Introduction To Variable Speed Drives

Lesson 4 – Basic Theory

Introduction to Variable Speed Drives
Lesson 1 - Basic Theory

Goal	IMO internal and external sales staff will have a basic introduction to Variable Speed Drives and applications.
Objectives	• Lesson 1 is intended to provide the participant with a fundamental understanding of AC Variable Speed Drives, and should be attempted following successful completion of the course: *Introduction to industrial motors (lesson 1) – Basic theory*. This lesson introduces AC drives as supplied by IMO. We look at fundamental operating principles, loads, EMC and EC standards. This lesson further prepares the participant for dealing with simple drives and automation questions from customers. • To widen the knowledge and awareness of the delegate as to the interaction between Variable Speed Drives and the driven load. • To prepare the participant for Lesson 2 – Hands-on
Length	This lesson should be completed at the participant's own rate.
Content outline	**1. General Overview and operating principles** **2. I/O and communication** **3. Application, inc EMC, harmonics, etc**
Learning Activities	Delegates will engage in the following activities at the end of this lesson • Quiz (3) • Test at later date
Evaluation Strategy	Delegates may be deemed to have an appropriate understanding of this course by obtaining at least 90% in the test.

The AC Variable Speed Drive (VSD)

Introduction

A static Variable Speed Drive (VSD) is an electronic unit which provides infinitely variable control of the speed of a three-phase ac induction motor by converting fixed mains voltage and frequency into variable quantities. Whilst the principle has always been the same, there have been many changes from the first VSD's which featured thyristors to today's microprocessor controlled digital units.

Because of the ever-increasing degree of automation in industry, there is always a need for automatic controls, and a steady increase in production speeds, better methods to further improve the efficiency of production plants are being developed all the time. Today, ac induction motors are an important standard industrial product. These motors are designed to run at a fixed speed and work has been going on for years to optimise their running speed.

It was not until the static frequency converter was introduced that three-phase ac motors with infinitely variable speed control could be used effectively. Frequency controlled three-phase AC motors are a standard element in all automated process plants. Apart from its ability to use the good properties of three-phase ac motors, infinitely variable speed regulation is often a basic requirement because of the design of the plant. In addition, it offers a number of further advantages:

Energy savings - Energy can be saved if the motor speed matches requirements at any given moment in time. This applies in particular to centrifugal pumps and fan drives where the energy consumed is reduced by the cube of the speed. A drive running at half speed thus only takes 12.5% of the rated power.

Process optimisation – Adjusting the speed to the production process offers a number of advantages. These include increasing production, while reducing rejection rates and decreasing material consumption and wear.

Smooth machine operation – The number of starts and stops with full speed change can be dramatically reduced. Using soft start-up and stop ramps, shocks and impacts on the machine components can be avoided.

Frequency converters

Since the late 1960's frequency converters have undergone very rapid changes, largely as the result of the development of microprocessor and semi-conductor technologies and their reduction in prices. Large-scale integration of components using surface mount technologies and better thermal management has meant that unit sizes have shrunk dramatically compared to their predecessors. However the basic principles of frequency converters remain the same.

Frequency converters can be divided into four main components:

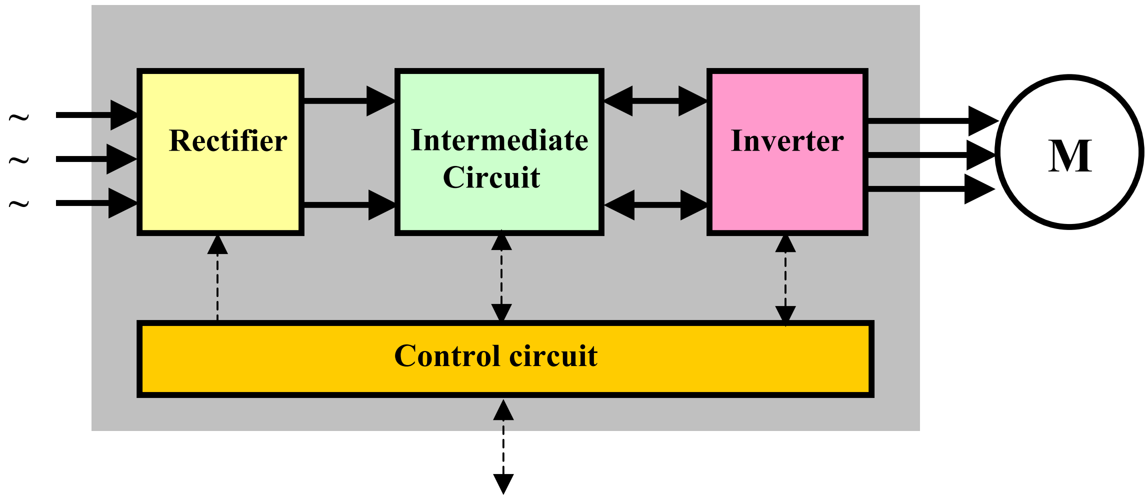
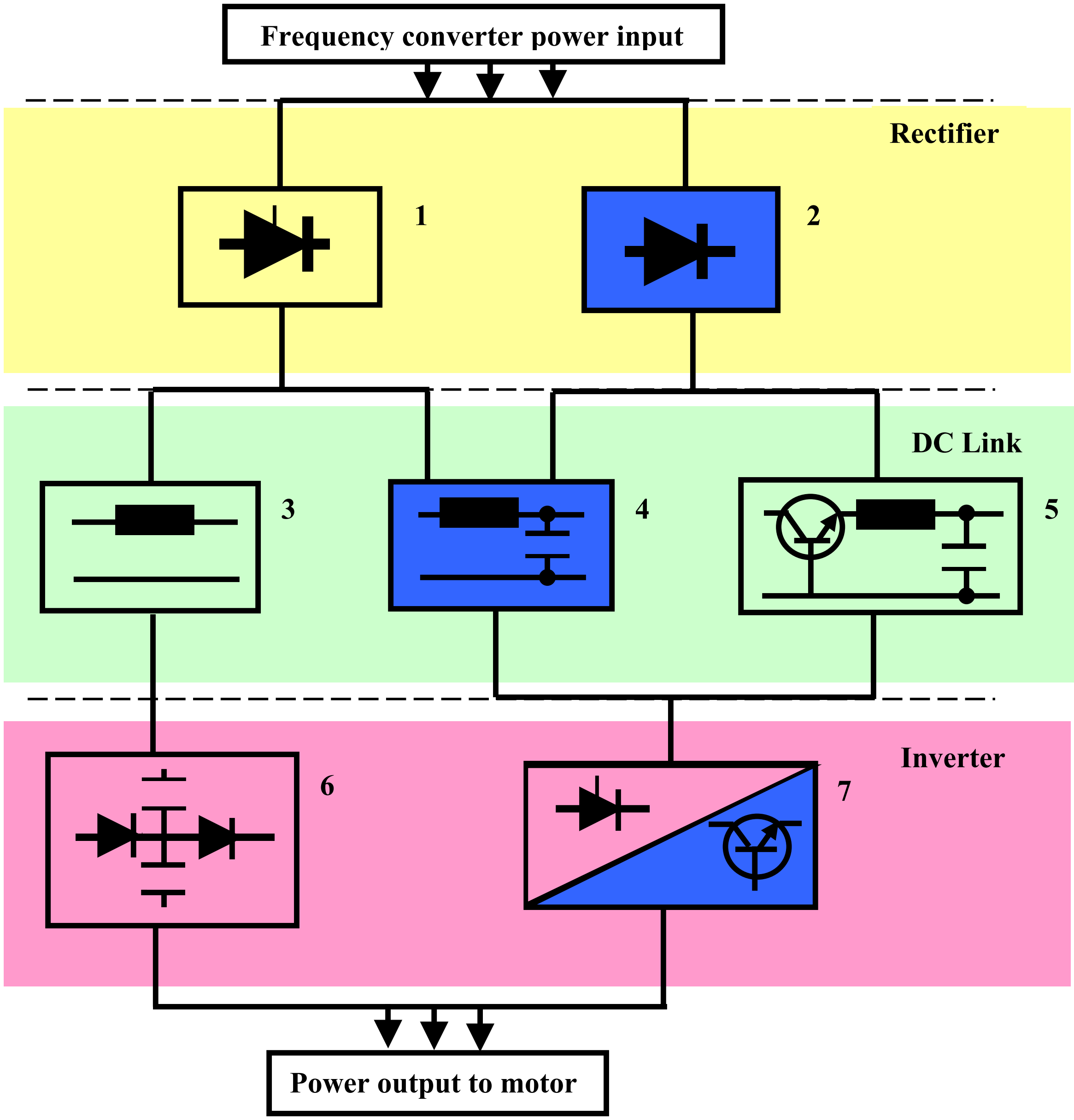


Figure 1. Simplified block diagram of a frequency converter

1. The **rectifier**, which is connected to single or three-phase AC mains supply and generates a pulsating DC voltage.
2. The **intermediate circuit (DC link)**, which stabilizes or smoothes the pulsating DC voltage and places it at the disposal of the inverter.
3. The **inverter** which generates a variable voltage, variable frequency for the motor.
4. The **control circuit,** which transmits signals to - and receives signals from – the other parts of the frequency converter. Probably the most important signals are transmitted to the power semiconductors in the inverter stage, to switch on or off. This switching pattern can be built up according to different principles. Frequency converters can be grouped according to the switching pattern controlling the motor. **All IMO Jaguar frequency converters use combinations 2 + 4 +7 as coloured blue in Figure 2 on the next page**.



Current Source Inverters (CSI) – [1 + 3 + 6]

Pulse-amplitude-modulated converters (PAM) – [1 + 4 + 7] [2 + 5 + 7]

Pulse-width-modulated converters (PWM) – [2 + 4 +7]

Figure 2. Different control principles

The rectifier

The rectifier forms the power input circuit of the frequency converter. The most usual form of rectifier being the uncontrolled type as fitted inside the complete **IMO Jaguar** range of frequency converters (drives).

The uncontrolled rectifier – Consists of six diodes (or four in case of single phase).

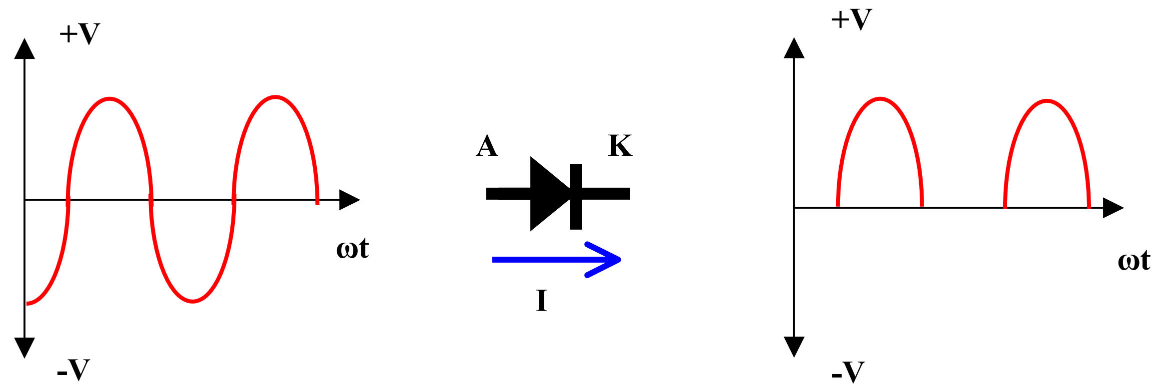


Figure 3. Mode of operation of the diode

A diode permits current to flow in one direction only, from Anode **A** to Cathode **K**. If any attempt to send current in the opposite direction is made, the diode cuts out. It is not possible to control the current size as it is with other semiconductors. When an AC voltage is placed across a diode, the out put side becomes a pulsating DC voltage. When a three-phase AC voltage is connected to an uncontrolled three-phase rectifier the DC voltage will still be pulsating. See Figure 4 below.

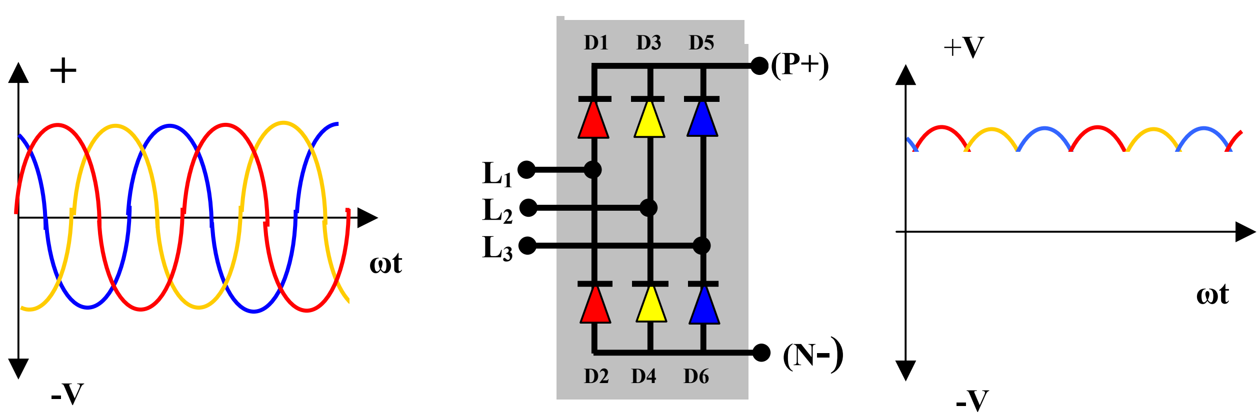


Figure 4. The 6-diode uncontrolled rectifier

Figure 4 shows that the rectifier is made up of two groups of diodes. One group contained diodes **D1, D3** and **D5,** the other group containing diodes **D2, D4**, and **D6.** Each group is conducting for $^{1}/_{3}$ **T** (120º). The two groups of diodes are conducting in turns. The time interval between the two groups is $^{1}/_{6}$ **T** (60º).

The group **D1, D3** and **D5** will be conducting the most positive voltage. If the AC voltage on mains input L_1 is most positive, then terminal **(P+)** will have the same value as terminal L_1. Across the other two diodes will be reverse (i.e. negative) voltages V_{L1-L2} and V_{L1-L3}.

In the groups of diodes **D2, D4** and **D6**, terminal **(N-)** will have the most negative voltage of the three phases. Where phase L_3 has the most negative voltage then diode **D3** will be conducting. Across the other two diodes will be reverse voltages V_{L3-L1} and V_{L3-L2}.

The output voltage of the uncontrolled rectifier is the difference between the voltages of the two-diode groups. The average value of the pulsating DC voltage is **1.4 x the AC mains voltage.**

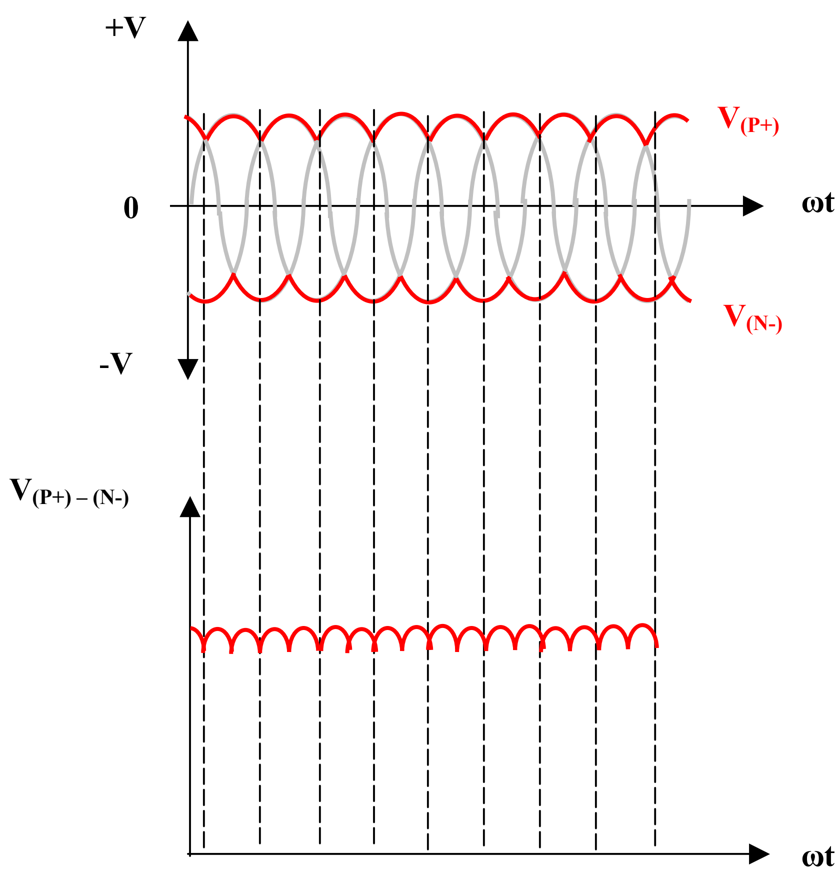


Figure 5. The output voltage of an uncontrolled three-phase rectifier

The DC link (and current distribution)

The DC link circuit can be regarded as a store where the motor, through the inverter can get its energy. The DC link can be built up according to 3 different principles, and the actual principle used depends on the type of rectifier and inverter used. For the sake of clarity, we shall only comment on the type used in the IMO Jaguar range of frequency converters-the constant voltage DC link.

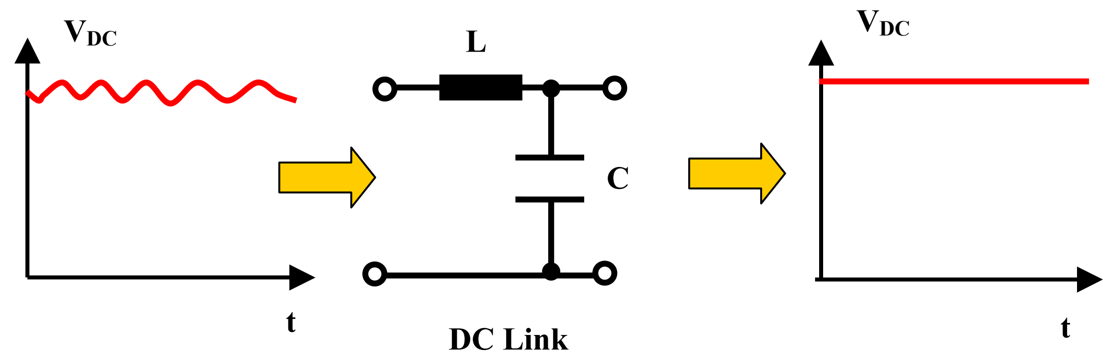
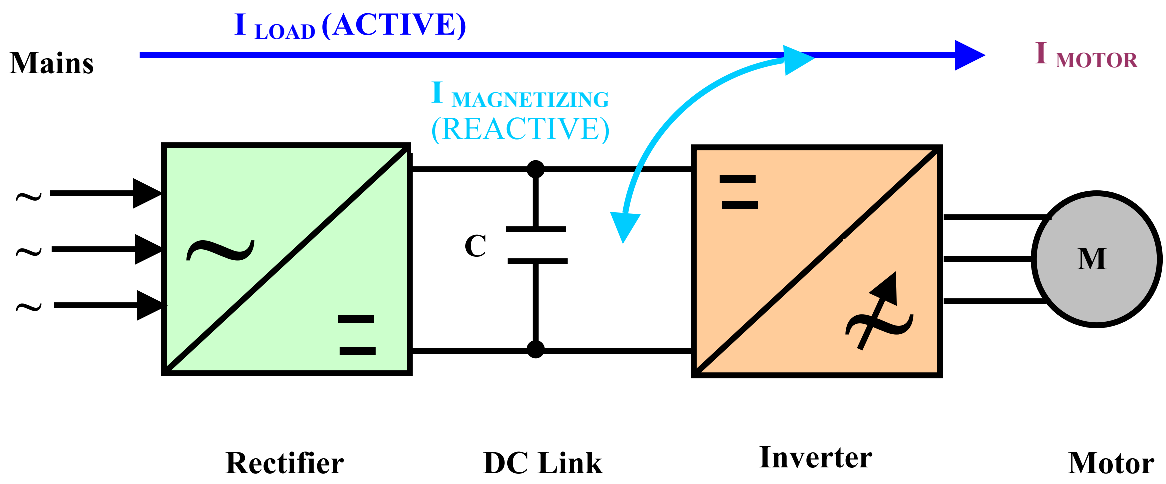
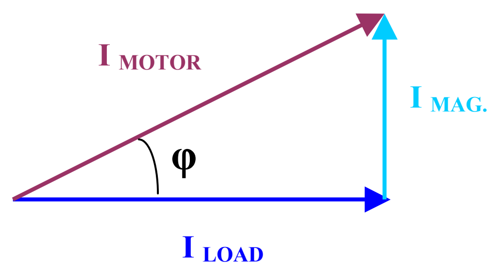


Figure 6. Constant Voltage DC link

The constant voltage DC link consists of large electrolytic capacitor(s) and on larger frequency converters – an inductor (coil). These components form an L-C filter which smoothes the pulsating voltage from the rectifier. The Jaguar range of frequency converters use uncontrolled diode bridge rectifiers, and when the L-C filter is applied the input to the inverter output stage becomes a smooth DC voltage of constant amplitude. With this type of DC link, the load determines the size of motor current. The large DC link capacitor(s) also supplies the magnetizing current for the motor. This is because the magnetizing current is reactive and if it came from the main power input it would have to return there. The diodes in the rectifier block prevent this action, so the capacitor(s) are charged up to the value of peak mains, then discharge into the motor, out of phase with the main load current by up to 90 degrees, as magnetizing current is demanded. This is one reason why the output current or current measured on the motor input wires is always bigger than the input current.

Motor manufacturers normally state the cos φ of a motor at rated current. At lower values of cos φ the rated motor current – at the same voltage and power – will be bigger, as shown in the equation. See Figure 6a below.





$$I_{MOTOR} = \frac{I_{LOAD}}{\cos \varphi}$$

Figure 6a. Currents flowing in the frequency converter and relationship with Cos φ

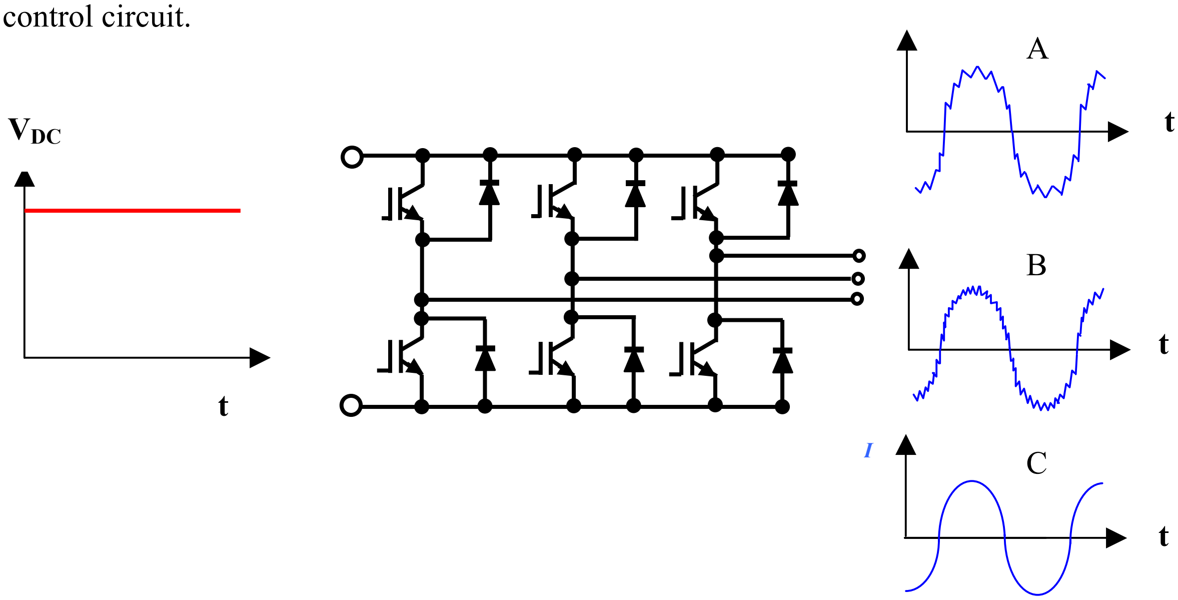
The inverter

The inverter is the last power module in the frequency converter before the motor. Here the final adaptation of the output voltage takes place. If the motor is connected direct to the mains supply the ideal working conditions will be in the nominal the nominal working point. The frequency converter provides excellent operational conditions in the whole control range, as the output voltage is matched to the load conditions. It is thus possible to keep a constant motor magnetization.

From the DC link the inverter receives a constant DC voltage.
The inverter must take care to ensure that the supply to the motor is always an AC value. The inverter must in other words produce the required frequency for the motor and the correct level of voltage.

The function of inverters differs, but in principle they are constructed in the same way. The main components are controlled power semiconductors placed in pairs in three

branches or bridges. Today, all but the largest frequency converters or those that run off higher voltages such as 3,300V for example, use transistor technology. The main inverter switching devices are known as Insulated Gate Bipolar Transistors (**IGBT**'s). The biggest advantage of IGBT's is the **switching frequency** range (how many times they can be switched on and off per second) typically **300Hz to 20kHz**.
The IGBT's used in the inverter stage of the frequency converter are only two position solid-state electronic switches. They are turned on and off by signals generated by the control circuit.



A – **Low switching frequency**, B – **Medium switching frequency**
C – **High switching frequency (nb. also known as carrier frequency)**

Figure 7. Inverter for constant DC link voltage and the output current depending upon the switching frequency of the inverter.

For constant voltage DC link type frequency converters there are six switches. The control circuit switches them on and off using a number of different **modulation** techniques, thus changing the output frequency of the inverter bridge.

With a fixed DC link voltage, the motor voltage can be made variable by delivering the DC link voltage to the motor for varying lengths of time. The frequency is changed by varying the voltage pulses along the time axis – positively for one half cycle then negatively for the next.

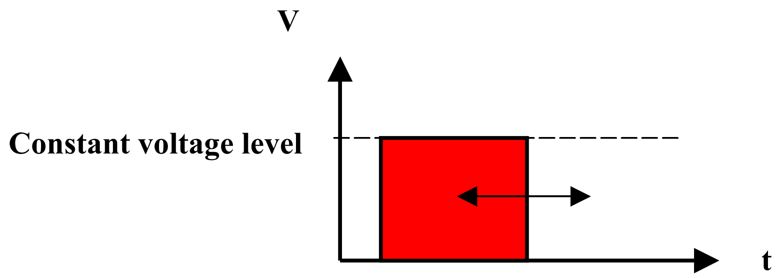


Figure 8. Modulation of voltage pulse width

As the technique changes the width of the voltage pulses, it is called **Pulse-Width-Modulation** or **PWM**. PWM and related techniques such as sin-controlled PWM are the most common techniques for inverter control.

In basic PWM techniques the control circuit determines the on and off switching times of the semiconductors at the intersection between a triangular delta voltage and a superimposed sinusoidal reference voltage (sin-controlled PWM). See Figure 9 below.

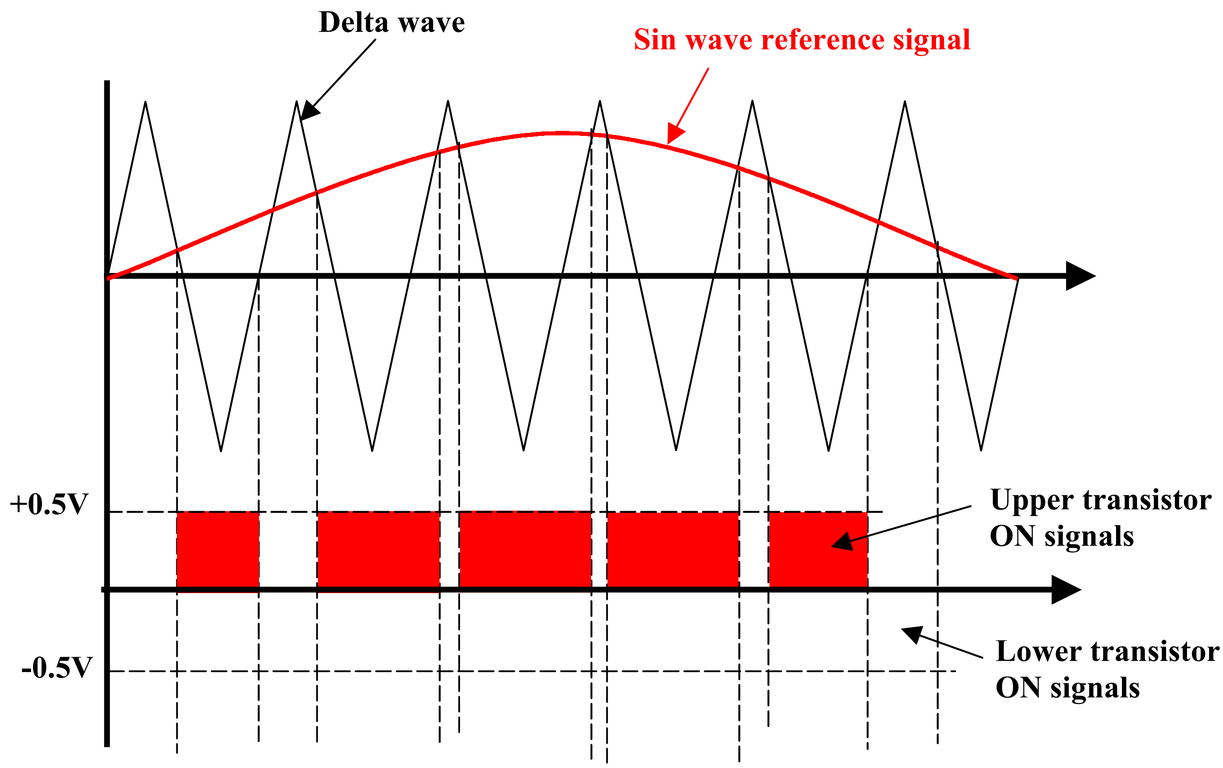


Figure 9. Traditional control circuit generation of PWM by comparison of delta voltage with sin reference voltage. The +/- 0.5V pulses are the small 'firing' (turn-on) signals for the power output devices / IGBT's.

Fuses

Generally the frequency converter is not supplied with built in fuses, apart from a special high speed fuse protecting the DC link of drives over about 11kW capacity. The fast current measuring techniques used internally and electronic protection is normally all that is necessary.

However, the whole installation must be protected by fuses or a circuit-breaker installed ahead of the frequency converter. The fuses must be able to carry the input current of the frequency converter even when it is operating at up to 150% overload for a short time. The fuses are required to protect the cables and contactors only, not the frequency converter. The fuses must not be dimensioned according to the normal starting current of the motor, because under control of the drive, the motor starting and reversing currents will be applied softly under 'ramped' accelerating conditions, and therefore no prolonged inrush will be applied to the mains.

Applying mains power to the frequency converter

When power is applied to the frequency converter, the DC link capacitors are assumed fully discharged and their impedance is low. Initial charging current through the capacitors would be high enough to damage the diodes of the rectifier, or contactors etc up-stream of the frequency converter if precautions to limit this current were not taken. The DC link circuit is fitted with a power resistor, connected in series with the capacitor to limit this current accordingly. See Figure 9a below.

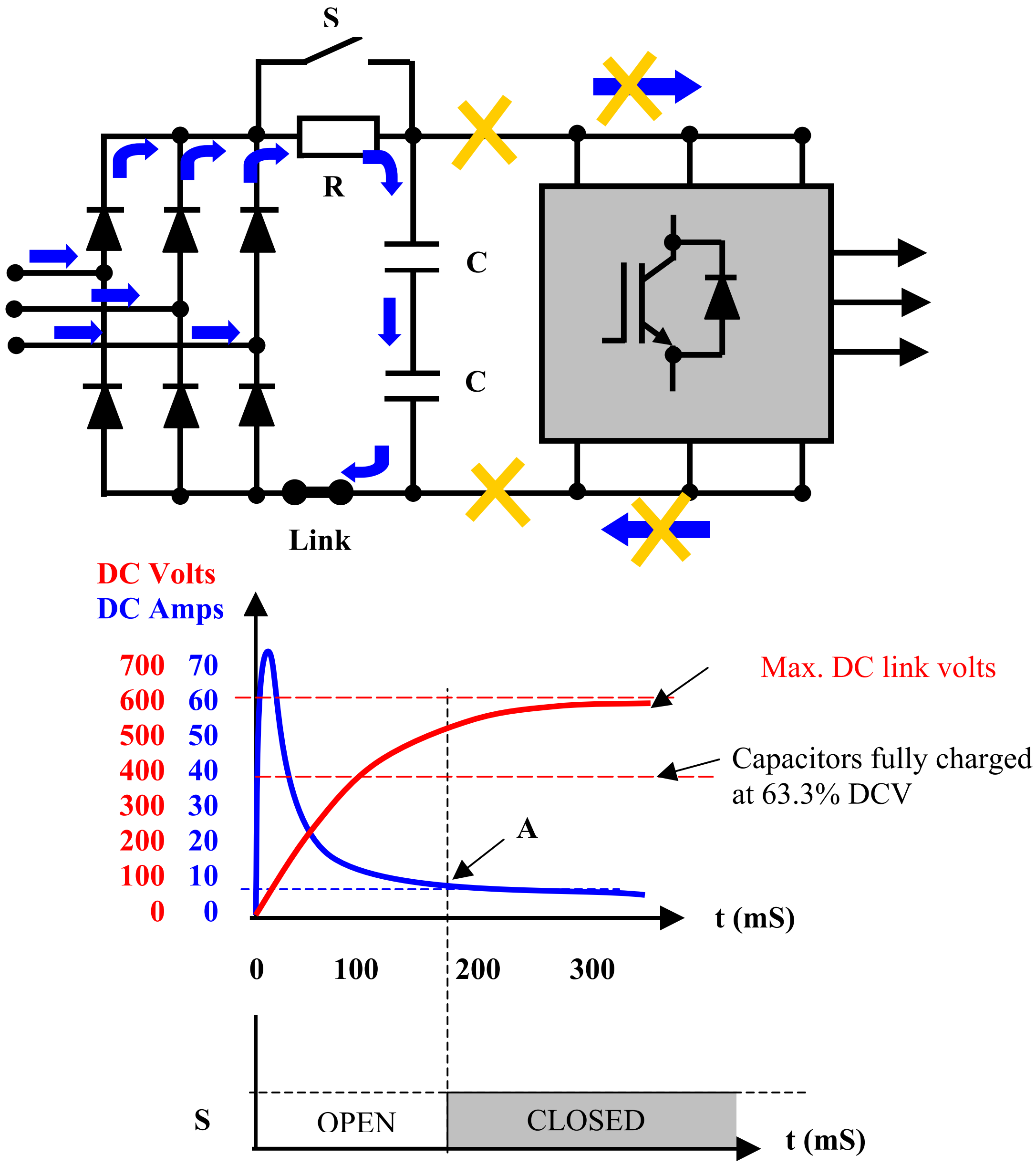


Figure 9a. DC link charging current and voltage, at power –up.

S = In-rush contactor / SCR, R = Charging resistor

At power-up, current surges through the positive half of the rectifier into the large electrolytic DC link capacitors via the resistor 'R', the **soft-start** or **charging resistor**. As the voltage across its plates rises this current begins to charge the capacitors, and begin to decay in value. The voltage rise across the capacitor is not linear but exponential with time. The DC link capacitors (like all capacitors) are said to be fully charged when the charge across their plates reaches 63.3% of the applied voltage. The time taken to reach this level depends upon the value of capacitance 'C' and the value of 'R', and is known as the circuit **time constant 'T'**. Hence it follows that **T = C.R.** seconds.

At the moment power is switched on, the resistor 'R' is in circuit, and charging current flowing into the capacitors is decreasing rapidly as the voltage increases. No current is flowing in the inverter stage at this point because all of the IGBT's are turned off. At point 'A' the charging current has fallen to such a low level that 'R' is not needed any more. The control circuit closes a contact 'S' which is in parallel with 'R', to by-pass the load current (when it starts to flow) around the resistor, so as not to heat it up and lower the DC link voltage unnecessarily. In smaller frequency converters such as IMO's VXM range up to 22kW (VXM2200G), 'S' is a solid state device called a Silicon Controlled Rectifier (**SCR**). In higher power drives-for example 30kW (VXM30K) and above, there are much larger capacitors in the DC link, and it is more convenient to use a contactor for this purpose. Which ever device is used, the DC link has to be at the correct potential and stable - i.e. the capacitors fully charged and the charging resistor out of circuit, before it is possible to run the motor. Figure 9a shows this routine diagramatically.

CAUTION:- The frequency converter is designed to have power applied to the input continuosly. Motor control should be via the low voltage control circuit only.
It is acceptable to remove input power under emergency stop conditions, but under no circumstances should a contactor be used to continuously make and break the mains power. Premature failure of the rectifier will occur and warranty will be void.

WARNING:- The DC link capacitors are very large. When AC power is removed from the frequency converter, the DC link capacitors can hold their charge for several minutes. During this time, the capacitors are capable of delivering a nasty shock! Always allow 10 minute for the capacitors to discharge to a safe level before opening a frequency converter for inspection or maintenance.

Transistors

As transistors can be switched on and off at high speeds, the magnetic noise generated by the 'pulse' magnetization of the motor can be significant at low switching frequencies. An advantage of high switching frequencies is the flexible modulation of the output voltage which enables a sinusoidal motor current to be generated as the control circuit only has to turn the transistors **on and off**.
The inverter switching frequency is a balancing act as high frequencies can lead to radio frequency interference and high peak voltages at the motor, both particularly if the cable connecting the frequency converter to the motor is long.
Today, IGBT devices are the most widely used as they combine the control properties of MOS-FET transistors (i.e. high input impedance means they can be turned on and off by very low current and voltages in the order of those found direct from integrated circuit 'chips') and LTR transistors. They have the right power range, conductivity, switching frequency, and ease of control for modern digital inverters.
With latest generation IGBT's for smaller frequency converters up to a few kW's, both the inverter power semiconductors and their controls are placed in a resin-filled, moulded plastic case called the **Intelligent Power Module – IPM.**

Table 10 below gives the major differences between MOS-FET, IGBT, and LTR type transistors, used in the inverter stages of frequency converters.

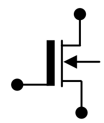
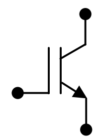
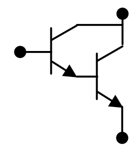
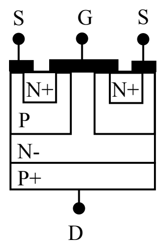
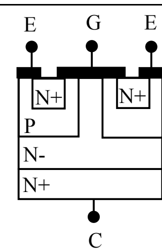
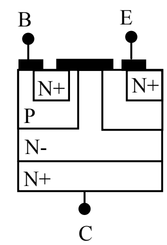
Semiconductor / Properties	MOS-FET	IGBT	LTR
Symbol			
Design			
Conductivity Current conductivity Losses	 Low High	 High Insignificant	 High Insignificant
Blocking conditions Upper limit	 Low	 High	 Medium
Switching conditions Turn-on time Turn-off time Losses	 Short Short Insignificant	 Medium Medium Medium	 Medium Short Large
Control conditions Power Driver	 Low Voltage	 Low Voltage	 High Current

Table 10. Comparison of power semiconductors used in frequency converters

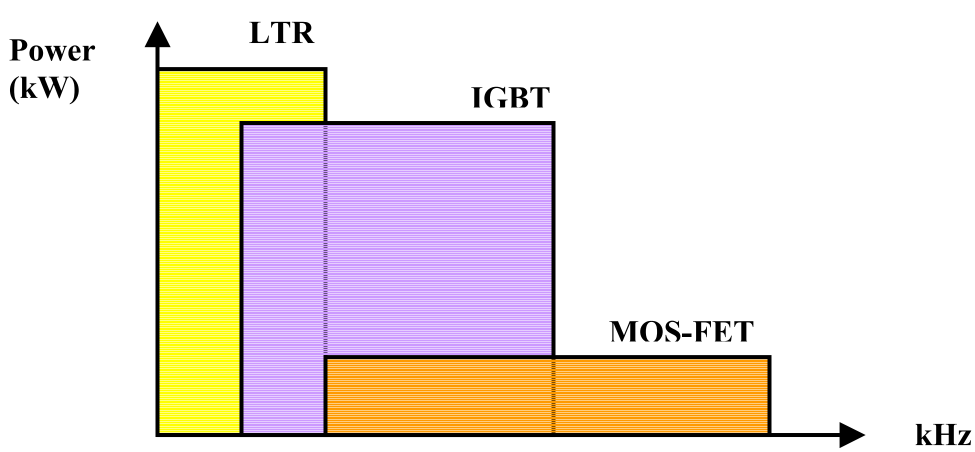


Figure 11. Power and frequency ranges of power transistors

Breaking the motor circuit

Modern frequency converters using IGBT's do not have the problems that plagued early drives that used bipolar output transistors. These devices were easily damaged by voltage spikes, so it was not possible to use a contactor in the output wiring to stop the motor in an emergency. However, IGBT's are much more rugged, and it is possible to break this circuit if required by the application.

If the motor is rotating, regardless of speed, the magnetic flux in the machine will be significant. If the frequency converter's output circuit is opened by a contactor, the magnetic field will collapse and the motor's inductance will set up a back emf that opposes the change of flux. The contactor will arc and burn at the contact faces, as the current tries to flow.

If the contactor is then re-closed onto the motor, with the frequency inverter output on, there may be a high current flow as the motor starts under similar conditions to DOL.
This may cause the drive to trip out on over-current or other trip condition. It is however, unlikely that damage will be caused to the frequency converter in either mode.

If either of the above conditions are unavoidable, it is always a good idea to install a suitable reactor (3-phase AC inductor) in the motor lines, close to the drive's output terminals U, V, W.

A reactor (inductor/choke) will always oppose any sudden change in current through it (see earlier lessons), and so damp any sudden shock loads or such effects.

IMO supply such reactors for small power drives, for example part numbers **LO15/3** (L = Inductor, O = for the drive output, 1 = 1 milli-Henry, 5 A, / 3-phase), **LO19/3, LO120/3,** etc. If in doubt, refer to appropriate drives engineer.

Heat losses

The IGBT's either individually or in a standard IPM module, are designed to switch high voltages at high current levels, extremely quickly – a typical IGBT will switch between it's ON and OFF states in 200 nano-seconds (200 x 10^{-9} seconds or two hundred, thousand-millionths of a second). For this reason the devices get hot when rated load current is flowing through them, especially if the PWM carrier frequency is high.
The IGBT's are mounted directly onto carefully designed metal heat-sinks, whose job it is to dissipate as much heat as possible away from the devices by radiation into the surrounding air, and conduction into the metal surface that the frequency converter is mounted to.

Frequency converters in all but the very lowest power ratings, usually have cooling fans mounted above or below the heatsink, to aid heat dissipation. It is essential that frequency converters are installed in such a way that the hot exhaust from the cooling fans is not prevented from escaping, and their discharge path is not blocked by other equipment that has been installed too close. Generally, it is good practice to leave a space a minimum of 100mm top and bottom of the frequency converter, and unless otherwise stated, at least 50mm left and right (100mm on higher power drives). The single biggest cause of premature failure of ‘quality’ frequency converters is excess heat build up in the devices. The heatsink of a drive can reach 90°C, so it is important that they are never mounted on combustable surfaces.

It is also important to adequately ventilate and if necessary, force cool with additional fans, any enclosure that contains multi-drives or an enclosure that will be positioned in a high ambient temperature. Extra fan cooling is also required where the frequency inverter is mounted in a smaller enclosure than recommended by the supplier.

If the drive is to be used in hot climates or at altitudes over 1000 metres, it is a good idea to **derate** (reduce) the load to be connected accordingly to lower than the standard rated capacity.

Pulse width modulation (PWM)

PWM is the most widely used procedure for generating a three-phase voltage with corresponding frequency.

With PWM the full DC voltage ($\sqrt{2}$ x V_{MAINS}) is switched on or off by the power stage IGBT’s. The pulse width repetition rate between the on and off switching times is variable and causes the voltage adjustment at the output terminals.

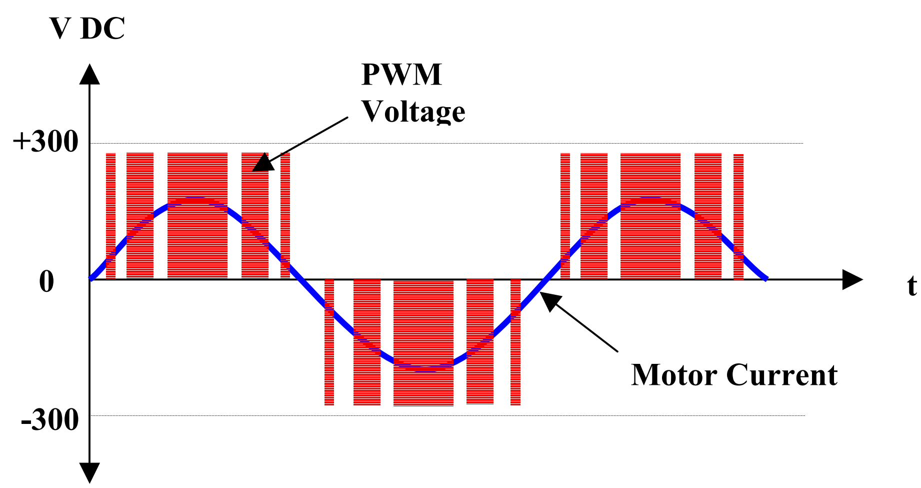


Figure 12. Inverter PWM output voltage and sinusoidal current waveform to motor windings, for 415V AC three-phase input

Each transistor in the output stage has a diode connected in anti-parallel to it. These diode are known as **Flywheel** diodes.

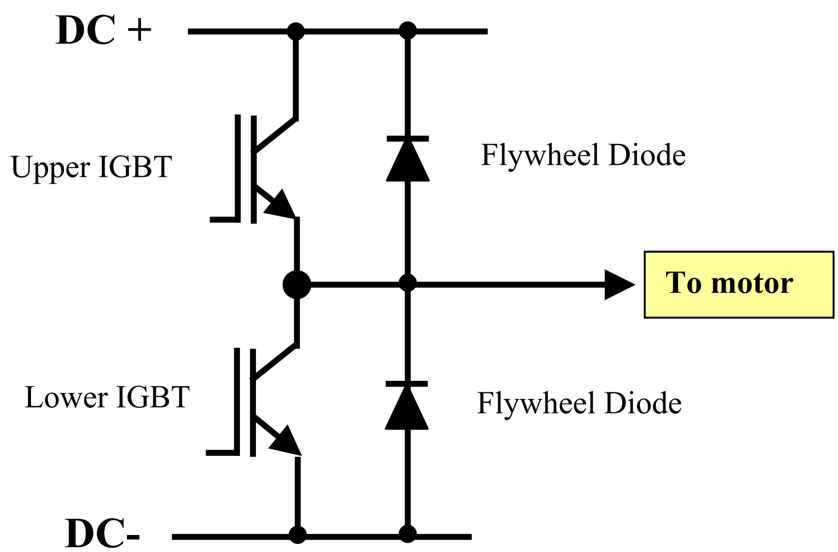


Figure 12a. Pair of IGBT's with their Flywheel diodes connected in anti-parallel - typical of the arrangement in one arm of the inverter power output stage

The transistors are only ever in one of two states –off or on. If a transistor is conducting (on) its flywheel diode will not be. If a transistor is off, its flywheel diode will be conducting. At any moment in time there will be one transistor of the upper three devices conducting and two devices of the lower three conducting. Alternatively, there may be two upper devices on and one lower device on.

For each of the three 'arms' of the inverter, if one transistor is conducting, the other diode will be conducting. At no time will an upper and a lower IGBT be both on together. If this were to occur, the DC link would be short-circuited and damage would occur.

A time delay between upper devices switching off and lower devices being switched on (and visa-versa) in the same inverter arm is incorporated into the control circuit to prevent damage. This is known as the **interlock delay** time.

Figure 13 shows the six transistors T1 to T6 represented as switches.

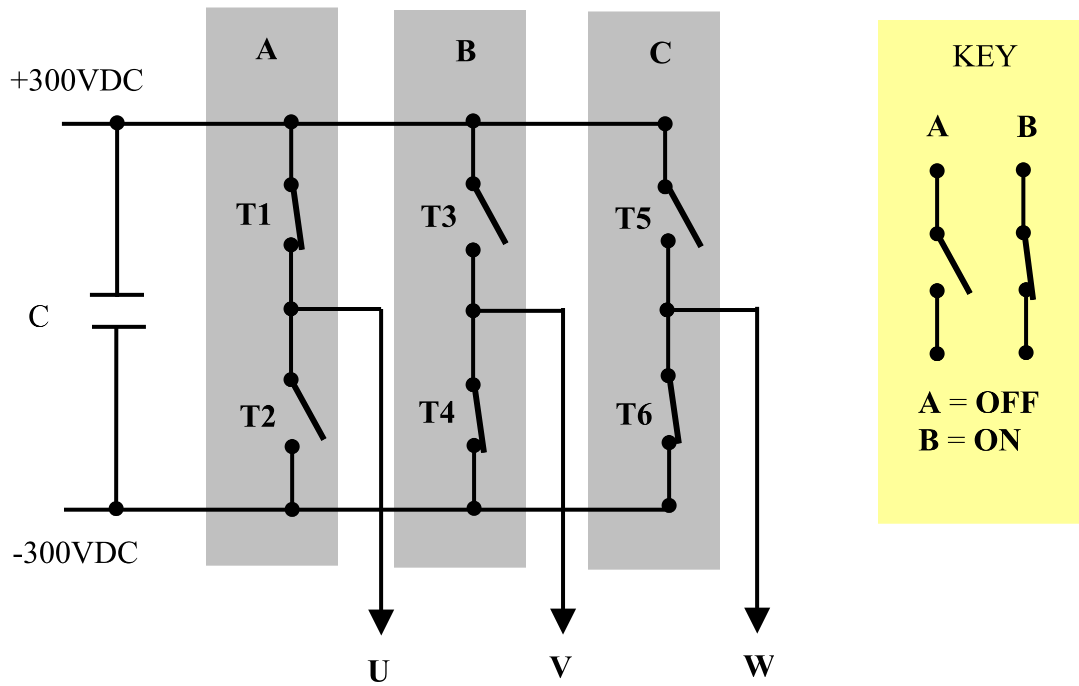


Figure 13. Inverter switches (omitting flywheel diodes for clarity)

In arm A, if transistor T1 is closed, T2 is open. In arm B, if T3 is closed T4 is open, and so on.

In the diagram T1 is shown switched on, so motor wire 'U' is connected to the positive side of the DC link at +300V. T4 and T6 are also shown in the ON state meaning motor wires 'V' and 'W' are both connected to the negative rail of the DC link, -300V. Although not shown for clarity, the flywheel diodes across the transistors in the OFF state (T2, T3 and T5) would be conducting current returning from the motor.

For example, at a particular moment in time as shown in Figure 13, T4 and T6 are both connected to the negative rail so current will flow from this rail via wires V and W to the motor windings. At the motor the windings will be connected together in a star or delta format, so current will return to the inverter via wire 'U'. Here this returning current will never return to the negative rail because it is at the same potential, but instead it flow through the now conducting flywheel diode connected in reverse parallel to T1, back to the positive rail. Nb. This current can not pass via T1 because although shown as a closed switch, it is really a transistor that can only pass current in the direction of the arrow shown on its symbol – refer back to Table 10 and Figure 12a

In the very first training course we introduced vectors to represent both the magnitude and direction of an electrical quantity. We can represent IGBT switching states by using voltage vectors, see Figure 14 below.

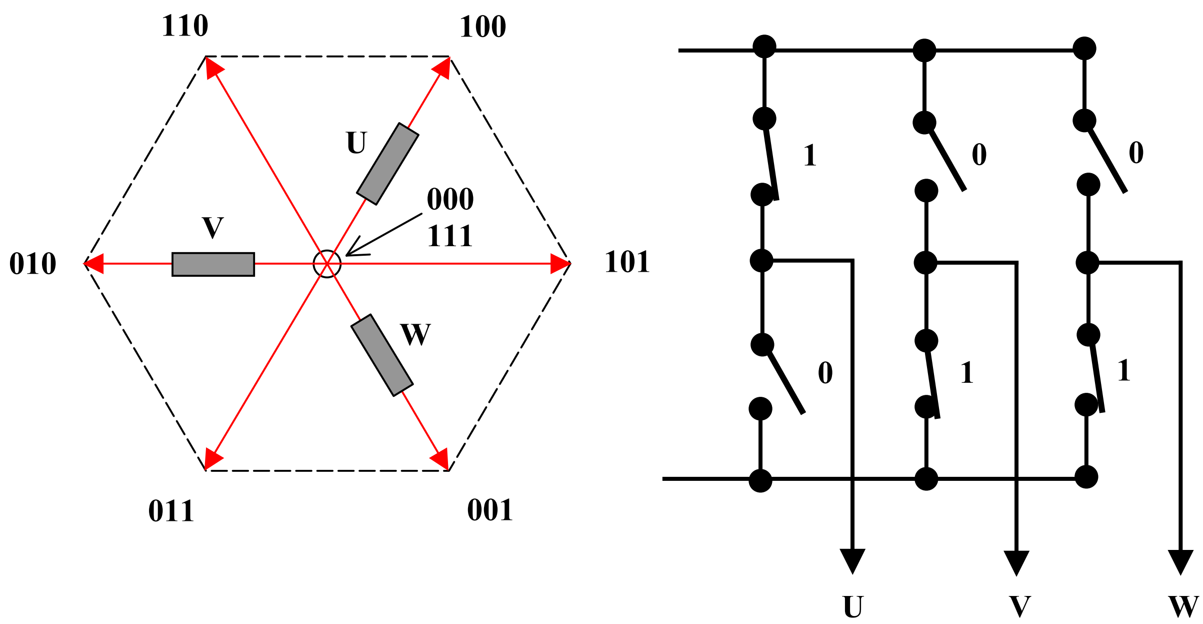


Figure 14. Using vectors to represent switching states of IGBT's

Each inverter upper or lower sets of IGBT's can have eight possible switching combinations **(2^3)** and therefore eight discreet voltage vectors at the output of the inverter and therefore at the stator winding of the connected motor. As shown in Figure 14, these vectors **100**, **110**, **010**, **011**, **001**, **101**, are placed at the corners of an imaginary hexagon, using **000** and **111** as zero vectors.

Now if we think back to how three separate sinusoidal voltages in a three-phase system are spaced 120 degrees apart, we can see that it is true that at any instant in time two phases are positive and one is negative or one phase is positive while the other two negative. The only deviation from this is when one phase is at zero volts.

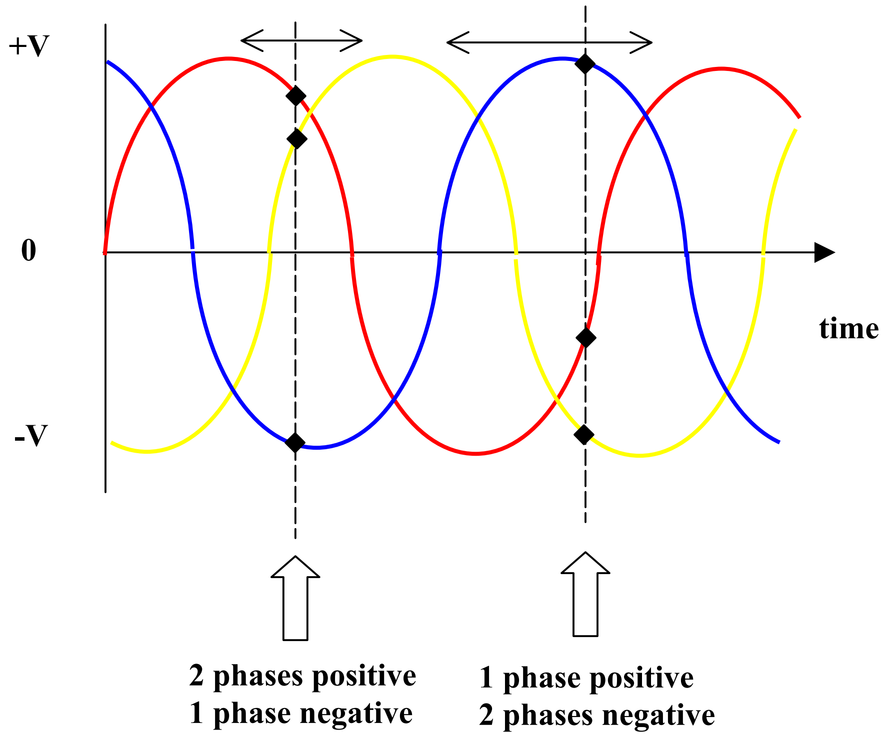


Figure 15. At any given time two phases are of opposite polarity to the third phase

The inverter switching pattern shown in Figure 14 replicates this requirement.
With switching combinations **000** and **111,** the same potential is generated at all three output terminals of the inverter – either a positive or negative potential from the DC link and no current can flow through the windings. For the motor this is almost a short-circuit, the 0 Volts being impressed on the motor windings.

We should now be able to see that the induction motor connected to the inverter is receiving a continuous string of voltage pulses of varying widths, but the current is close to sinusoidal. Figure 16 shows typical PWM outputs for a) motor running at rated frequency (speed) of 50Hz, b) half frequency 25Hz and c) twice rated speed 100Hz.

Note: Actual switching frequencies are in the order of several kHz. Even a very low switching frequency of say 1kHz would be made up of 500 variable width positive pulses and 500 negative – per period of one cycle (1Hz) of output current.
It is not possible to show so many pulses without the aid of an oscilloscope, so only two or three pulses +/- are shown in the diagram below. However the principle should now become clear.

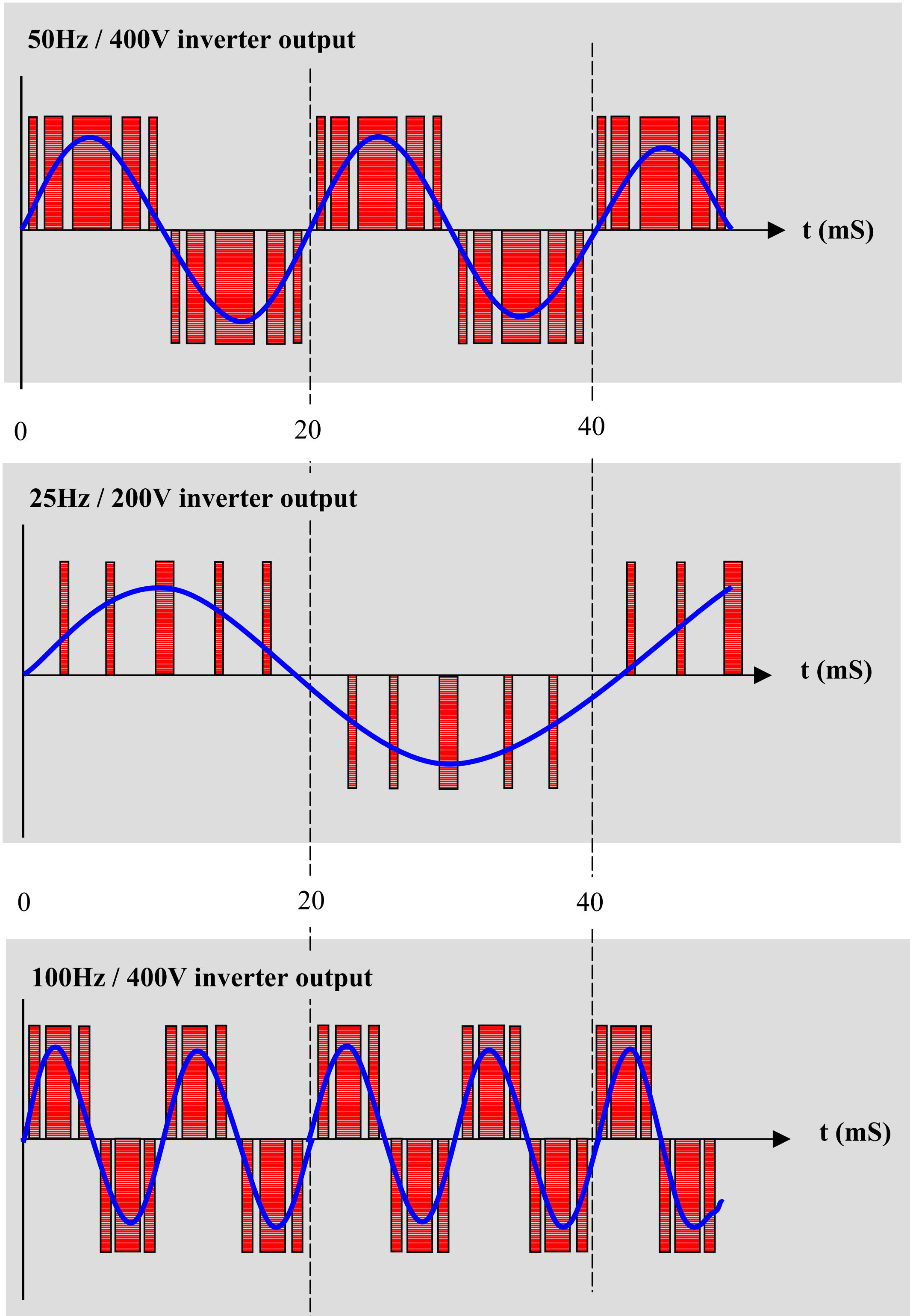


Figure 16. Typical PWM patterns at various output frequencies and voltages.

Power Supplies

All the electronic integrated circuits and components require a low voltage power supply to operate. For example, the LED display, the control circuit terminal rail, the cooling fans, IGBT firing circuits etc, all need a supply of power at the correct voltage and polarity.

In the very early days, power supplies were crude and bulky, using a mains transformer and rectifier to step down the voltage to a low level, before being distributed around the frequency converter. This was ok but the drawback was excessive size, weight and losses.

Modern frequency converters use very small and efficient power supplies which operate direct from the DC link. These are known as **Switch Mode Power Supplies (SMPS),** and operate using PWM techniques.

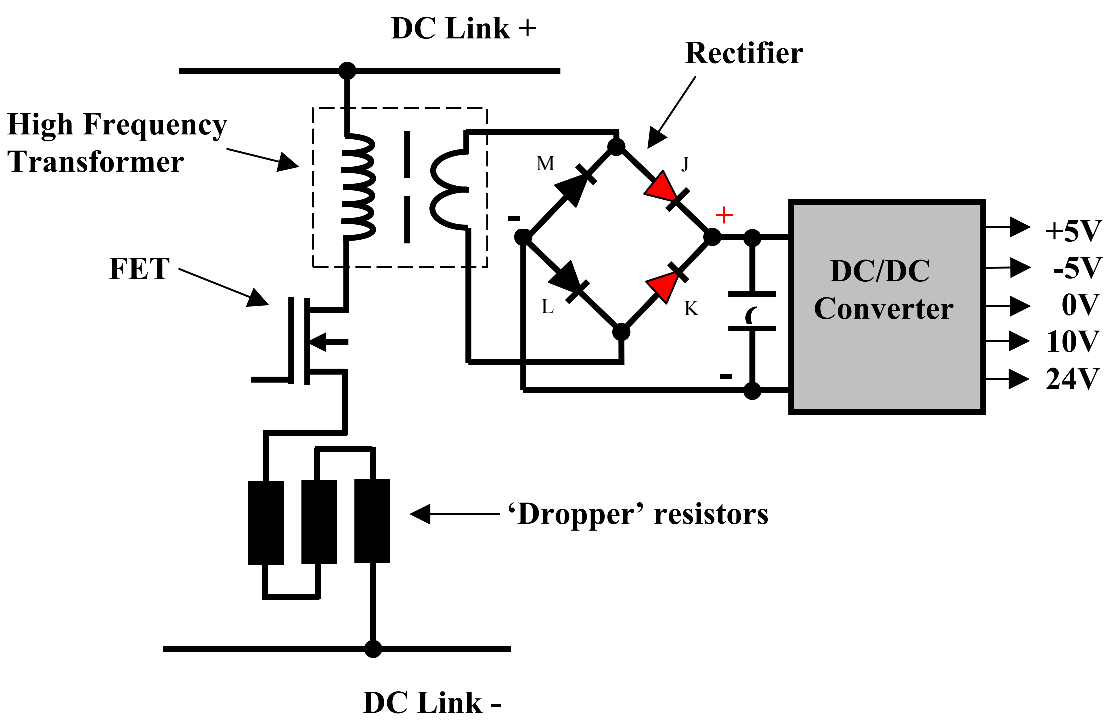


Figure 17. The Switch Mode Power Supply (simplified) and DC/DC converter

A small high frequency transformer is connected directly to the DC link and a high-speed electronic switch such as a **Field Effect Transistor (FET)**. The relatively high voltage of the DC link is reduced sequentially across 'dropper' resistors until it is within the switching specification of the FET (maybe 30VDC). The FET is switched on and off at a high frequency – typically 400kHz – which produces a square wave through the primary side of the transformer. The square wave may not be sinusoidal, but is still changing value between two voltage levels so essentially AC. This AC is transformed and the secondary winding produces a rough low voltage AC output.

The rectifier can be of the full-wave or half-wave type, depending upon the number of diodes. The full-wave type shown in Figure 17 produces an output with less ripple.
When the top end of the secondary winding is positive (in the positive half cycle), diode 'J' conducts but diode 'M' will block. When the bottom end of the secondary winding goes positive in the next half cycle, diode 'K' will conduct, but diode 'L' will block.
This means that the out put from the rectifier is always polarized in the same direction – one terminal always positive and the other always negative.

Any ripple at the output of the rectifier is smoothed by the electrolytic capacitor 'C' before being fed to the DC/DC converter. The DC/DC converter is usually a sealed unit whose primary function is to convert the fixed polarity low voltage input into different low voltage DC outputs.

In practice, the SMPS may have multi-stages, and several different secondary windings on the transformer. It may have its own on board protection in the form of a special 'supervisor' chip that shuts down the FET and hence the outputs if an overload or other fault is detected.

Control Circuit

The control PCB operates at very low voltages and is isolated from the power voltages on the DC link by opto-coupling techniques.

The control PCB inside the modern digital frequency converter contains the micro-computer which forms the heart of the system. In its simplest form this is usually a microprocessor and some memory on one chip. As with all such systems, a clock pulse is used to synchronize the execution of commands, and all the processor inputs and outputs (I/O) are scanned sequentially. The physical connection of signal wires is made at the terminals of this board, and there are usually some terminals of fixed designation i.e. analogue or digital, and some that are programmable to suit the user's application. All of the incoming and outgoing signals are processed digitally, accuracy depending on the resolution of the I/O.

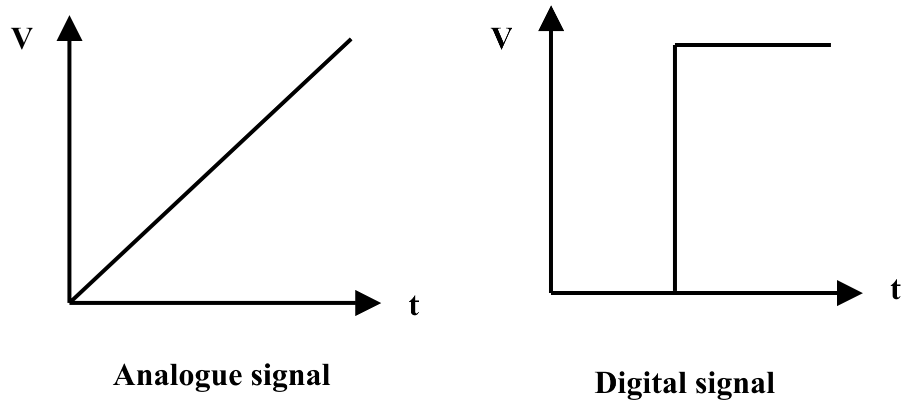


Figure 17a. Analogue and digital signals

Analogue inputs

For example, a 0-10V varying DC signal from the process plant comes into the frequency converter's speed reference input terminal. If the signal is at 10V the motor will rotate at maximum set speed, if at 0V the motor will run at minimum set speed or zero. If anywhere in between 0 and 10V, the motor speed will be proportional to this signal strength – i.e. 5V = half speed etc.

Assuming the input resolution is quoted as 10 bit, this means that the analogue 10V signal will be sampled and broken down into 2^{10} individual steps, i.e. 1024. The resolution of the input would therefore be 10/1024 = 0.01V approximately. If the resolution was 4 bit (2^2) this would equate to only four states 2.5. 5.0, 7.5 or 10 V, i.e. quarter, half, three-quarter or maximum motor speed.

This means that the higher the resolution of the input (or output), the finer and more accurate the control of the application – in this case motor speed. Figure 17b below, shows some of the control circuit components in block format.

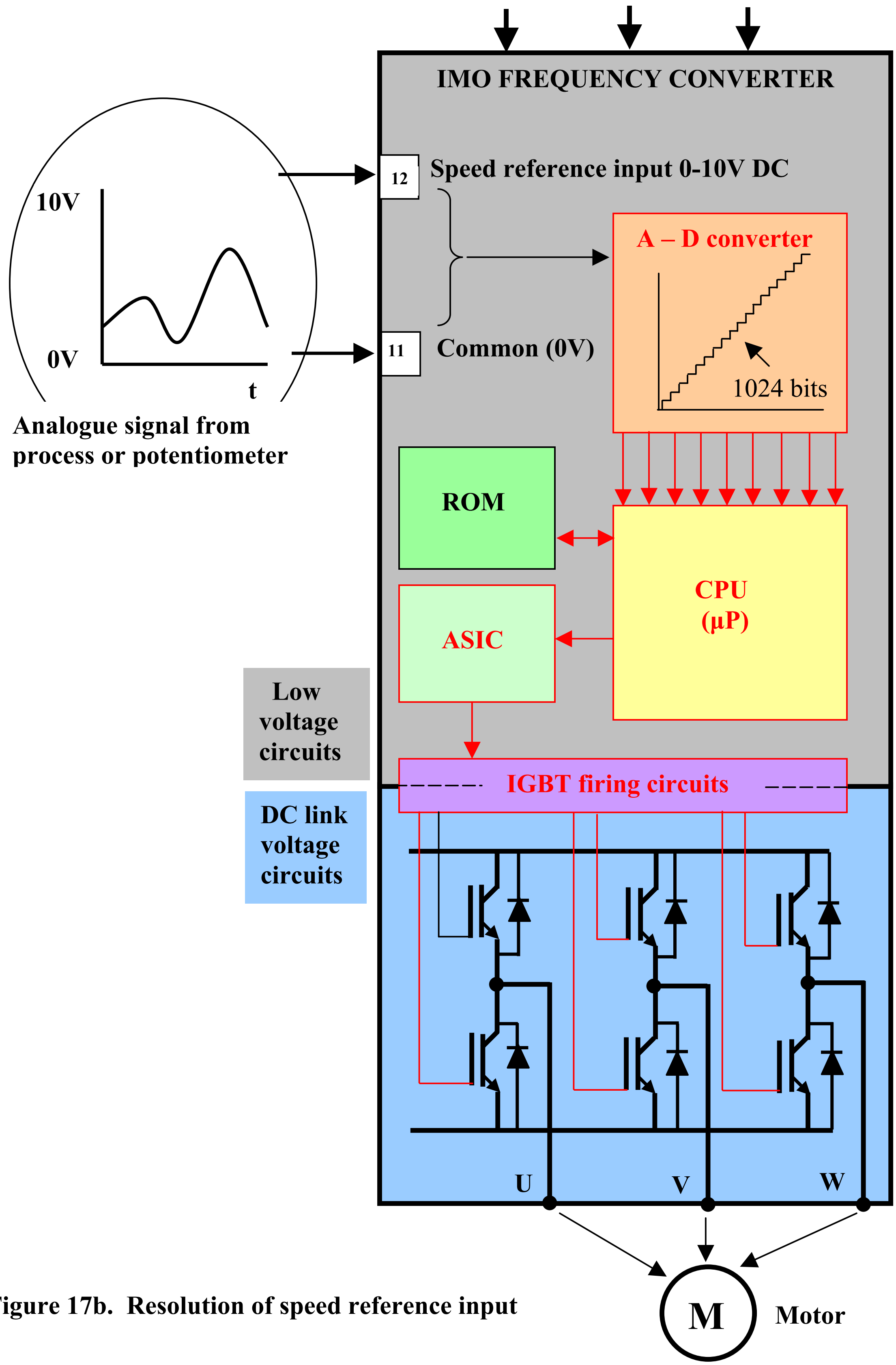


Figure 17b. Resolution of speed reference input

The analogue signal is first filtered of any high frequency ‘noise’ (filter not shown) as it enters the frequency converter’s speed reference input terminals 12 and 11. The resolution of the input is determined by the A to D converter **(A/D).** The central processor (**CPU**) then mathematically interprets the instructions from the A/D and compares its results with predetermined values already programmed into the firmware **ASIC** chip (application specific integrated circuit). The ASIC then runs the firing circuits (**gate drives**) at the correct pulse timing levels, to enable the main power devices to control the motor speed in exact proportion to the signal level at terminals 12 and 11.
The same method is used for driving analogue output signals from the frequency converter, but this time a **D/A** circuit is used to convert digital signals to analogues.

In the case of all IMO Jaguar frequency converters, the on-board SMPS provides a 10V DC supply for use by external analogue devices such as a potentiometer, etc. These terminals are designated ‘11’ (0V) and ‘13’(+10V).

Another terminal ‘C1’ is provided for use if the analogue input is a current loop type.
Current loops, commonly 4 – 20mA or 0 – 20mA, are favoured signals when the wiring is likely to cover long distances. Current signals are not as susceptible to high frequency interference (‘noise’) as voltage signals, therefore their integrity is higher.

Both types of analogue signal are fully scaleable by the frequency converter, i.e. half signal can equal full output frequency, or full signal can equal half output frequency, etc.

The analogue common for both voltage and current signals is terminal ‘11’ on all IMO frequency converters.

Digital inputs

The frequency converter must be able to accept digital commands as well as analogue.
IMO drives have some digital inputs whose functions are fixed – for example, forward (FWD), reverse (REV).

Some digital inputs are more flexible, and can be programmed to different jobs. The programmable inputs are called ‘X1’, ‘X2’, ‘X3’, ‘X4’, etc

A digital signal can only have one of two states, off or on (high or low). This type of signal may be transmitted from a switch, relay, PLC, etc, and is used for simple commands such as stop/start, run forward/run reverse, change speed to pre-set value, etc.
The SMPS supplies different voltages to the control circuit terminal rail, for use by other devices in the field or process plant.

As with all IMO drives, it is usual to supply a pair of terminals with a 24V power supply, rated anywhere between 50mA and 250mA depending on the SMPS capacity. In the case of IMO drives, these terminals are known as ‘P24’ which carries +24V DC, and ‘CM’ (common) which is the negative side of the power supply, tied to 0v.

Alternatively, an encoder attached to the motor shaft may transmit a series of digital pulses to the frequency converter. In this case, the frequency of the pulses is translated into rotational speed by the CPU.

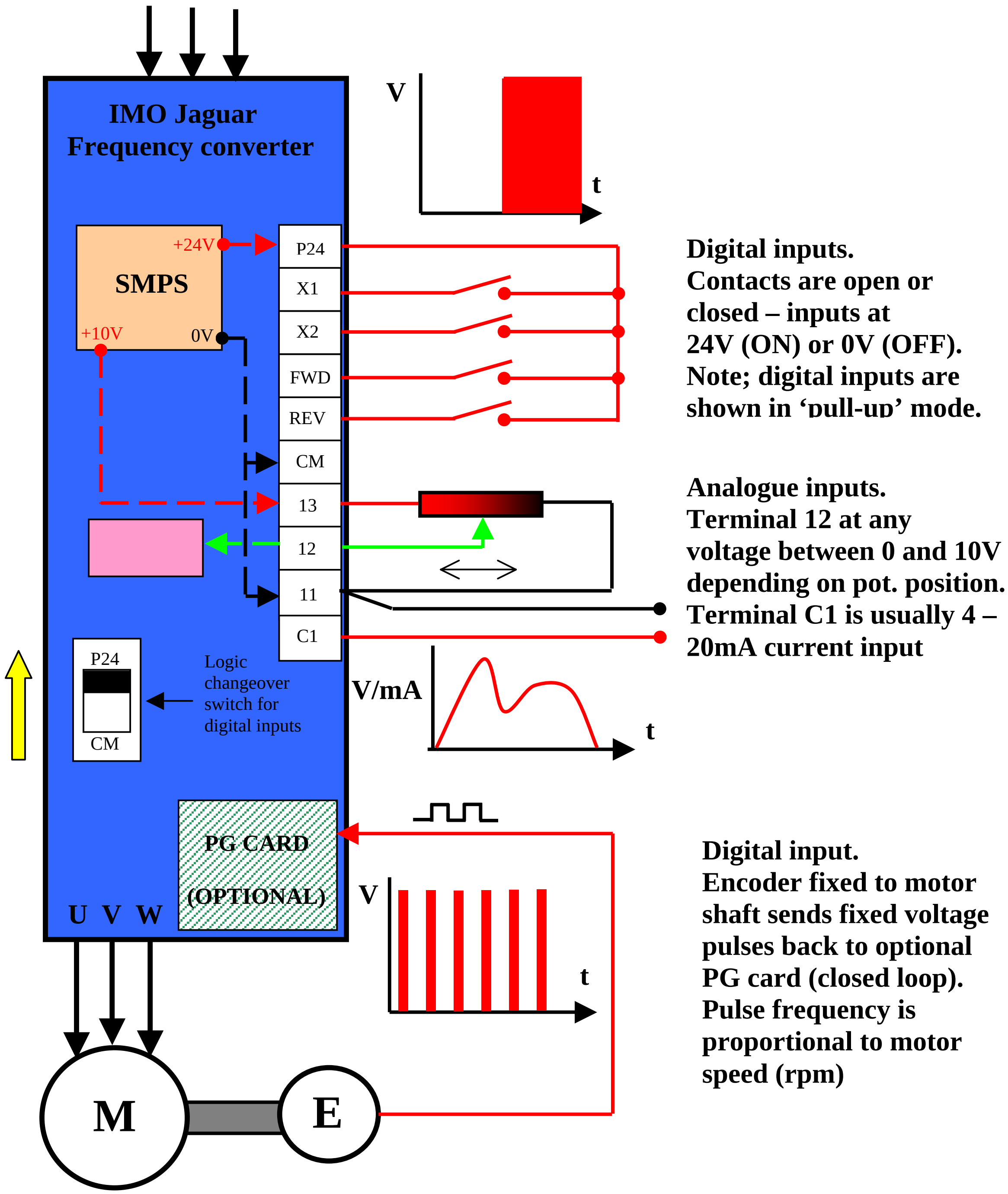


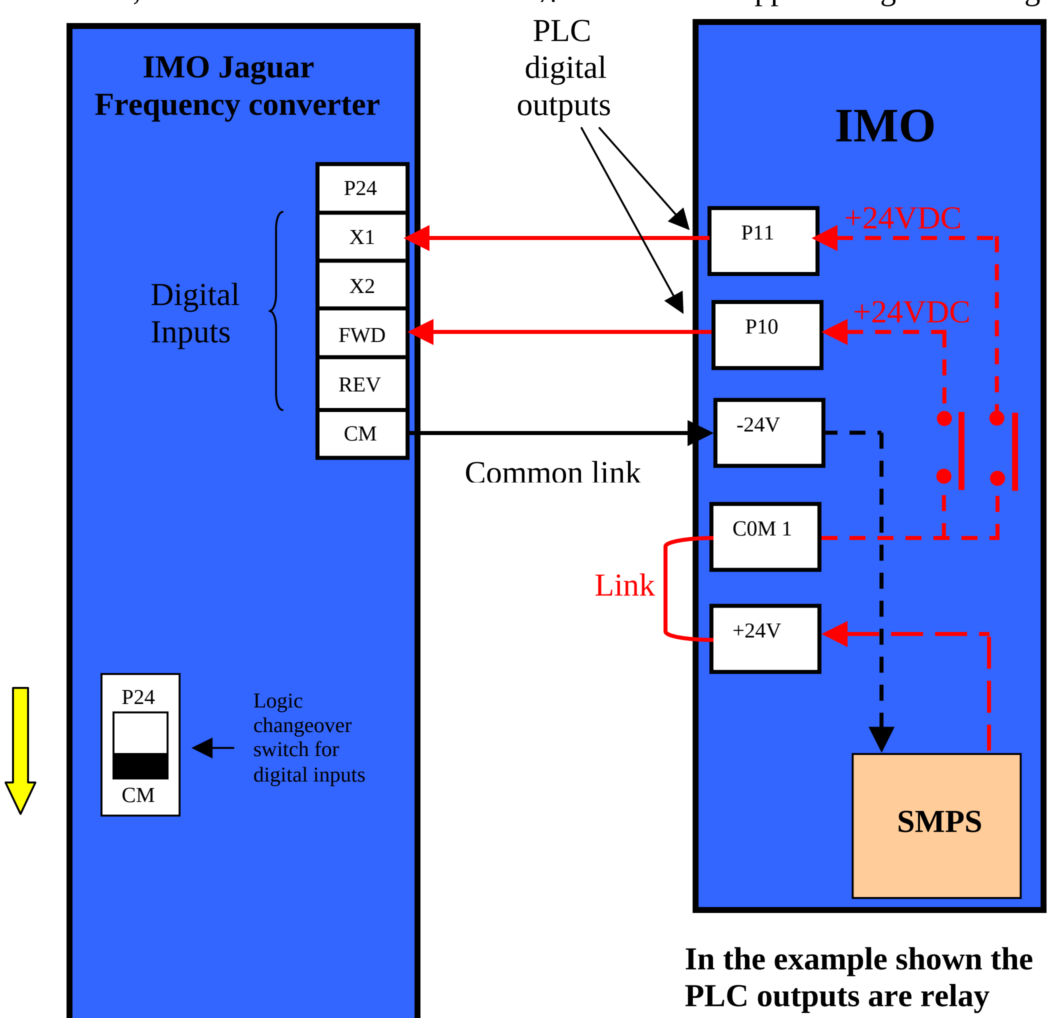
Figure 17c. Digital and analogue inputs and their power supplies as found on IMO Jaguar frequency converters. Note. The PG (pulse generator) option card is only available on top of the range models such as Jaguar VXM.

Digital inputs can be configured in one of two ways:-

1. ‘**Pull-up**’ In this configuration each of the digital inputs are at very low potential close to 0V when they are in the off state. To activate an input, it is simply connected to the power supply positive terminal P24, i.e. the input is pulled up. Because of the transistor switching logic used internally, this method is also known as PNP configuration. This is the default logic of Jaguar drives.

2. **‘Pull-down’** This is the opposite to pull-up. The digital inputs are ‘high’ in the off state. To activate them it is necessary to switch them to 0V (CM), i.e. pull them down. Standard Jaguar drives do not have this facility.

Switching digital inputs using a PLC – It is possible to connect the digital inputs of a frequency converter directly to digital outputs of a PLC. To achieve this on an IMO Cub drive, a selector switch must be changed over to the opposite logic. See Figure 17d.



Note the position of the logic change over switch.

In the example shown the PLC outputs are relay driven. Relays are operated by the program. Some PLC’s have transistor outputs.

Figure 17d. Switching the frequency converter’s digital inputs using a PLC.

Analogue outputs

The frequency converter will usually have at least one analogue output. This output may be a 0 –10V signal or a current signal (4 – 20mA). It is derived from a D/A converter in the control electronics, and can be made to represent any value – frequency, load current, torque, motor volts, DC link volts, etc - depending on the cost of the frequency converter. The analogue output (terminal FM or FMA) is only capable of supplying a small current say 1mA at maximum voltage, but is ideal for driving an indicating device, a PLC analogue input or the analogue input of another frequency converter, for speed slaving or master/slave applications. Again, the analogue common is terminal 11 on all IMO drives.

Digital outputs

Depending on the cost of the frequency converter there will be a number of digital outputs. These outputs are transistor driven, and can only be in one of two states, off or on. The outputs, 'Y1', 'Y2', 'Y3' etc on IMO drives, are flexible and can be programmed to turn on when a certain event occurs. Typical events could be:- speed reached, drive running, time-up, service required, etc.

Fault relay

All frequency converters have a fault relay. This is usually mounted on the control board and is connected to the terminal rail. The fault relay generally is of the change-over type, having one common terminal and a normally open contact, and a normally closed contact, all volt-free (isolated from any internal source of voltage). These contacts will change state if the frequency converter goes into a fault condition. It is therefore possible to wire a control circuit through the fault relay, at mains voltage (110V/240V) if required, and so provide total integration of the frequency converter into the process control.

Communication

Basically, digital frequency converters are able to exchange data with the peripherals using three interfaces, see Figure 18.

- The control terminals for digital and analogue input and output signals
- The touch panel with displays and keypad.
- A serial interface for diagnostic and control functions

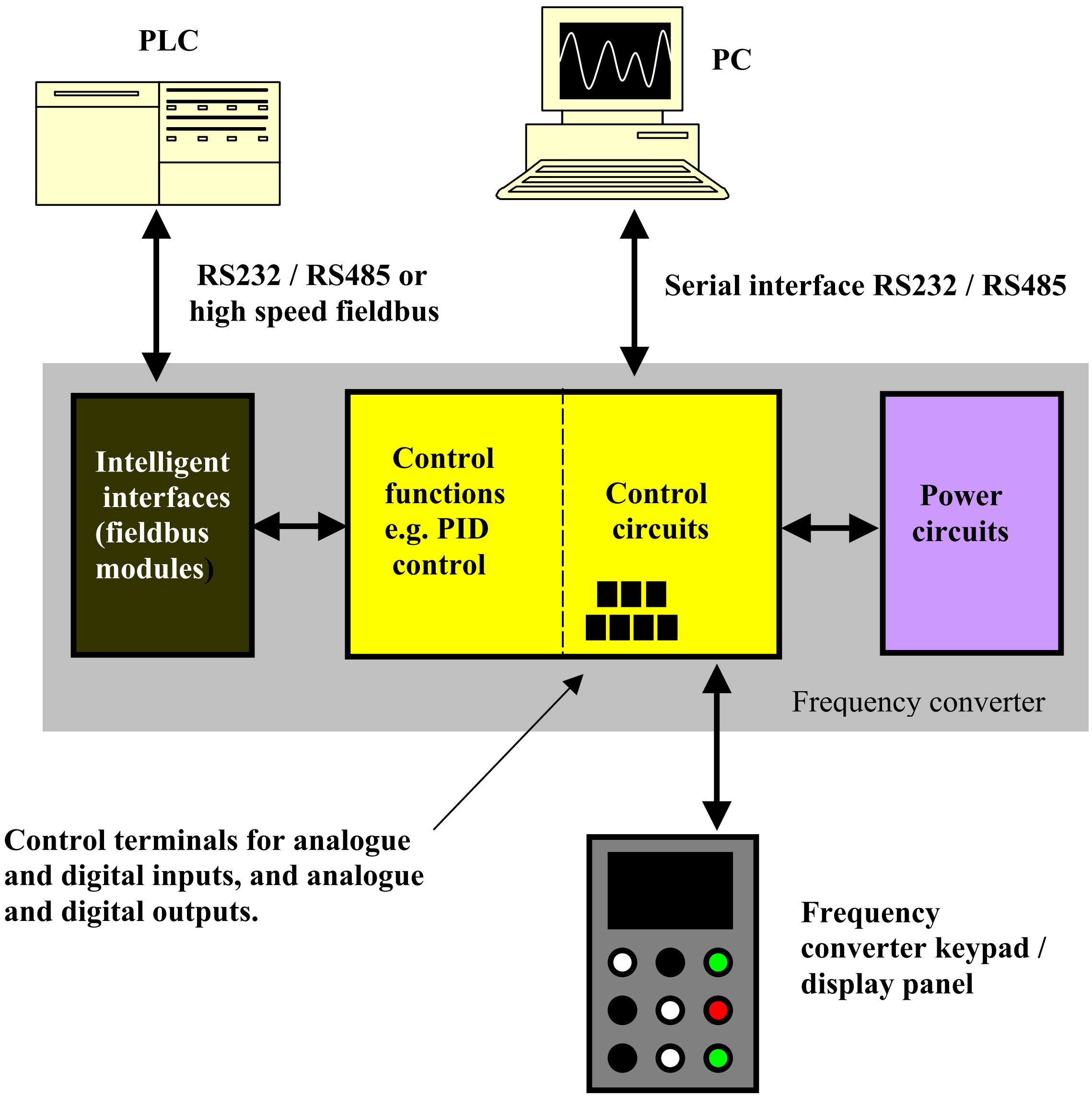


Figure 18. Basic concept – communications and the frequency converter

A control panel with display and keypad can be integrated into a digital frequency converter, and be supplied with the kit as standard or as an optional extra. All IMO frequency converters are supplied with this module as standard.

Serial Communication

In a process the frequency converter is an active part of the equipment. It is either installed in a system without feedback (control) or in a system with feedback (regulation) from the process.

A system without feedback can be built up with one single potentiometer. A system with feedback is more demanding and usually it includes a programmable controller (PLC).

Note. A potentiometer (pot) is a low cost, hand operated, rotating device for varying DC voltage.

The PLC can deliver both analogue and digital control signals (speed) and digital command signals (start, stop, reverse, etc).

The output signals of the frequency converter, e.g. motor frequency, motor voltage, etc are often read with indicating instruments such as voltmeters or ammeters. However, the PLC can also read the output signals and therefore this type of data can be registered continuously.

A control program (software) is entered into the CPU of the PLC by means of a computer or programming unit. The CPU 'sorts' the input signals and activates the output signals according to the program. As with the frequency converter's CPU, the PLC's CPU can only process digital signals, i.e. a signal that changes between two values – say 0V and 24V. The high voltage can be stated as "1" or "ON" and the low as "0" or "OFF".

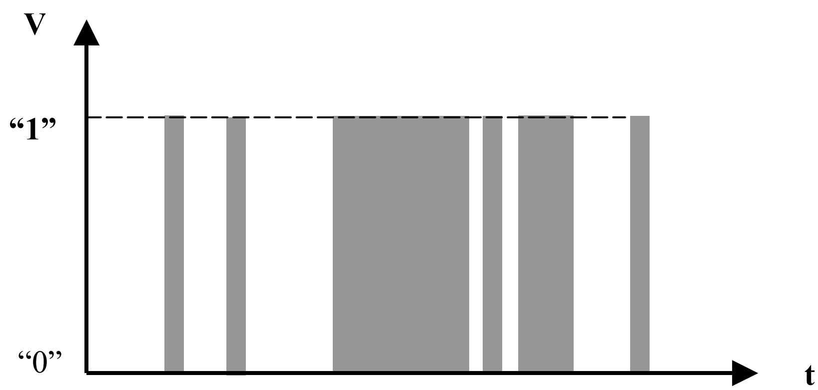


Figure 19. Digital signals can be ON or OFF for long or short intervals of time

Basically, a frequency converter and a PLC can be linked together in two ways.
One method is to connect all of the required inputs and outputs of the PLC one by one over separate wires with the inputs and outputs of the frequency converter (see digital and analogue I/O above). The PLC inputs and outputs thus replace the individual control components such as potentiometer, relays, meters, etc.

The other method is to transfer many signals at different times over one pair of conductors. This method is called serial communication (comms).

There are several different operating principles for comms but the number of frequency converters (nodes) to be connected via the comms link and the distance the nodes are apart, influence the type that should be used.

For example, command and control functions can be sent and received by the PLC to up to 31 frequency converters or other compatible nodes, using a single standard **RS485** comms link. Each node is given a unique address, and when the PLC wants to send data to one node only –for example a start command to node 1, or request for data – i.e. "what is your motor speed?" to node 4, only that particular address is used.

All sorts of data can be transmitted over the comms link, for example, status, alarms, error messages and re-programming information.

The speed of transmission of 'bits' across the link (baud rate) will be up to 19,600 bits per second (19.6kB). This is quite a slow baud rate by comparison with other serial communications protocols used widely for factory automation systems.

Depending on the application, the communication can be supplemented by a high-speed intelligent serial interface for a high performance bus such as PROFIBUS, DEVICENET, INTERBUS, CanOPEN or MODBUS PLUS. This may be in the form of an independent group of plug-in modules for the frequency converter, which contain their own supporting micro-processor and peripherals (e.g. Dual Port Ram). The speed of data transfer in these intelligent **fieldbus** systems is much faster, for example 500kB to 12MB, so much more data can be transported than using an slower RS485 type comms system.

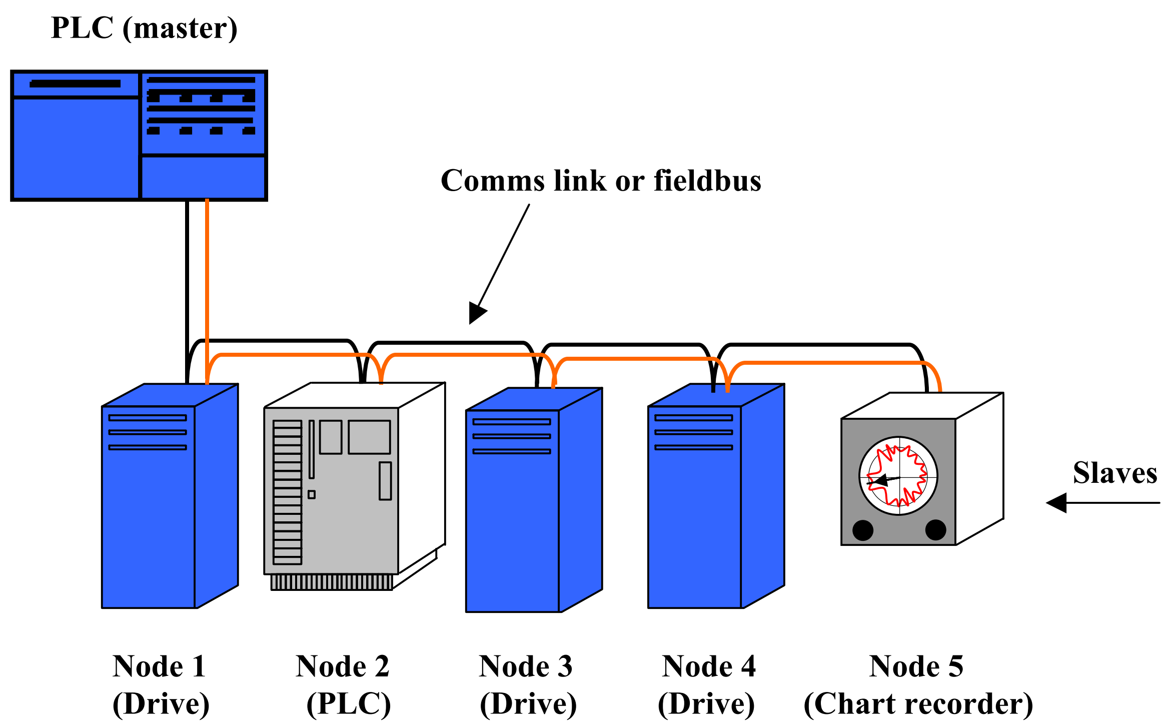


Figure 20. Typical construction of serial communication link

Ramps

When a digital start command is received at the FWD or REV input, the motor will accelerate at a certain rate to a set speed (proportional to the analogue input setting at terminal 12 or C1) and run at that speed until a further command is given. When a stop command is given by breaking the FWD or REV input, the motor decelerates to stop.
What really happens is the synchronous field inside the motor is steadily increased in speed from zero to desired operating speed. Because the rotor then tries to follow speed of the field, it is 'dragged' along with it. When a stop command is given, or a reduction in the speed reference signal is made, the field and rotor speeds reduce accordingly.
In a frequency converter, it is possible to precisely control the accelerating time and the decelerating time as required by the application. These time/speed functions are commonly known as ramps. See Figure 21 below.

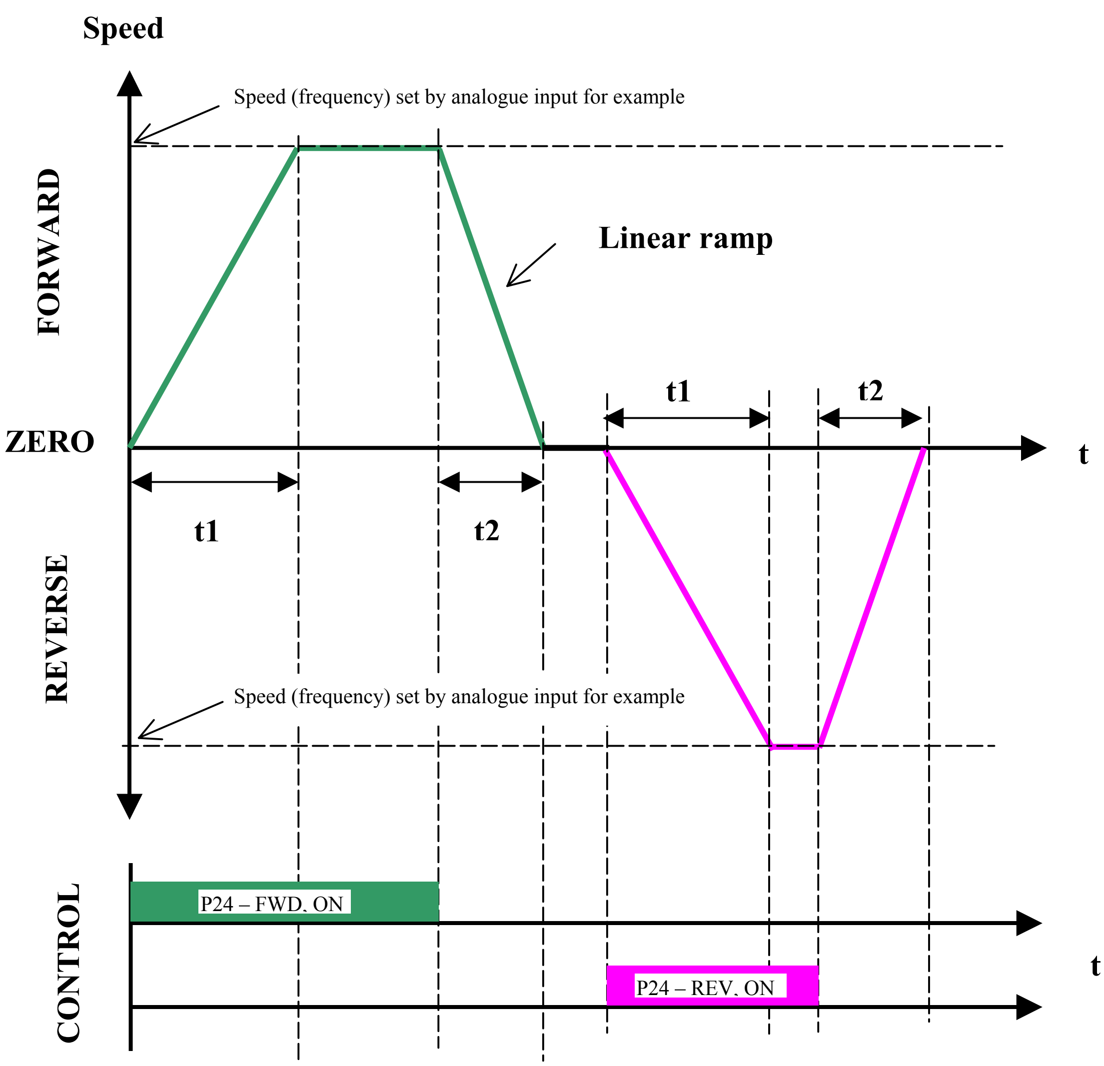


Figure 21. Linear acceleration and deceleration ramp control

In Figure 21, time period ‘**t1**’ represents the accelerating time, and ‘**t2’** represents the decelerating time. Their triangular shapes look like ramps. Both times can be set independently of each other at totally different values if required. When digital control terminal FWD is connected to P24, the motor accelerates to the set value in the time set in the acceleration time function. This speed (frequency) is maintained until the FWD-P24 signal is removed, whereupon the motor decelerates to stop in the time set in the deceleration time function. If the REV terminal is now connected to P24, the motor accelerates to the same speed as previous and in the same time, but in the opposite direction. If both FWD and REV inputs are on at the same time, the motor **coasts** to stop, i.e. the output PWM is switched off immediately (no ramps).

Care must be taken when selecting suitable ramp times, for even though the factory set default ramp times of **6 seconds** are adequate for many applications, this will not be the case for all. For example, for some high inertia loads such as big fans etc, setting the decelerating ramp too short may cause the frequency converter to trip (go into fault condition ‘OU2’) through power regeneration from the motor. This will be covered in more detail later.

Another example would be setting the accelerating time too short for loads such as a press. This could result in the frequency converter trying to deliver too much current, too quickly, and again a trip condition may occur - ‘OC1’.
Optimum accelerating time can be calculated from the accelerating torque, inertia/mass and speed requirements of the load.

Although standard ramps are linear, it is possible to set certain frequency converters to perform non-linear ramps. These are called ‘**S-ramps**’ because of their shape.
S-ramps are useful in applications such as lifts or hoists, where the persons or goods in the lift/hoist are to experience no shock movements. See Figure 22 below.

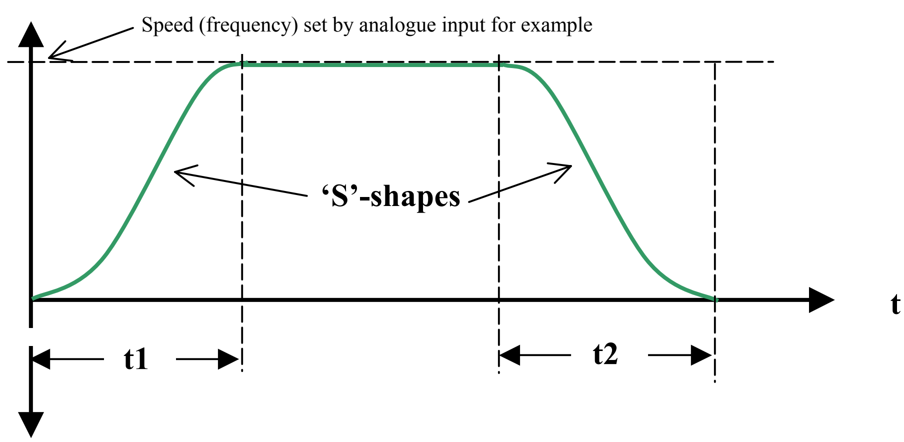


Figure 22. ‘S’-ramps

Thermal Overloads

To protect a motor from an overload condition while running without a frequency converter, it is necessary to install a thermal overload module of correct current rating and with suitable characteristics. For convenience, this device is sometimes fixed to the 'load' side of a 3-phase contactor, and the two operate as a pair.

While it is a good idea to use a contactor at the input to the frequency converter – to ensure that all supply phases are connected at exactly the same time, on no account should a stand-alone thermal overload device be used with the contactor. An overload device of this kind may react adversely to the non-linear input current and cause unwanted nuisance tripping of the frequency converter.

On the frequency converter output side (U, V, W) it is again not normally necessary to install a thermal overload device.

The frequency converter has its own built-in flexible thermal overload, and can be configured by the user for many different motor sizes and conditions. Overloads can occur in induction motors for many reasons, but mostly they are mechanically derived, i.e. faulty motor bearings, mechanical load too large, seizure, etc. In these cases, the motor current increases beyond the rated level and the over time cause overheating and failure of the motor windings. Thermal (heat) overloads are two dimensional, having both current and time directly contributing to the condition. Reduce either and the problem can be controlled. This type of overload is sometimes referred to as I squared t **(I^2t)** due to its connection with heat losses (Watts). As with a stand-alone thermal overload device (such as IMO's **MC0R-1/2/3** range) the frequency converter uses the same type of characteristics ('curves') to control a motor overload, but this is achieved in software. See Figure 23 on the next page.

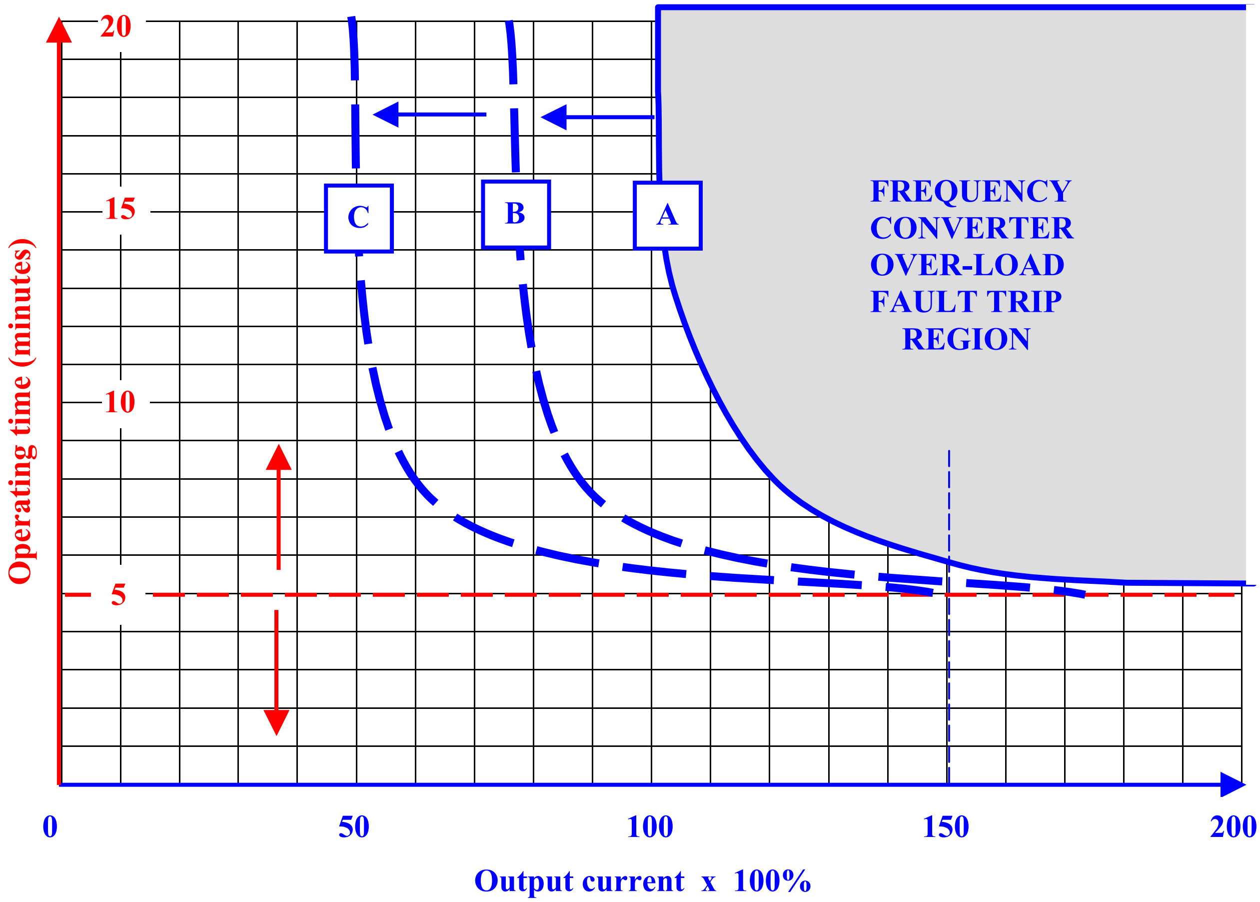


Figure 23. Frequency converter basic thermal overload characteristics

All areas to the right of the solid curve (shaded grey) are prohibited, and the inverter will trip if operated here. The fault code will be 'OL1' We can see that on the solid curve 'A' it is possible to operate at 100% rated load current indefinitely. At the setting shown on Figure 23, if the output current increases to 150% of rated current (50% overload), this condition will be tolerated for approximately 6 seconds while the timer times out and the drive trips.

Upon a trip condition, the motor will free-wheel to standstill, and the frequency converter will usually require manual reset either from the keypad or a preset digital reset 'RST'. In the case of a smaller motor than rated, we can see that it is possible to slide the curves to the left for example at positions 'B' or 'C' or other.

On some frequency converters it is also possible to select what length of time the motor will continue to operate at when 150% rated current flows, in case of curve 'A' shown in Figure 23; approximately 6 seconds. This is known as the '**thermal time constant'** and can be adjusted to suit the motor / application.

Parallel operation of motors

It is perfectly acceptable to run two or more motors connected in parallel from the output of a frequency converter. For example, a 22kW drive can run one 22kW motor or two 11kW motors, four 5.5kW motors etc. <u>It is essential that the total load current of all the motors sums to less than or equal to the rated current of the frequency converter</u>.
For parallel operation, frequency converter's own integrated overload cannot protect each individual motor and must be disabled.

Each connected motor must have its own stand-alone overload unit connected in series with the motor. The auxiliary contacts of each overload can then be connected in series and wired to a thermal trip input on the frequency converter. On the IMO drives this is usually achieved by configuring a programmable digital 'X' input for 'THR' (thermal relay) mode. Either motor in overload condition will trip the 'THR' circuit and stop both under fault trip condition 'OH2'. See Figure 23a below.

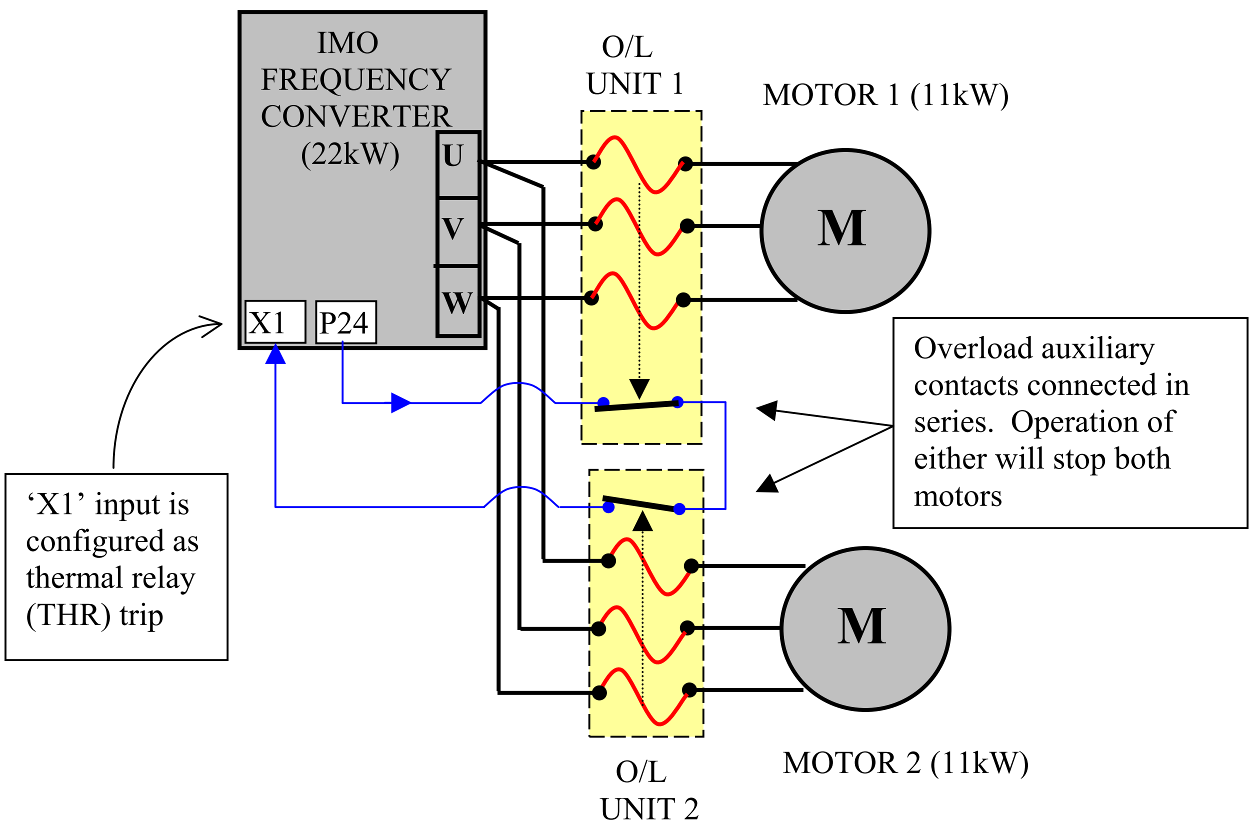


Figure 23a. Example of overload protection for two motors operating in parallel.

The 4 Quadrants of motor operation

Up until now we have only considered how the frequency converter delivers power to the motor in the form of PWM voltage and load current. The current flows into the load and the motor generates sufficient torque to accelerate the load up to a desired speed. In this mode, the motor is said to be operating in Quadrants 1 or 2 (torque positive, forward or reverse direction. However the motor can operate in Quadrants 3 and 4 also.

Example 1 - Consider a passenger lift that is empty and weighs 1000kg, that is stationary at the third floor of a six story building. The wire ropes attached to the lift car go up the lift shaft around the flywheel of the motor (installed at roof level of the building) and back down the other side of the lift shaft, where it is attached to a 1000kg counter-weight. As the lift goes down, the counter-balance goes up and visa-versa – the system is in perfect balance. Now if some people get in the lift at the third floor, one of two things can happen:-

a) They can go up. The motor has to develop sufficient **driving torque** to haul the car and payload up the shaft, because the car is now much heavier than the counter-balance. A heavy load current is drawn from the frequency converter by the motor. The motor is operating in **Quadrants 1 or 3**.
b) They can go down. Now the motor struggles to hold the car which is trying to 'run-away'. Gravitational forces are acting with the unbalanced lift, and the rotor will be running faster than rotating magnetic field says it should. In other words motor slip is positive and the motor is said to be operating super-synchronous. The motor will be developing a negative torque known **braking torque** and depending on direction of rotation will be operating in **Quadrants 2 or 4**.

Example 2 – A large flywheel is connected to a motor shaft. It has a large inertia so does not want to be moved from standstill. A lot of energy has to put into it to accelerate it up to a given speed. When it reaches the required speed, it stores that energy **(Q1 or Q3)**.
Now, if the motor is driven by a frequency converter and it a stop command is issued at the digital control inputs, the motor alone will try to obey the ramp, ie as the synchronous frequency is reduced linearly, the rotor sub-synchronously 'locked' to it will be 'dragged' down to zero speed also. However, the stored energy (**kinetic energy**) in the flywheel means that it does not want to be stopped. The rotor runs faster than the rotating field (super-synchronous) and the slip is again positive during stopping, and braking torque is developed by the motor (**Q2 or Q4**).

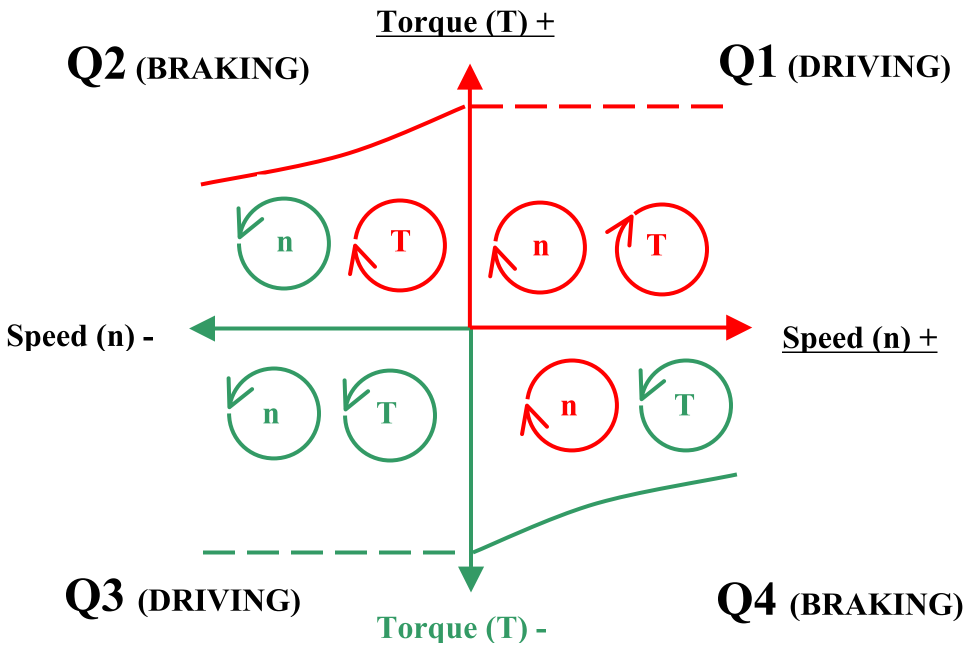


Figure 24. The four quadrant operating conditions of a motor

Dynamic Braking

When the motor is operating in the braking regions, it will be returning this braking energy to the supply in the form of current. This is known as **regeneration**. When an AC motor is connected to a frequency converter, the braking current returned from the motor will flow back to the DC link via the motor cables and flywheel diodes. However it will then be blocked from returning to the mains by the diodes in the rectifier.

With the regenerative current unable to go anywhere, and power still being returned from the motor at a high rate, the result is that the DC link voltage increases rapidly. The DC link capacitors in a 400V AC frequency inverter are nominally rated at 800V DC (about 850V maximum). If the DC voltage is allowed to exceed 850V, the capacitors are in danger of being damaged by the pressure of the voltage across their plates.

Frequency converters have a built-in (non-user changeable) over-voltage trip point. Regardless of if through motor regeneration or whether a higher than rated input voltage is applied, if the DC link goes higher than the trip point – about 790V, the IGBT's will be switched off, power will be removed from the motor, and the load will come to rest in a time dictated only by its speed, inertia, and friction. It is a bit like stopping your car by switching off the ignition (assuming no steering lock!).

The great danger in an over-voltage trip (OU) is that the load is now freewheeling out of control, and can cause damage to machinery, equipment, manufactured products and even pose a threat to the safety of persons close by.

To overcome this problem, a resistor(s) is connected intermittently across the DC link to absorb the regenerative energy. The resistor is switched in and out of circuit by a power transistor. This device is triggered into conduction at about 750V DC, where it pulses a short flow of regenerative current through the dynamic brake resistor. The more rapid the rate of rise of DC link volts, the more the brake transistor is in the on-state. The resistor passes this current, causing it to get hot and so the excess electrical energy is converted into heat.

This procedure is known as **dynamic braking** and is similar to how the brakes on your car work, i.e. the kinetic energy stored in the moving vehicle is converted to heat by the mechanical brakes on the wheels, when the brake pedal is pushed.

Figure 24a shows various events during dynamic braking as a timing diagram.

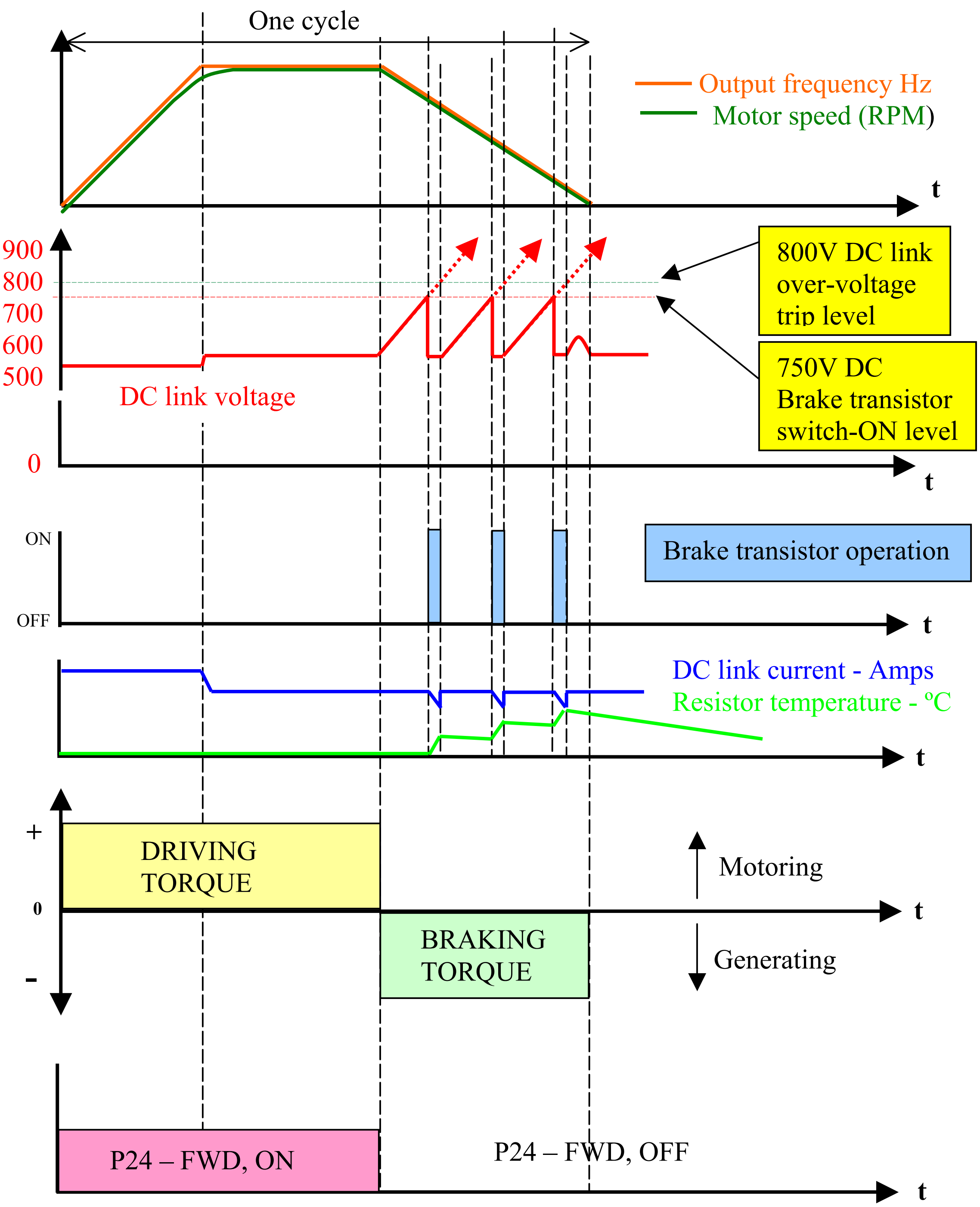


Figure 24a. Diagram of typical dynamic brake timing during one machine cycle (accelerate – run – decelerate – stop) of high inertia load (flywheel, etc) driven by frequency converter.

All IMO Jaguar VXM frequency converters of power rating 7.5kW or less, have a special braking transistor or '**brake chopper**' <u>and</u> a small dynamic brake resistor incorporated as standard within the drive.

For all IMO drives at 11kW and above this internal braking hardware is not available. If dynamic braking is required, an external 'stand-alone' brake module must be used, due to higher power levels and associated heat losses. For IMO Jaguar VXM drives, these brake modules are generally grouped in rating bands for use with a particular drive power range.

For example:- **VXDBU11-22** = **<u>D</u>**ynamic **<u>B</u>**rake **<u>U</u>**nit for **<u>11</u>** to **<u>22</u>**kW drives, and so on.

IMO frequency converters at 11kW and higher that require stand-alone brake modules such as the above, <u>also require external resistors of suitable ohmic value and duty rating</u>. IMO do supply a range of small power resistors for light duty use, i.e. non frequent stopping, but specialist resistor manufacturers should be consulted for larger or bespoke requirements. See Fig 25 on the next page.

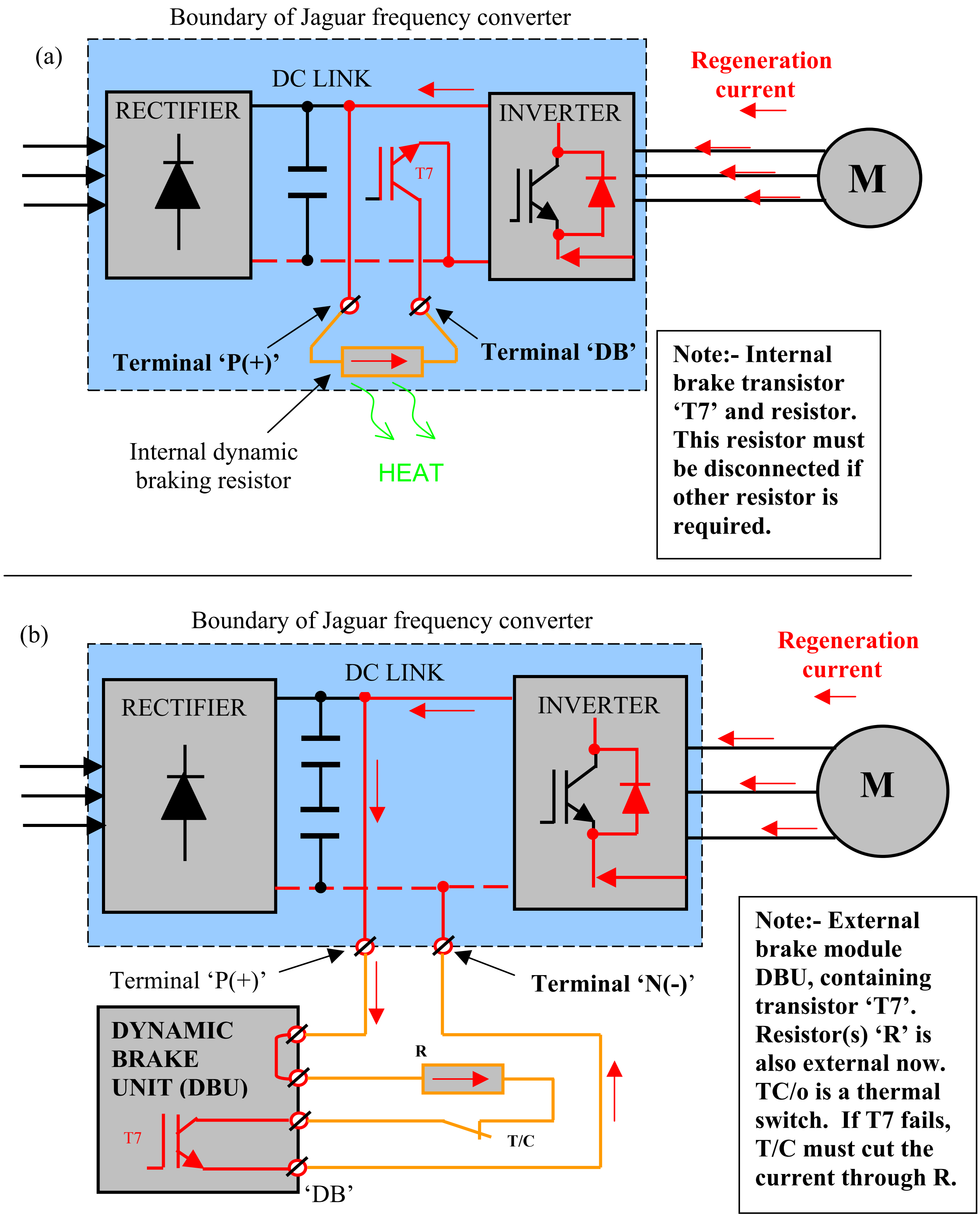


Figure 25. (a) Braking connections for IMO VXM drives of power ratings 0.4 to 7.5kW
(b) Braking connections for IMO VXM drives of power ratings 11kW and greater

Calculating the resistor size required

The actual resistor power rating and ohmic value can be calculated in many different ways, depending on how much and what type of information is available.

Generally, the higher the power rating of the motor, the higher the resistor power but the lower the ohmic value will be.

Electrical braking can be:-

- Once only – emergency stopping
- Repetitive – cyclic operation
- Continuous – load control, lifts/hoists etc

All but 3-5% of the regenerative energy is used to heat up the resistor, some is dissipated immediately and the rest after the stop while the resistor cools. The remaining energy is absorbed by the DC link capacitors. This is why we must know the duty cycle of the load, i.e. what proportion of the cycle time is spent braking. Figure 24a shows a typical example, about 40% braking duty (0.4 x total cycle time).

As already seen, the dynamic braking resistor (DBR) converts stopping energy into heat, so we must establish *how much energy* per stop, and how frequent the stops are.

Energy per stop: > resistor peak power
Energy per stop + frequency: > resistor average power

- **Man on a bike 2kJ**
- **Lift with four people 25kJ**
- **Car stopping from 50mph 250kJ**
- **Flywheel 600mm x 300mm thick, 1500rpm 375kJ**
- **40’ container lowered on to a ship 2MJ**
- **Eddie Stobart’s lorry from 65mph 15MJ**
- **London Underground train from 50mph 50MJ**

Stopping energy (remember friction, drag, etc work in our favour)

Kinetic energy (eg man on a bike)	=	$\frac{1}{2}$ **. m . v**^{2}

60kg man, 20kg bike, 15mph = (80 x 7 x 7) / 2
(15mph = 7 mts per second)

= 2000Joules = **2kJ**

Rotating energy **(**eg flywheel)	=	**J x** $\boldsymbol{\omega}^2$ **/ 2**

(600mm x 300mm thick, 1500rpm)
(where **J** = inertia of flywheel, and $\boldsymbol{\omega}$ is angular velocity in radians per second)

If J is unknown it can be calculated:- $J = \dfrac{\text{mass x radius squared}}{2}$

The mass of a flywheel takes into account the relative density (**ρ**) of the material.

For steel, the relative density is 8000kg/mts^3. mass (**m**) = **ρ.π.r**^{2}**.d** (thickness)

so, $m = 8000 \times 3.142 \times 0.3^2 \times 0.3 = 678\text{kg}$

Now we can calculate J. $J = \dfrac{678 \times 0.3^2}{2} = 30.5\ \text{kg/m}^2$

Now we must convert rotational speed into angular velocity 'ω':-

$$\omega = \frac{2\pi \times \text{speed (N) rpm}}{60} = \frac{2\pi \times 1500}{60} = 157 \text{ rads/sec}$$

Energy in flywheel $= 30.5 \times \dfrac{(157^2)}{2} = 30.5 \times \dfrac{24649}{2} =$ **375kJ**

Potential energy (eg crane)	=	**m . g . h**

(10 tonne container, 20 mts on to a ship) = 10,000kg x 9.81 x 20
(where 9.81 is a constant due to effect of gravity)

= 2,000,000J = **2MJ**

Energy must be divided by time to obtain power (kW).

For the flywheel example, if the required decelerating time is 60 seconds, then the resistor peak power will be:-

$$\textbf{Power P} = \frac{\text{Energy}}{\text{Time}} = \frac{375{,}000\text{J}}{30\text{ s}} = \textbf{12.5kW}$$

Remember that in the case of a lift or crane that is braking all of the time that the load is being lowered i.e. it is regenerating, so the denominator is the total lowering time, not just the decelerating time.

In general, most resistors wound for dynamic braking will tolerate ten times their rated power for a short periods, then require a long cooling down period to recover. This is beneficial for cost effective occasional stopping of some loads. The resistor manufacturer will confirm the cooling period for a given overload level and time from a set of curves. Always cross check with the manufacturer if unsure.

To calculate the resistance we need to know the maximum level of DC link voltage.

The nominal DC link voltage = **√2 x AC input volts** e.g. √2 x 415 = 587V

In practice, the brake transistor switch-on level is normally 150V or so above this level, i.e. 750V in the case of most frequency converters, so it is this level that must be used.

$$\textbf{Resistance R} = \frac{VDC^2}{P} = \frac{750 \times 750}{12{,}500} = \mathbf{45\Omega}$$

CAUTION:- Under no circumstances must a resistor(s) of a lower Ohmic value than the minimum stated in the frequency converter / brake module technical specifications be used, or damage will occur.

This subject will be covered in more depth in another lesson.

DC injection braking

This is another method of stopping a motor quickly. It is not as accurate as dynamic braking but if acceptable, it can offer a lower initial cost option to the user.

When DC current flows through an induction motor, the induction principle cannot work. The magnet poles do not rotate, so the rotor is 'clamped' in the stall position.
No internal or external resistors or any form of brake chopper are required for DC injection braking. Instead, the main transistors in the frequency converter's output stage are asked to perform a simple operation other than normal. For example, a certain transistor(s) in the top half of the bridge are held in the on state allowing DC current to flow from DC positive, through the AC motor, and returning to DC negative via the flywheel diodes. The value of DC current that flows will determine the speed of stopping and this can be controlled by adjusting how hard the transistors turn on. This is achieved by controlling the transistor gate signals to control the rate of current through the devices. All of the associated heat losses with DC injection occur inside the motor.
In all IMO drives, it is possible to combine a ramped stop with DC injection. It is possible to define at what point in the normal deceleration ramp DC injection takes over. If the DC injection holding time is set to continue after the motor has stopped, the shaft can be made to hold stationary (depending on load torque) for short periods, until the main mechanical brake comes on.
This type of braking is unsuitable for lift and hoist type applications.

Note: It is not possible to electrically control the shaft of an induction motor at zero speed with a load torque present, unless it is in closed loop control and the frequency converter has high performance flux vector control design such as IMO's Jaguar VXM drive. This type of control will be covered in the Level 3 Drives course.

Electro-magnetic compatibility –EMC

Electromagnetic interferences are unwanted electrical phenomena that originate from or affect the unit in an unwanted way. Electomagnetic phenomena may arise from nature or be generated by man.
Among the electromagnetic interferences that appear naturally are atmospheric interferences such as lightening. Another phenomenon is the magnetic field that surrounds the entire globe and protects us from the energy-intensive radiation that comes from space. Whilst atmospheric interference cannot be avoided its influence on electrical installations can be limited.

Unnatural interferences not caused by nature, are considered artificial electromagnetic phenomena and occur wherever electrical energy is used. This interference can disperse through air or through electrical wiring. Examples include interferences from light switches or ignition systems being experienced on radio or TV. Additionally if there is a short voltage drop-out, clocks may reset or PC's may not work properly.

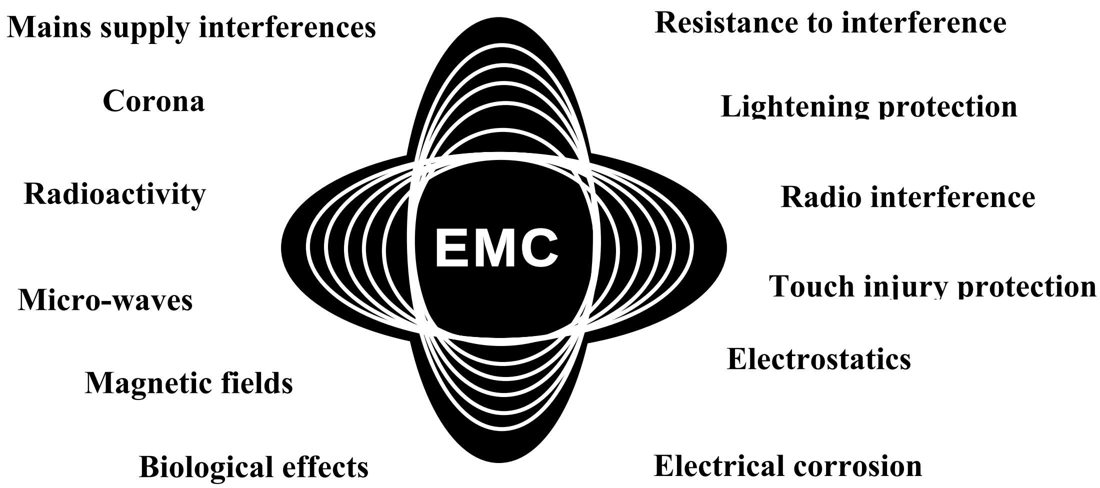


Figure 26. Electromagnetic phenomena

Electrostatic discharge can also lead to faults in electronic switches and even to fire hazards and there are a number of mutual effects on people, animals and plants.

The international term for radio interference is EMC or Electromagnetic Compatibility. This is described as the ability of a piece of equipment to resist electrical interference and not to emit interference to its surroundings.

In Europe, an EMC directive was adopted in 1989 and today Europe's EMC standards are divided into three groups.

- **Basic Standard –** These standards are phenomenon orientated. They describe the set-up of the required test equipment and measuring procedure.

- **Generic Standard –** These standards are environmentally orientated. They distinguish between residential areas, office areas, light industry, manufacturing industry and special applications.

- **Product Standard –** These standards relate to the specific requirements of given product families with respect to measuring procedures and assessment. Exact test levels and limit values are prescribed. These standards have priority over generic standards.

If a piece of electrical or electronic equipment adheres to European legislation, it must be submitted to, and substantiated by, the authorities at a specific time. This is done in the form of an **EC Declaration of Conformity** and by **CE** marking. The EC Declaration of

Conformity is issued as verification for a series of units, and the CE mark is placed on the equipment, packing and operating instructions. The CE mark is an authority symbol addressed to the relevant European authorities and confirms that the relevant rules and regulations have been complied with.
Products that require a CE mark in accordance with the EMC Directive must now carry this label:-

Figure 27. EU sign of compliance

If an electrical equipment operates in the range 50V to 1000V AC or between 75 and 1500V DC, the low voltage directive must be complied with. This directive came into force in 1997 and refers to dangers that may arise from electrical machinery for people, domestic animals, or objects.

Dispersal of interference

Emission (interference transmission) is the electromagnetic energy coming from the equipment. Immunity is the equipments ability to resist or suppress interference.
Radio frequency interference that comes from a frequency converter is mains supply interference in the low frequency range kHz to MHz, and radiated emissions into the air surrounding the equipment and motor cable at high frequency MHZ to GHz.

Coupling

Electrical circuits can be coupled by galvanic, capacitive or inductive coupling. Galvanic coupling may occur when two electrical circuits share a common electrical impedance Z.

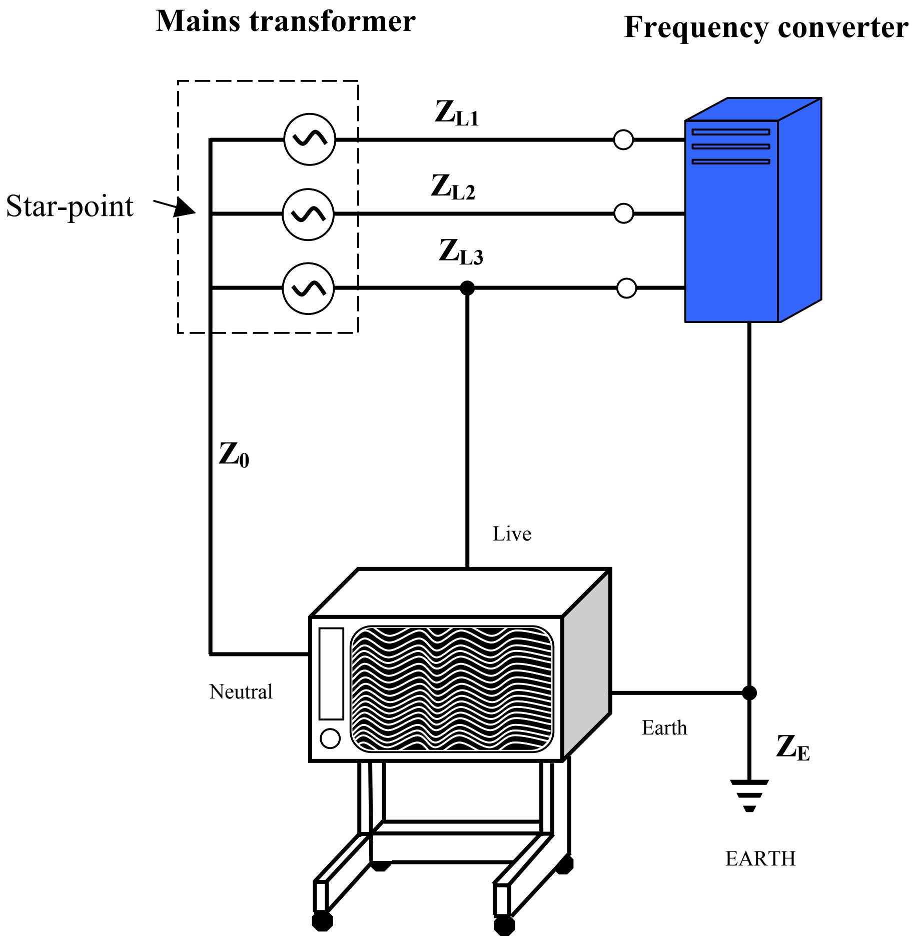


Figure 28. Galvanic coupling

Frequency converters and other electrical equipment operating in the same system are connected to each other by wires and have the same earth potential. Depending upon the impedance relationships, this coupling leads to an interference voltage at equipment (shown as a TV in figure 28) across the two shared impedances Z_{L3} and Z_0 .

Capacitive coupling occurs when two electrical circuits have a common earthing reference. Typically this occurs where a motor cable from a frequency converter has been laid too close to other cables. The capacitive interference current depends on the frequency of the motor cable, the related voltage and the distance to other cables. The relatively high PWM switching frequencies of today's frequency converters, with which the output voltage is generated, results in a low capacitive resistance in the motor cable and thus causes currents to leak across stray capacitances formed between conductors in close proximity.

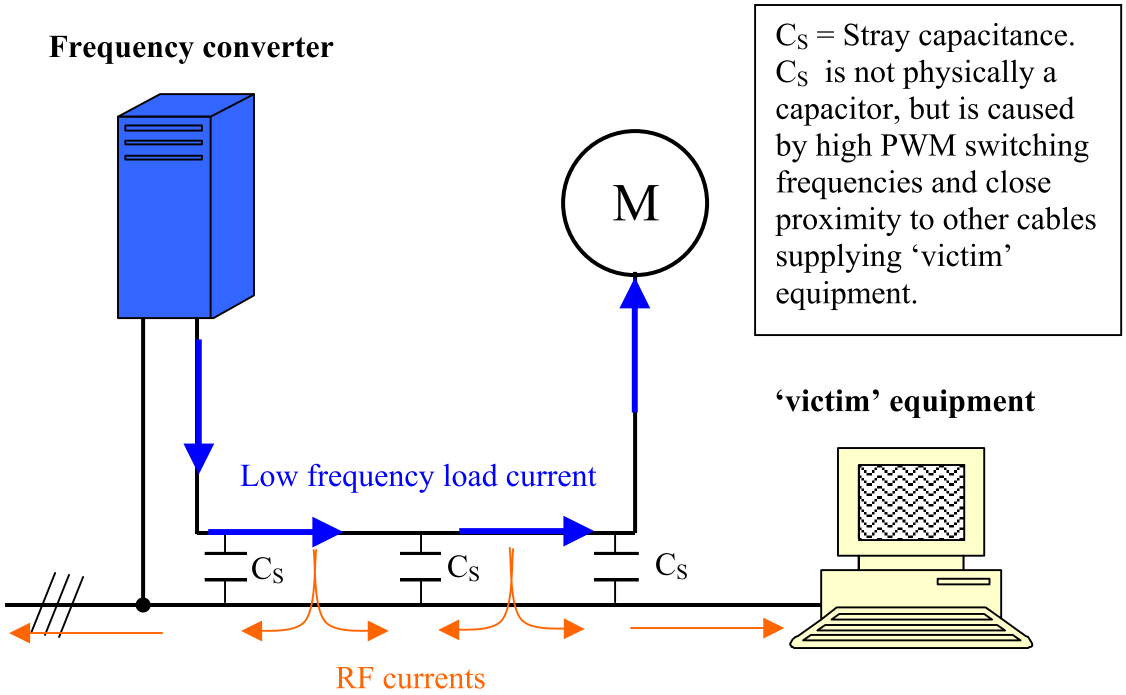


Figure 29. Capacitive coupling

Inductive coupling occurs when the magnetic field around a current carrying wire induces a voltage in another wire. The induced RF voltage depends upon the strength of the magnetic field, as well as the level of current in the motor cable, frequency and distance between cables.

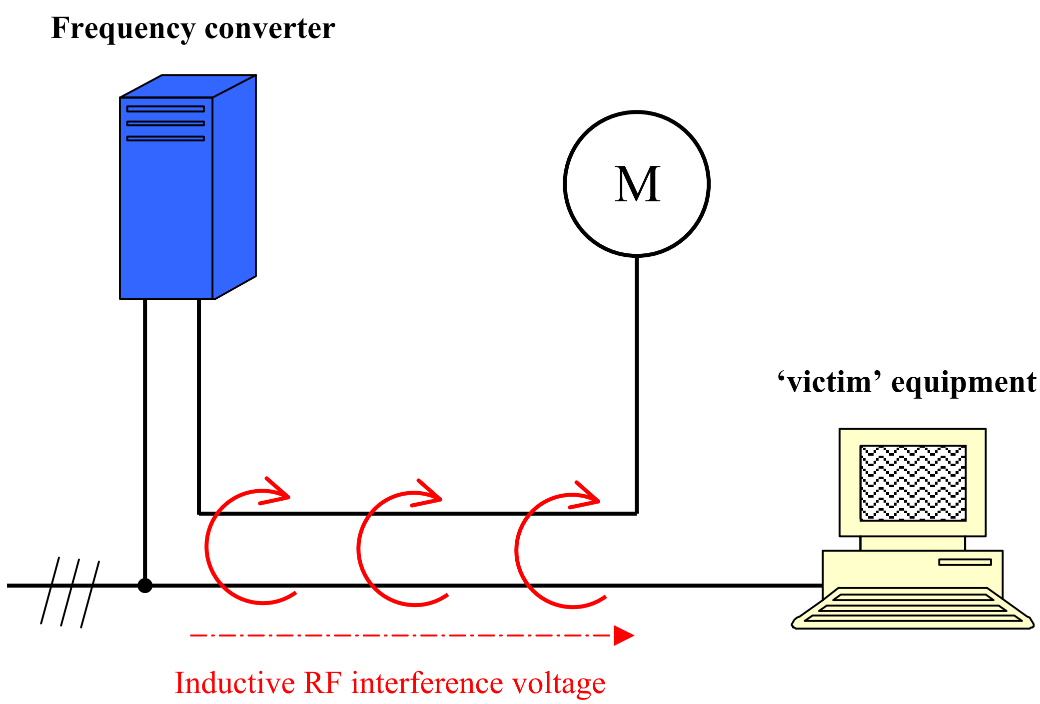


Figure 30. Inductive coupling

Hard-wired dispersal

Electrical noise can spread through the cables of the mains supply network. Higher frequencies are superimposed on the 50Hz sinusoidal voltage waveform. A distortion of the pure sinusoidal curve occurs.

Mains supply interference

Mains supply interference from electricity consuming units causes a distortion of the supply voltage. This distortion is created by high frequency components of the current drawn by the input circuits of frequency converters and other semi-conductor products, due to their non-linear nature. In other equipment that is connected to the same mains supply, interference causes an additional load, reflected by higher current consumption.

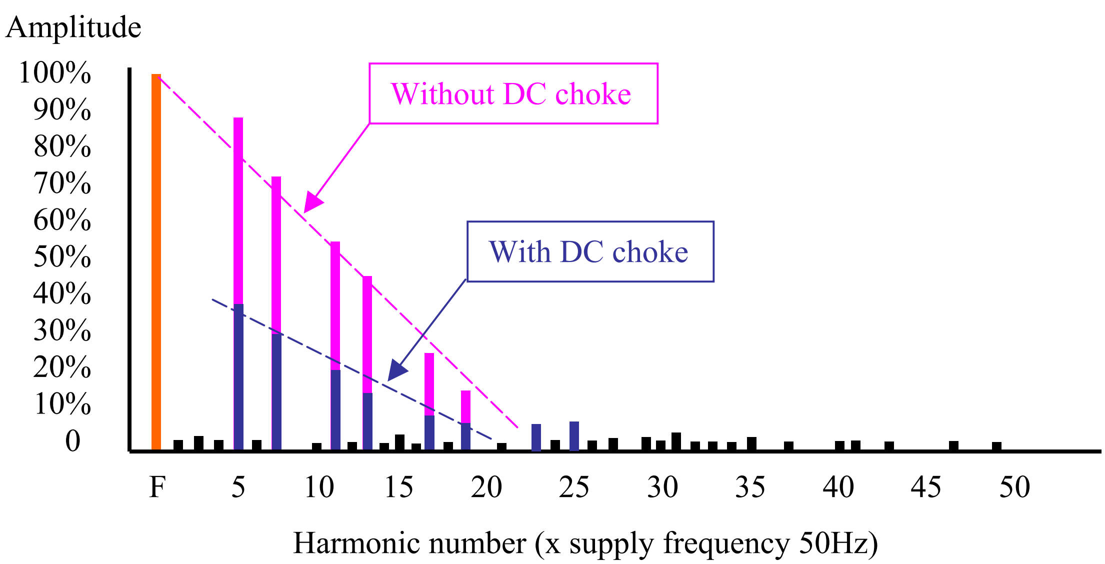


Figure 31. Reduction of harmonics by installing a DC link choke

The rectifier of a frequency converter generates a pulsating DC voltage. The capacitor in the DC link that follows the rectifier is charged at each voltage peak. During this charging process, input currents with relatively high amplitude occur. Because of this pulse-shaped, non-sinusoidal load, the sinusoidal shape of the supply voltage is distorted and the degree of distortion depends upon the load current and the supply impedance 'Z'.

In the UK and Europe, the maximum permissible distortion is given in the standard **EN61000-3-2** for public networks and in **EN61000-3-4** for public low voltage networks. The mains supply interference consists of the high frequency parts in the form of **harmonics** of the basic frequency of the supply voltage.
The total harmonic content is termed Total Harmonic Distortion (**THD)**.

In the UK, supplementary guidelines have been issued by the electricity supply companies to limit the amount of harmonic distortion on their networks. This publication is called **G5/4,** and is enforceable by refusal to connect new loads or disconnection of existing loads that exceed the THD limits etc.
The maximum permissible size of the individual mains voltage harmonics is given in EN61000-3-2, table 1.
The mains supply interference can be reduced by limiting the amplitude of the pulse currents. The cheapest and most efficient way to do this is to install a DC choke inside the frequency converter in the DC link circuit. An AC choke (reactor) will perform a similar function if installed at the input to the frequency converter, but not as effectively. As the power rating of the drive goes up it becomes more and more essential that a DC choke is fitted. Chokes can be ordered separately and installed at a laterr date if required.

<u>Although IMO's policy is to leave the choke as a user option in lower power drives, at 75kW and higher, DC chokes are supplied with the equipment as standard.</u>

Transients / over voltage

Transients, or brief over-voltage peaks up to several thousand volts-can occur in the mains supply, both in industry and in domestic premises.
They can be caused by heavy loads in the mains supply being switched on and off, or due to power factor correction equipment. If lightening strikes directly onto the supply cables, for example, there will be a high over-voltage peak resulting in damage to installations up to 20km away. In open-air installations, jumping of the isolators to other cables may occur.
Short-circuits and safety switch-offs of the mains supply also lead to transients. Through magnetic inductive couplings, cables laid out in parallel may also cause high voltage peaks.
The shape of these transients and the energy they contain are explained in **EN61000-4-1.**

The harmful effects of transients and over-voltages can be limited in a number of ways. To combat energy-intensive transients and over-voltages, gas eliminators or spark gaps can be applied. In electronic equipment such as frequency converters, voltage-dependent resistors (varistors) are often used in the power input circuit to dampen over-voltages. In the control signal circuits, protection can be given by a breakdown (zener) diode.

Radio frequency interference (RFI)

AC current and voltage that deviates from the pure sinusoidal form contains components with higher frequencies. The magnitude of these frequencies depends upon the rate of change of the process.

When an electrical contact opens or closes, the current change takes place very rapidly and a very steep current change is registered. This is also reflected in the voltage. On radio, this phenomena can be heard as a crackling noise. In this context, a single noise pulse is not considered to constitute interference. However, since a frequency converter's

semi-conductors (IGBT's in the power circuit, and FET's in the SMPS) are switched so rapidly, with each current pulse having such steep edges (change in voltage or current with change in time – dv/dt or di/dt), permanent radio frequency interference RFI is generated and radiated.
RFI is defined as electrical oscillations with frequencies between 10kHz and the GHz range.
The extent of this interference depends upon a number of factors:

- The impedance of the mains supply
- The switching frequency of the semi-conductors
- The mechanical design of the frequency converter
- The frequency of the output voltage to the motor
- The length and type of cable feeding the motor
- The anti-interference measures taken

Radio frequency interference is emitted by conduction or radiation and is limited by EN standards in Europe and IEC standards worldwide.

Limit values and measuring procedures for radio interference from industrial, scientific and medical high frequency equipment (ISM equipment), which until recently covered frequency converters, are covered by EN55011. Limit values for emissions from domestic electrical appliances are covered by EN 55014.

Frequency converters are now covered by the **Power Drives Standard, EN61800-3** augmented by the latest amendment **A11**.

EN61800-3 +A11, like other EMC standards, makes clear definitions between environments where interference producing equipment may be used, with appropriate limits for each.

First Environment – environment that includes domestic premises. It also includes establishments directly connected to a low voltage power supply network that supplies buildings used for domestic purposes. Other standards refer to 'Class A' or 'Class B' as the typical equivalent of first environment.

Second Environment – environment that includes all establishments other than above, for example industry, factories, manufacturing plants, etc.
Overall, emission limits are much lower for use in the first environment due to the likelihood of disturbance to radio and TV reception, telephone signals, etc. **To meet the First Environment limits, a frequency converter needs a good purpose-built filter and has to be installed carefully to manufacturers / suppliers instructions.**

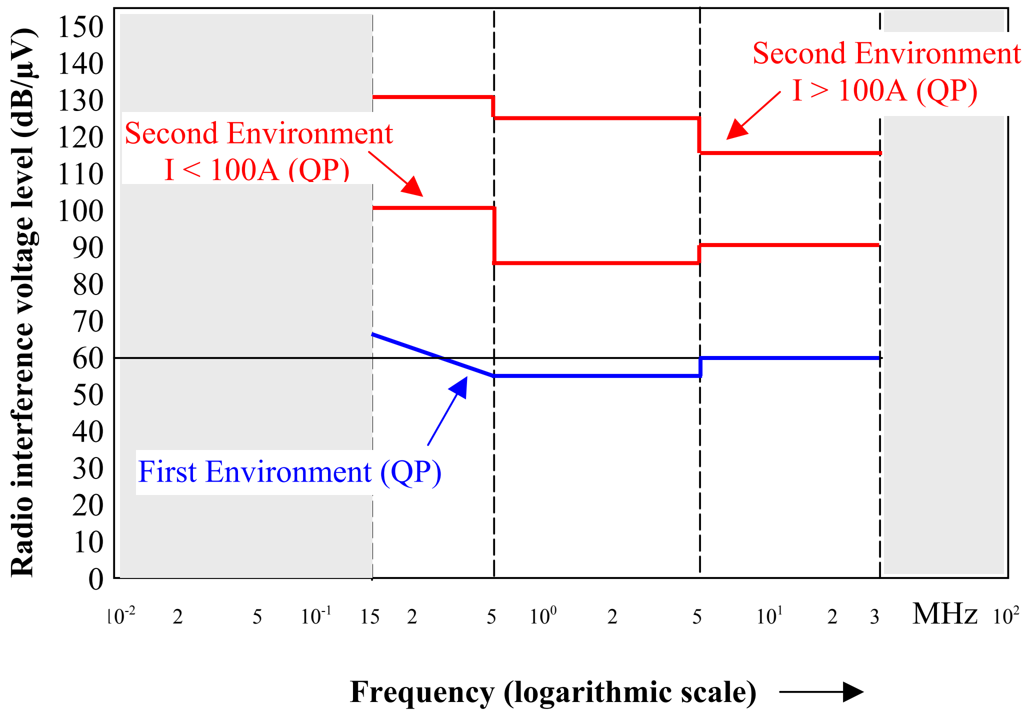


Figure 32. Quasi-Peak radio interference limit values as defined in EN61800-3 amendment A11 for First and Second Environments

EMC filters

High frequency mains conducted interference can only be reduced effectively by using an EMC filter that consists of inductors and capacitors. The filter uses integral capacitors connected to earth, so it is essential that the earthing wire is connected to the filter, not only to make it safe, but also to make it work at all. Unfortunately, the use of these capacitors can lead to a small leakage current of a several mA flowing to ground, and may be detected by some safety residual current devices (RCD's). This can lead to the RCD device tripping out and so removing the mains supply from the frequency converter. Some frequency converters are supplied with a small built-in EMC filter. However, in practice, such filters are usually limited in performance, and if the motor cable is over 5 or 10 meters long, can become largely ineffective.

Some models in the current ranges of IMO frequency converters do have built-in filters. This is because some applications only require a very short motor cable, and if the power rating is reasonably low, an integrated filter solution is often cost-effective.
Sometimes it is better to let the user / installer decide upon the correct and most cost effective solution for limiting emissions to the appropriate level, backed up with technical advice from IMO support staff.
On the cable from the frequency converter to the connected motor, RF emissions can be limited using special dv/dt type filters or screened/armoured cables.

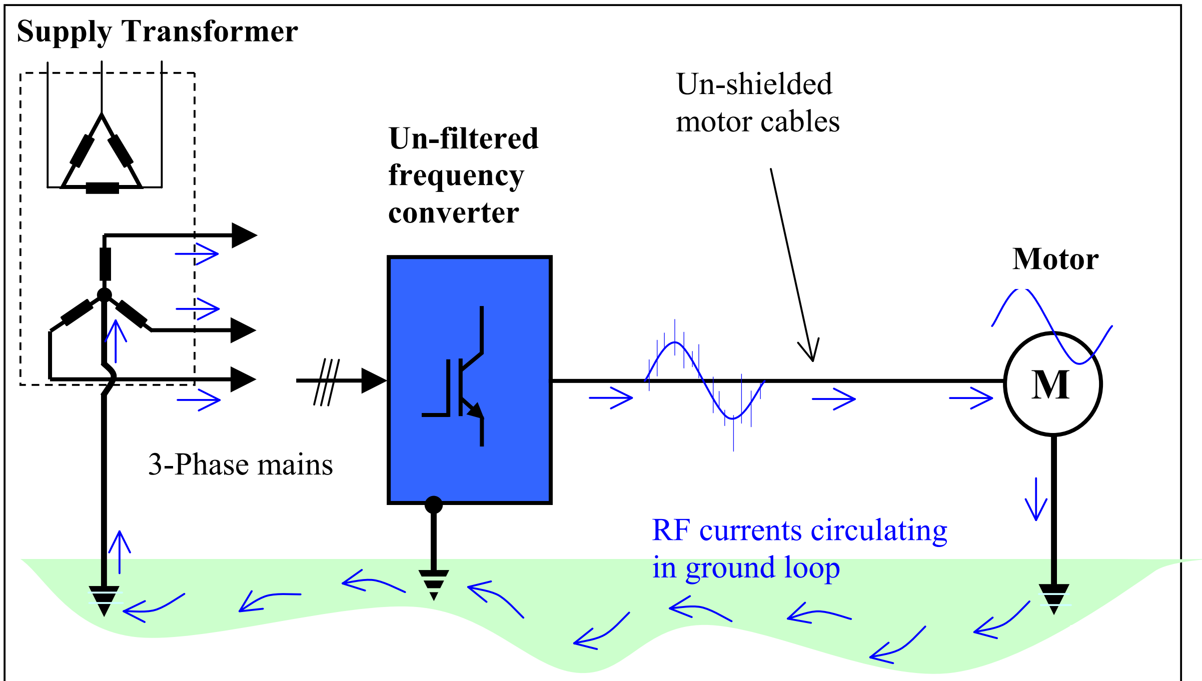


Figure 33. Unfiltered drive installation with poor cabling practice and high conducted emissions flowing in earth system and transformer star point

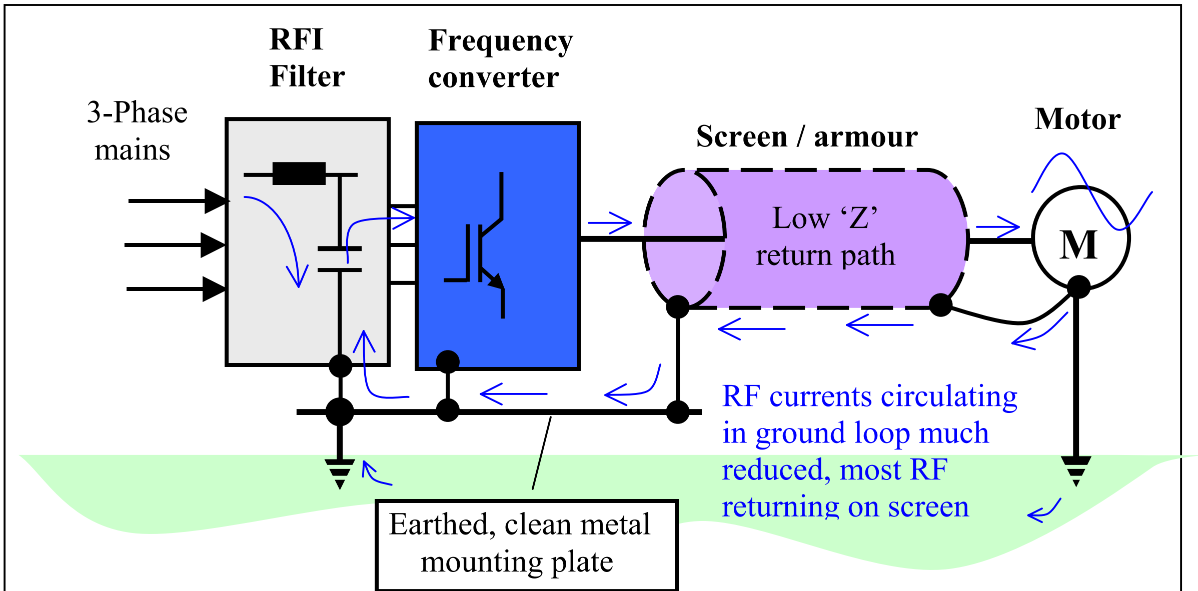


Figure 34. Filtered drive installation with screened / armoured cable and reduced conducted emissions flowing in earth system

Screened / armoured motor cables

Screened or armoured cables must be used to limit radio interference**. For the screen to be effective, it should be connected to earth at both the frequency converter end and at the motor end, and should be continuous between both ends.** In practice, if it has to be broken, for example, if a plastic housed isolator is to be mounted close to the motor, then a low impedance link should be made across this break – preferably with a wide braided tape. A good contact between screen and earth potential is important, as a poor connection reduces the screening effect.
In the case of analogue or digital signal cables, it is equally important that the screen is only connected to ground at one end or the low level signals at which they operate could be 'swamped' by RF interferences, i.e. the signal-to-noise ratio would be high and signal corruption could occur causing incorrect speed of the motor or other data error etc.

When a frequency converter is purchased and installed, it must be considered how and to what extent radio interference is to be limited, and the technical documentation should state the radio interference class with which the frequency converter complies. Additionally, it is not always clear whether a filter is integrated or whether it has to be purchased and installed separately, and for what motor cable lengths it is suitable.
The supplier should be able to offer clear advice to the user/installer, and should be able to provide a relevant EC Declaration of Conformity, stating this information.

Screened or armoured motor and control cables are usually required and are mandatory if a given radio frequency protection class is to be complied with.

<u>Selection of a frequency converter for different applications</u>

Selection of a frequency converter for some applications requires a lot of experience. However, there are many applications that are quite straightforward. The following is a brief checklist of points that should be considered:

1. **Details of the machine to be controlled**
    - Required plant machine characteristics
    - Torque characteristics and dynamic performance
    - Speed control range, cooling
    - Power consumption of the converter and the motor
    - Is braking required, if so what type?
    - Any specific I/O or features required for control purposes?
    - Computer or PLC serial communication required?
    - Design and IP protection type

2. **Environmental details**
    - Installation altitude and ambient temperature
    - Cooling requirements
    - Climatic conditions – humidity, dust, gas, water, etc
    - Are special regulations in force eg. for mining, chemicals, explosive areas?

- Is acoustic noise a problem?

3. **Mains power supply**
   - Mains voltage, and fluctuations
   - Frequency and frequency variation
   - Mains disturbances

4. **Maintenance, operation, personnel**
   - Training of operators
   - On site servicing / maintenance required?
   - Spare parts / spare units

5. **Financial criteria**
   - Initial purchase costs
   - Space requirement
   - System design costs
   - Installation and commissioning costs
   - Operating costs
   - Efficiency of the system (frequency converter and the machine)
   - Harmonic filtering (initial or retrospective)
   - EMC filtering (initial or retrospective)
   - Product lifetime

6. **Protective measures for operators / converter / motor**
   - Phase loss protection
   - Input/output switching for E-stop condition?
   - Earth and short circuit protection
   - dv/dt protection for motor with long cables
   - Thermistors in motor

7. **Standards / regulations**
   - National BS, UL, cUL, VDE, DIN, C tick, etc
   - International EN, IEC, CE

8. **Environmental considerations**
   - Ability to recycle the product at end of life and W.E.E.E. compliance
   - RoHS (Restriction of Hazardous Substances within the product)
   - Energy saving

Using this checklist a frequency converter can be selected which covers many items as standard, but you should double check:

- The rated output current of the frequency converter is ok for the load (it is incorrect to dimension a drive only by matching it's kilowatt rating with that of the motor – *one day you will come unstuck*!)

- Does the frequency converter need to be higher power rated than the motor it is driving for example on a deep well pump or on a large press, etc?
- If the drive requires AC or DC chokes to reduce harmonics etc
- The correct EMC filtering method is selected for the application environment
- Motor de-rating or forced cooling is not required for low speed operation etc

THE IMO JAGUAR RANGE OF FREQUENCY CONVERTERS

IMO have supplied frequency converters since 1986 when we launched the Jaguar Cub and VL ranges-first up to 7.5kW, then followed by the VL11-22 series up to 22kW . Then, frequency converters (or drives / inverters as they are sometimes known) were in their infancy, and potential purchasers were given little choice of product. They were much larger and heavier by comparison with today's products and were controlled by logic as opposed to microprocessors as we know them. They were somewhat unreliable due to semiconductor technology also being in its infancy, so returns that had genuine faults were much more common place.

In 1989 came a breakthrough in technology when IMO launched the Jaguar CD range. The CD75-750 range (0.75 to 7.5kW) was controlled by 8 bit microprocessor and came with built in RS485 serial communications and switch mode power supply.
The CD was complemented by a new digital Jaguar CubVC, with single phase input and available up to 1.5kW from stock.

In 1991 the CD was given a new look and became the CDII, with optional integrated EMC filter and detachable keypad. The CD range was then extended to cover the power ratings between 11 and 90kW for fan and pump applications.

By the time the Jaguar VX, VXS and Cub were launched in 1995, technology and miniaturization were well advanced, with 16 bit processors, IGBT's, programmable I/O and intelligent displays being the norm, along with revolutionary sensorless vector control systems with automatic tuning feature (these will be covered in level 3 drives).

From the very beginning when IMO launched the Jaguar drive, through to today, the brand name has always been a best seller. The Jaguar range became clear market leader in the UK in the early 90's below 22kW, mainly due to its popularity in the food and beverages industry, packaging industry and motor car manufacturers.
The brand still has a very high profile today, synonymous with performance and value for money and renowned for its reliability and **Unique Five Year Warranty**.

Today the IMO range consists of two families of frequency converter:

- **Jaguar Cub**
- **Jaguar VXR**
- **Jaguar VXM**
- ***iDrive* EDX**

Each family in the range is designed to meet the requirements of a specific area within the general-purpose drives market, based upon features, performance, power rating, and cost. The '*non-Jaguar*' *iDrive* being at the lower-cost, lower-specification end of the range and the flexible JaguarVXM at the opposite end were high dynamic performance, high specification is required but at higher price.

Range	*iDrive*-EDX	Jaguar Cub	Jaguar VXR	Jaguar VXM
Initial cost	£	££	££/£££	£££/££££
Features	Low-Mid	Mid-High	Mid-High	High
Performance	Standard	Good	High	Excellent
Output Power rating	0.4 – 2.2kW (230V/1-ph) 0.75 – 2.2kW (415V/3-ph)	0.4 – 2.2kW (230V/1-ph) 0.4 – 4.0kW (415V/3-ph)	0.4 - 2.2kW (230V/1-phase) 0.4 – 15kW (415V/3-phase)	0.4 – 400kW (415V/3-phase only)
V mains	230V or 415VAC	230V or 415VAC	230V or 415V AC	415V AC
F mains	50/60Hz	50/60Hz	50/60Hz	50/60Hz
V motor	0 – V mains	0 – V mains	0 – V mains	0 – V mains
F motor	0.1 – 200Hz	0.1 – 400Hz	0.1 – 400Hz	0.1 – 400Hz 0.1 – 120Hz (VT)
Fan/pump	Yes	Yes	Yes	Yes
Dual rated	No	No	No	Yes (from 5.5kW)
Vector control	V. simple open-loop version	Simplified open-loop version	Open-loop only	Open-loop or Close-loop (option)
Internal brake control	No	Yes	Yes	Yes (7.5kW or less)
EMC filter	Internal or External	Internal or External	Internal or External	Optional
DC choke	No	Optional	Optional	Optional. Standard >55kW
Option cards	Yes	RS485 only	Yes	Yes
Serial comms	(RS485/Modbus RTU option)	(RS485/Modbus RTU option)	RS485 or Modbus RTU	RS485 or Modbus RTU
Fieldbus	No	No	Options	Options
Standards	CE, UL, cUL, etc	CE, UL, cUL, etc	CE, UL, cUL, etc	CE, UL, cUL, etc
Enclosure	IP20	IP20	IP20	IP40 to 22kW IP00 from 30kW
Warranty	2 years	5 years	5 years	5 years

The above table shows the FOUR current IMO frequency converters by comparison. The product instruction manuals should always be referred to for detailed data.

The IMO Jaguar part numbering system

- **Jaguar Frequency converters –**

-1 = 230V/1-phase i/p
-4 = 415V/3-phase i/p

CUB Examples of part numbers:

Cub8A-1 = 8A output & 1-ph 230V i/p to Cub and o/p to 1.5kW motor (max)
Cub3A7-4 = 3.7A o/p & 3-ph 400V i/p to Cub and o/p to 1.5kW motor (max)
Cub9A-4 = 9.0A o/p & 3-ph 400V i/p to Cub and o/p to 4kW motor (max)

VXR Examples of part numbers:

VXR5A-1 = 5A o/p & 1-ph 230V i/p to VXR and o/p to 0.75kW motor (max)
VXR5A5-4 = 5.5A o/p & 3-ph 415V i/p to VXR and o/p to 2.2kW motor (max)
VXR30A-4 = 30A o/p & 3-ph 415V i/p to VXR and o/p to 30kW motor (max)

VXM Part numbering (all 400V as standard)

Example: VXM75 = 0.75kW / 400V rated

Example: VXM1500 = 15kW / 400Vrated
(OR 18.5kW FAN or PUMP type load)

Example: VXM30KP = 30kW / 400Vrated
(FAN or PUMP type load ONLY)

Example: VXM37K = 37kW / 400Vrated
(OR 45kW FAN or PUMP type load)

Example: VXM132K = 132kW / 400Vrated
(OR 160kW FAN or PUMP type load)

VT = Variable Torque; (Fan, Pump, etc)
CT = Constant Torque; (Mixer, Conveyor, Crane, Piston type Pump, etc)

40 = 0.4kW (CT or VT)
75 = 0.75kW (CT or VT)
150 = 4.0kW (CT or VT)
220 = 2.2kW (CT or VT)
400 = 4.0kW (CT or VT)
550 = 5.5kW(CT) or 7.5kW(VT)
750 = 7.5kW(CT) or 11kW(VT)
1100 = 11kW(CT) or 15kW(VT)
1500 = 15kW(CT) or 18.5K(VT)
1850 = 18.5kW(CT) or 22kW(VT)
2200 = 22kW (CT or VT)
30KP = 30kW (VT ONLY)
30K = 30kW(CT) or 37kW(VT)
37K = 37kW(CT) or 45kW(VT)
45K = 45kW(CT) or 55kW(VT)
55K = 55kW(CT) or 75kW(VT)
75K = 75kW(CT) or 90kW(VT)
90K = 90kW(CT) or 110kW(VT)
110K = 110kW(CT) or 132kW(VT)
132K = 132kW(CT) or 160kW(VT)
160K = 160kW(CT) or 200kW(VT)
200K = 200kW(CT) or 220kW(VT)
220K = 220kW(CT) or 280kW(VT)
280K = 280kW(CT) or 315kW(VT)
315K = 315kW(CT) or 355kW(VT)
355K = 355kW(CT) or 400kW(VT)
400K = 400kW(CT) or 500kW(VT)

- **EMC Filters (external option)**

Frequency converter Part number	Applicable filter Part Number	Footprint type (Y=Yes, N-No)	Env./Class 1st A or B or 2nd Env.
Cub3A, 5A-1	RF12A-1A	N	1A
Cub8A, 11A-1	RF29A-1A	N	1A
Cub3A, 5A-1	RF10A-1B	Y	1B
Cub8A-1	RF17A-1B	Y	1B
Cub11A-1	RF25A-1B	Y	1B
Cub1A5, 2A5, 3A7, 5A5, 9A-4	RF15A-4A	N	1A
Cub1A5, 2A5, 3A7, 5A5-4	RF8A-4B	Y	1B
Cub9A-4	RF13A-4B	Y	1B

Note: All Cub with suffix 'E' in part number denotes built-in filter, ie external EMC filter option not required.

VXR VXR VXR VXR	ALL VXR EMC FILTERS ARE UNDER REVIEW AT THIS TIME – DETAILS T.B.A. SHORTLY		
VXM40, 75,	RFM75FP	Y	1B
VXM150, 220, 400	RFM400FP	Y	1B
VXM550, 750	RFM750FP	Y	1B
VXM1100, 1500	RFM1500FP	Y	1B
VXM1850, 2200	RFM2200FP	Y	1B
VXM30KP, 30K (CT)	RFM30K	N	2nd Env.
VXM30K (VT), 37K, 45K, 55K, 75K, 90K (CT)	RFM90K	N	2nd Env.
VXM90K (VT), 110K, 132K (CT)	RFM132K	N	2nd Env.
VXM132K (VT), 160K, 200K, 220K (CT)	RFM220K	N	2nd Env.
VXM220K (VT), 280K, 315K (CT)	RFM315K	N	2nd Env.

Comparison of EMC filtering methods and performance between IMO Frequency Converters and competitors models

Make	Model	More Filtering	←	→	Less Filtering	
		1st Environment		2nd Environment		Drives specific category pre 2005
		Unrestricted Sales	Restricted Sales	< 100A	> 100A	
		C1	C2	C3	C4	Drives specific category post 2005
		Class B	Class A	No equivalent standards		Normal Applied Machine standards
						Comments
IMO	Cub-E	x	10m (15kHz)			Integrated Filter type (ie Cub3A-1E)
IMO	Cub	10m (15kHz)	50m (15kHz)			Footprint Filters RFM (ie Cub 3A-1)
IMO	Jaguar <18kW	10m (15kHz)	50m (15kHz)			Footprint Filters RFM FP
IMO	Jaguar > 18kW	x	50m			Separate Filter RFM
IMO	Jaguar	x	10m			Low cost Filter 'A'
IMO	EDX xxx-21-E	5m (6/10kHz)				0.4 & 0.75kW (@10kHz), 1.5, 2.2kW (@6kHz)
IMO	EDX xxx-43-E	x	5m (10kHz)			
ABB	ACS150	x	x	30m (4kHz)		2nd Environment ONLY
ABradley	Powerflex40	x	5m			
Control Techniques	SK	x	x			2nd Environment ONLY
Danfoss	VLT2800	x	25m			
Lenze	SMD	x				
Lenze	8200	x	20m			
LG	iC5	x				
Mitsubishi	F700	x	x	10m		
Telemecanique	ATV11	5m (4kHz)	10m(4kHz)			
	ATV31	x	5m			
KEY						
	OK					
x	No Good					
	No internal EMC filter					

Quiz 1

1. What are the four main sections of the frequency converter?

2. How many diodes are in the rectifier of a standard frequency converter?

3. What is the main component of the DC link?

4. What do the letters 'IGBT' mean?

5. What is the typical switching frequency band of the IGBT's?

6. What is the name of the technique used to switch voltage pulses to the motor?

7. Only one statement below is correct – which one? (a) The IGBT's convert variable voltage DC into fixed voltage AC (b) The IGBT's convert variable voltage DC into variable voltage AC (c) The IGBT's convert fixed voltage AC into variable voltage DC (d) The IGBT's convert fixed voltage DC into variable voltage AC

8. Why do we need to install fuses or similar protection at the power input ?

9. What function does the 'soft-start' resistor have?

10. If the DC link capacitor is 500 microFarads and the soft-start resistor is 30 Ohms, what is the time constant?

11. If a contactor is used to break the motor circuit, what device can be installed in the motor cable to limit the effects of collapsing motor flux?

12. What prevents upper and lower IGBT's switching on at the same time?

13. What is the name of the device connected in reverse parallel to the IGBT's ?

14. What is the SMPS?

Quiz 2

1. If a drive's analogue input is described as 8 bit, how many individual segments is the signal devided into by the A-D converter?

2. Digital inputs can be configured in one of two ways, what are each called?

3. Why is it essential to connect the 'Common' terminals together of a drive and a PLC when using the PLC outputs to operate the drive's digital inputs?

4. Name an industry standard serial communication protocol?

5. What are typical upper and lower data transmission speeds for a fieldbus?

6. When several drives are connected to a PLC via a comms link, how can the PLC only communicate with one particular node if it is required?

7. For a high inertia load, only two statements below are correct – which two?

(a) Setting the acceleration ramp too short may cause an over volt trip

(b) Setting the deceleration ramp too short may cause an over volt trip

(c) Setting the acceleration ramp too short may cause an over current trip

(d) Setting the deceleration ramp too short may cause an over current trip

8. Name a typical application where we may use S-ramps ?

9. Why should a thermal overload device not be used on the drive mains input?

10. When should stand-alone thermal overloads be used on the drive output side?

11. What is the difference between the second and third quadrants?

12. What is a typical switch-on level for a dynamic brake transistor fitted in or to a 400V frequency converter (approximately)?

13. Why should a dynamic brake resistor circuit incorporate a thermal switch?

14. A 500kg lift moves from the 10^{th} floor of a building to the ground floor. What would be the approximate maximum braking energy during the move assuming each floor is 4 metres apart? (ignore losses)

Quiz 3

1. A motor and load decelerate to stop in 15 seconds, and during this time 30kJ are developed. What power is generated?

2. The frequency converter driving the above motor is supplied by 460V AC. Approximate a suitable DB resistor value (Ω) for this application (max).

3. What type of resistors are used for DC injection braking?

4. What voltage ranges is covered by the Low Voltage Directive?

5. Name two EC standards cover mains distortion?

6. What device can be fitted to a frequency converter to reduce harmonics?

7. Which of the following is not related to EMC? **(a) RFI** **(b) Immunity** **(c) Cos φ** **(d) CE**

8. Which standard takes priority, Generic standards or Product standards ?

9. What frequency range best describes RFI?

10. What is EN61800-3

11. What is meant by the 'Second Environment'?

12. Why do EMC filters sometimes cause RCD type protection equipment to trip out and disconnect the main power?

13. Apart from the filter, what other item should be used for good EMC practice when using a frequency converter?