, the front panel has the input power terminals viz R/L_1, S/L_2 and T/L_3 where 3 phase AC 415V, 50Hz supply is connected. The 3 phase induction motor is connected of output power terminals viz. U/T1, V/T2 and W/T3.

There are control terminals viz M0, M1, M2, M3, GND, +10V, AV1 etc. for starting/stopping/ reversing and speed control actions. Names and locations are given in Fig 9

Fig 9



CONNECTION DIAGRAM OF AC DRIVE & MOTOR

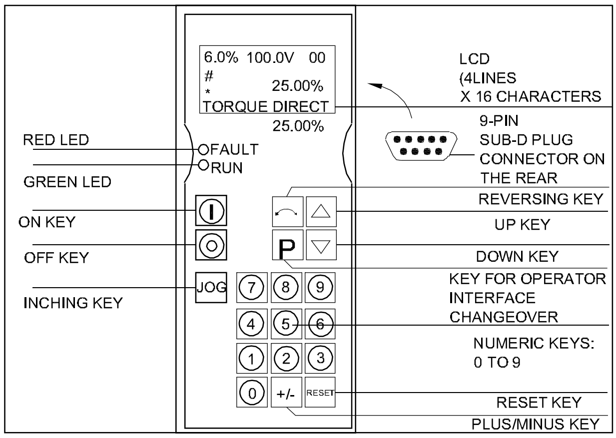
Parameter settings of DC drive

As discussed in previous chapter, the speed of DC motor is directly proportional to the armature voltage (E_b) and inversly proportional to the field current(I_f) and also the armature current (Ia) is proportional motor torque.

In armature controlled DC drives, the drive unit provides a rated current and torque at any speed up to rated speed.

The Fig 10 shows **Basic Operator Panel (BOP)** keypad provided on the front panel meant for controlling the drive.

Fig 10



BASIC OPERATOR PANEL (BOP) KEY PAD

The LCD is used to monitor the parameter. To start the motor, 'ON' key is to be pressed, and to stop the motor 'OFF' key is to be pressed. There is 'JOG' key provided for inching operation.

There is a key 'P' given for operator interface, changing over the parameter setting can be done by using this key in association with (Δ) key and key (∇). Parameters like, voltage current, Torque etc will be displayed turn by turn on each pressing of 'P' key /button.

The (Δ) or (∇) keys are used to increase or decrease the values. Numeric keys are also can be used to enter the values directly.

LED indicators are provided to indicate the status of drive. Green LED indicates the system running where as Red LED indicates when fault is occurred.

Programming of DC drive is possible through, personal computer (PC) also. For this purpose a connector for connecting PC through interfacing cable is provided at the rear panel.

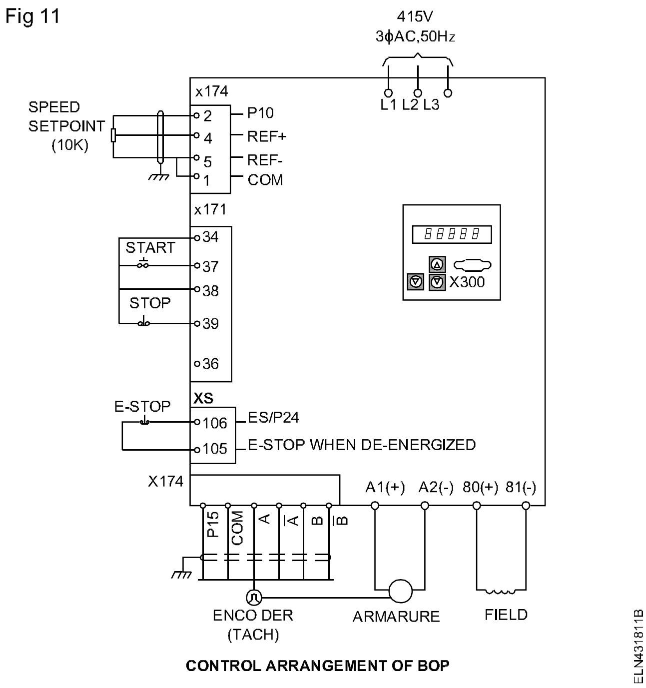
There may be variations in terms of names of key, display setting etc for different brands.

Operation of motor through DC drive

Fig 11 shows the operation of controls arrangement which is called as basic operator panel (BOP) .

The input supply connections and armature and field connections are well illustrated in Fig 11. Input 3 phase AC, 415V, 50Hz supply can be connected L_1, L_2 and L_3. The armature is connected across A_1 and A_2 where as the field is connected across B_0 and B_1 (The terminal names may vary depends on the type and make) an equipment ground conductor (Ground wire) must be connected to the controller mounting panel. Separate equipment grounding conductors from other major components Viz, motor, drive enclosure isolation transformer case (if used) in the system must also be connected continuously to a control connection point.

Fig 11



CONTROL ARRANGEMENT OF BOP

The AC input supply is provided should match the voltage and frequency given on the controller's name plate. Improper voltage may damage the equipment and insufficient current will cause erratic operation of the drive.

The shielded cable is recommended for the tachometer and all low level signal circuit to eliminate the possibility of electrical interference.

In some DC drives a speed adjusting potentiometer is provided to vary motor speed by controlling armature input voltage after the controller has been started. Some time a torque adjusting potential meter is used in place of speed adjusting potentiometer. It controls motor torque by controlling the DC current in the motor armature.

Starting and controlling the speed of DC motor

When the 'ON' button in BOP is pressed, the motor will start running. The desired speed can be attained by using 'P' button and Δ & ∇ buttons.

When the "OFF" button is pressed the motor will stop but AC line voltage remains connected to the controller and full field voltage is present. Armature voltage is reduced to zero. When pressing the "ON" button again the motor will accelerate to the preset speed.

Inching operation

For inching operation the 'JOG' position should be selected. Then the controller will operate only as long as the "ON" button is held pressed.

Changing the direction of rotation

In some model a 'reversing switch' is provided to change the direction of rotation of the motor. This switch is responsible for changing the polarity at the motor armature connection. First start the motor by pressing 'ON' button. The motor will run in forward direction. To change the direction of rotation, press "OFF" button and ensure that the motor is completely stopped. Now press the reversing button and then press the "ON" button. The motor will now run in the reverse direction. The reversing key has a provision which prevents direct transfer from one direction to the other.

Precautions during installation, connection and operation of DC drive

- Ensure all screws are tightened to the proper torque rating.
- During installation, follow all local electrical and safety codes.
- Ensure that appropriate protective devices (circuit breaker MCB or fuses) are connected between the power supply and DC drive.
- Make sure that the drive is properly earthed.
- Do not attach or remove wiring when power is applied to the DC drive.

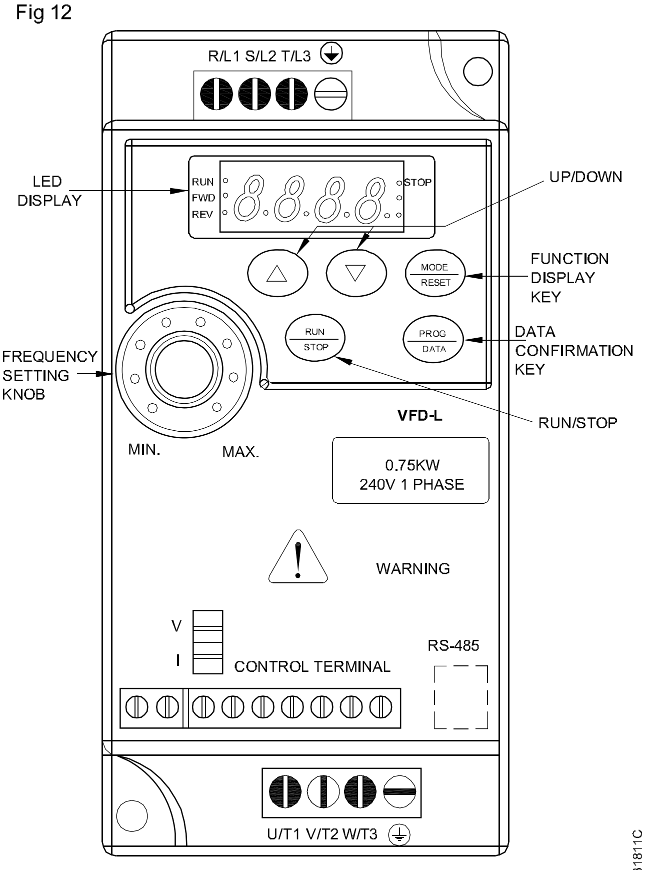
Parameter setting of AC drive

As explained earlier the speed (N) of AC induction motor is directly proportional to the voltage (V) and frequency (f) of the applied power supply. Within the base speed limit, the torque (T) can be kept constant by maintaining a constant voltage / frequency (V/F) ratio. By increasing of speed to above base speed limit is also possible but at the cost of the torque.

(VFD /VVVFD (Variable Voltage Variable Frequency Drive) drives are used for efficient speed control of AC motors. The advantages of using drives to control the speed is already explained.

The AC drive has a front panel which includes two parts. Display panel and keypad. The display panel is provided with the parameter display and shows operation status of the AC drive. Keypad provides programming interface between users and AC drives. The Fig 12. shows the location of buttons and display unit on the front panel of AC drive.

Fig 12



DISPLAY UNIT OF AC DRIVE

Mode /Reset button

By pressing this button repeatedly the display will show status at the AC drive such as the reference frequency and output current. If the drive stops due to a fault, correct the fault first, then press this button to reset the drive.

Prog/Data button

By pressing this button will store the entered data or can show factory stored data.

Run/Stop button

To 'start' or 'stop' the AC drive operation this button is to be pressed.

This button can only be used to 'stop' the AC drive, when it is controlled by the external control terminals.

UP∆ / down ∇ button

By pressing the 'Up' or 'Down' button momentarily parameter setting can be changed. These key may also be used to scroll through different operating values or parameters. Pressing the 'Up' or 'Down' button momentarily it will change the parameter setting in single unit increments. To quickly run through the range of settings, press 'Down' and hold the button.

Frequency setting knob

By using this knob, the frequency variation can be done.

'RS 485' communication port

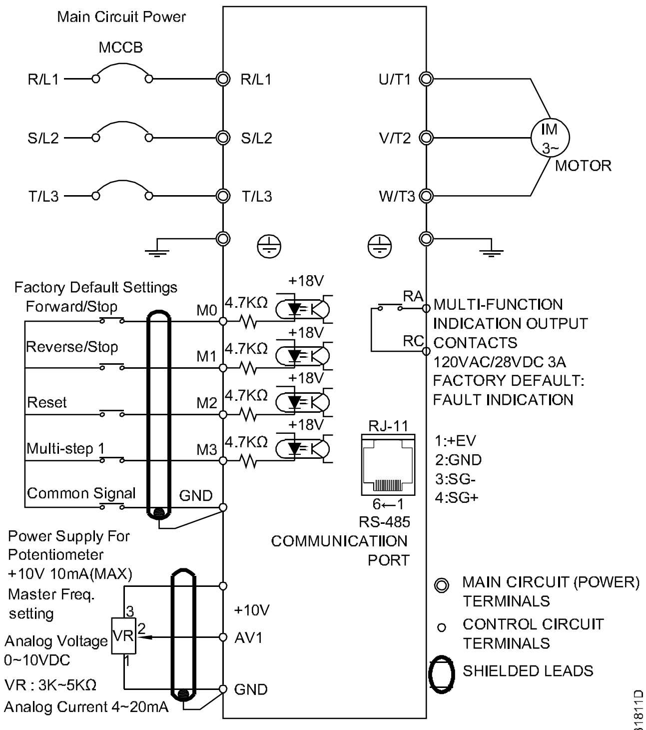
Programming of AC drive can be done through personal computer (PC) also. For this, the drive should be interfaced with PC through 'RS 485' port.

LED displays are also given in the display unit to indicate the status of drive like 'RUN', 'FWD' and 'REV'.

Operation of AC motor through drive

The motor and drive connections are well illustrated in Fig 13. A 3∅ , 415V, 50Hz AC supply is connected to the drive input terminals R/L_1, S/L_2 & T/L_3. Similarly output terminals of this drive is such as U/T_1, V/T_2 & W/T_3 are connected to 3 phase induction motor. (The terminal names may vary depends on the type and make)

Fig 13



CONNECTION DIAGRAM OF AC DRIVE AND MOTOR

Both input end and output ends are earthed separately.

Changing of speed

The AC input supply provided, should match the voltage and frequency given on the nameplate. Improper voltage may damage the drive.

Programming can be done through 'MOD/RESET' button in association with ∆ and ∇ button and the drives speed can be changed by using these buttons. The drive is started through 'RUN'/STOP' button.

The motor can be run at different speed by programming for the required speed.

Changing the direction of rotation

The direction of rotation can be changed. To do this, press 'RUN/STOP' button. When the motor is completely stopped, select 'rev' parameter and press 'RUN/STOP' button again. Now the motor will run in opposite direction.

Same procedure can be followed to change the direction of rotation of double cage induction motor also.

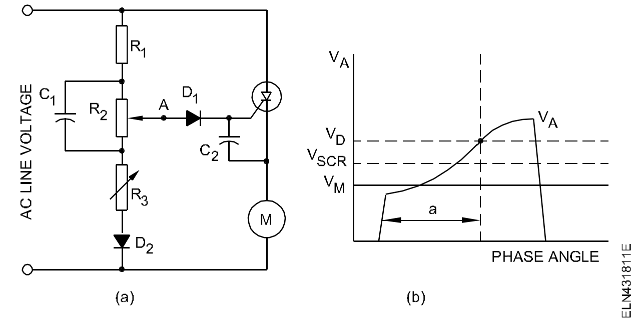
Precautions to be observed during installation, connection and operation of AC drive

- Do not connect the AC power to the U/T1, V/T2, W/T3 terminals, as it will damage the AC drive.
- Ensure all screws are tightened to the proper torque rating.
- During installation, follow all local electrical and safety codes.
- Ensure that the appropriate protective devices (circuit breaker or fuses) are connected between the power supply and AC drive.
- Make sure that the leads are connected correctly and the AC drive is properly grounded. (Ground resistance should not exceed 0.1Ω)
- Use ground leads that comply with standards and keep them as short as possible.
- Multiple VFD-L units can be installed in one location. All the units should be grounded directly to a common ground terminal.
- Make sure that the power source is capable of supplying the correct voltage and required current to the DC drive.
- Do not attach or remove wiring when power is applied to the AC drive.
- Do not monitor the signals on the circuit board while the AC drive is in operation.
- If filter is required for reducing EMI (Electro Magnetic interference), install it as close as possible to AC drive.

Speed control of universal motors using SCR : Majority of domestic appliances like electric drilling machine, mixer etc., incorporate universal electric motors. Any of the half wave or full wave controls discussed earlier can be used to control speed of universal motors. Universal motors have some unique characteristics which allow their speed to be controlled very easily and efficiently with a feedback circuit is in Fig 14.

The circuit at Fig 14a provides phase controlled half wave power to the motor; that is, one the negative half cycle, the SCR blocks current flow in the negative half cycle, the SCR blocks current flow in the negative direction causing the motor to be driven by a pulsating direct current whose amplitude is dependent in the phase control of the SCR. The operation of the circuit shown in Fig 14 is as follows.

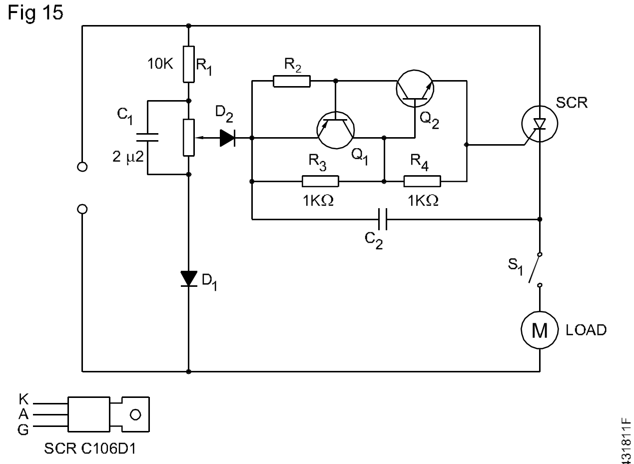
Fig 14



- Assuming that the motor is running, the voltage at point A in the circuit must be larger than the forward drop of diode D_1, the gate to cathode drop of the SCR, and the emf generated by the residual mmf in the motor, to get sufficient forward flow to trigger the SCR.
- The wave form at point A (V_A) for one positive half cycle is in Fig 14b and with V_{SCR}, V_D and motor generated emf V_M. The phase angle at which the SCR would trigger is shown by the vertical dotted line.
- For any reason if the motor speed increases, then V_M will increase, the trigger would move upwards and to the right along the curve so that the SCR would trigger later in the half - cycle thus providing less power to the motor, causing it to slow down. Similarly, if the motor speed decreases, the trigger point will move to the left and down the curve, causing the SCR to trigger earlier in the half cycle providing more power to the motor thereby speeding it up.
- Resistors R_1, R_2, R_3 along with diode D_1 and C_1 forms a ramp generator. Capacitor C_1 is charged by the voltage divider R_1, R_2 and R_3 during the positive half cycle. Diode D_2 prevents negative current flow during the negative half cycle, therefore C_1 discharges through R_2 and R_3 during negative half cycle. Varying the value of R_2 varies the trigger angle α.

A practical version of the circuit for controlling the speed of universal motors is in Fig 15.

Fig 15



CIRCUIT DIAGRAM OF UNIVERSAL MOTOR SPEED CONTROLLER

As can be seen, the circuit at Fig 15 is quite similar to that at Fig 14 but for the addition of two transistors and a few resistors.

In Fig 6, the action of Q_1 - Q_2 is to provide adequate gate current to trigger the SCR into conduction.

Q_1 - Q_2 and their associated resistors acts as a voltage sensitive switch. In each half cycle, C_2 is able to charge via R_1. As soon as voltage across C_2 rises to suitable value. Q_1 and Q_2 both switch- on and partially discharge C_2 into the gate of the SCR, thus delivering a pulse of high current to the SCR gate, independent of any current drive limitations of RV1. The Q_1 - Q_2 and C_2 network thus enables virtually any SCR to be used in the circuit almost irrespective of its sensitivity characteristics.

The universal motor speed control circuit is in Fig 15 enables the motor speed to be smoothly varied from zero to 75% of maximum via a single control. It also incorporates built - in feedback compensation to maintain the motor speed virtually constant at any given speed setting, regard-less of load changes.