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A Guide to Electromagnetic Compatibility (EMC) for Variable Speed Drives



This guide is one of a series covering subjects such as harmonics, safety features, EMC, feedback devices, industrial communications and motion control.

These can be accessed via www.controltechniques.com/guides.





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1 Introduction

1.1 General

The purpose of this section is to set out the necessary considerations for system designers and others when incorporating electronic variable speed drives into complete machines and systems without encountering problems with electromagnetic interference, and in compliance with relevant regulations. Due to the wide variety of practical drive installations this guide can only give general guidance. The underlying principles are explained as far as possible, to enable the designer to apply the guide to a range of specific applications.

1.2 Principles of EMC

All electrical equipment generates some degree of electromagnetic emission as a side effect of its operation. It also has the potential to be affected by incident electromagnetic energy. Equipment using radio communication contains intentional emitters and sensitive receivers.

The basic principle of EMC is that electromagnetic emission of electrical equipment, whether intentional or unintentional, must not exceed the immunity of associated equipment. This means that controls must be in place on both emission and immunity. Given the variety and uncertainty of effects and situations, some margin of safety must be provided between these two factors.

Although all equipment exhibits some degree of emission and susceptibility, the limiting factors in most common environments tend to be related to radio equipment, with its powerful transmitters and sensitive receivers. Therefore the majority of EMC standards are related to the requirements of radio communications systems.

In principle, EMC covers phenomena over an unlimited range of frequencies and wavelengths. The EU EMC Directive limits itself to a range of 0 to 400GHz. This range is so wide that a perplexing number of different effects can occur, and there is a risk that all electrical phenomena become included in the scope of EMC. This is also the reason for the proliferation of EMC "rules of thumb", some of which are contradictory. A technique which is effective at a high radio frequency will probably not be effective at power frequency, and vice-versa.

With current industrial electronic techniques, it is unlikely that equipment will exhibit unintentional sensitivity or emission above about 2GHz. Below 2GHz, it is convenient to make a first rough separation into "high-frequency" effects, which correspond to radio frequencies beginning at about 100kHz, and "low-frequency" effects. Broadly speaking, low frequency effects operate only by electrical conduction, whereas high-frequency effects may be induced and operate at a distance without a physical connection. Of course there is no precise dividing line between the two and the larger the geometry of the system, the lower the frequency at which induction becomes effective. However this division is helpful in understanding the principles.



1.3 EMC regulations

Regulations exist throughout the world to control intentional and unintentional electromagnetic emission, in order to prevent interference with communications services. The authorities generally have the power to close down any equipment which interferes with such services.

Many countries have regulations requiring consumer and other equipment to be tested or certified to meet emission requirements – for example, the FCC rules in the USA and the C-tick system in Australia. The EMC Directive of the European Union is unusual in requiring immunity as well as emission to be certified.

It is not possible in the limited space available to explain all of these regulations. The EU EMC Directive has been the subject of much written material. Most emission regulations are based on international standards produced by CISPR, and the three basic standards CISPR11, CISPR14 and CISPR22 underlie most other emission standards.

2 Regulations and standards

2.1 Regulations and their application to drive modules

The underlying principle of all EMC regulations is that equipment should not cause interference to other equipment, and especially to communications systems. In addition, in many countries there is a requirement that equipment must be certified in some way to show that it meets specific technical standards, which are generally accepted as being sufficient to show that it is unlikely to cause interference.

Equipment standards are primarily written to specify test methods and emission limits for self-contained products such as electrical consumer goods and office equipment which are basically free-standing units, even if they have the capability to inter-connect with peripherals and networks. The emission levels set in such standards allow to some extent for the possibility that several items of equipment may be co-located. A corresponding approach in the realm of industrial products such as variable speed drive modules has caused difficulty, since it is clear that some drive modules are used as virtually self-contained units, whereas others are built in to other end-user equipment, sometimes singly but also possibly in considerable numbers. The module cannot meaningfully be tested without its associated motor, cables and other peripherals, and the effect of a number of co-located modules is difficult to predict. Large fixed installations may contain numerous drives and other electronic products, and cannot practically be tested against standards which were primarily intended for compact free-standing consumer products.

Most drive manufacturers have adopted a practical approach by testing their products in arrangements which are reasonably representative of their final use, and providing installation guidelines.



The original EU EMC Directive was replaced in 2004 (implemented 2006) by a revised version which contained useful clarifications of these topics. In particular, sub-assemblies liable to generate or be affected by electromagnetic disturbance were specifically included in the definition of "apparatus", and requirements were added for such apparatus to be provided with information for its installation and operation so as to meet the essential requirements of the Directive. This means that the practical approach adopted by many drives manufacturers has now effectively been endorsed, with the added requirement that a CE mark for EMC is now specifically required.

2.2 Standards

Standards with worldwide acceptance are produced by the International Electrotechnical Commission (IEC). Standards for application under the EU EMC Directive are European Harmonised standards (EN) produced by CENELEC. Every effort is made to keep these two families of standards in line, and most of them have the same number and identical technical requirements.

Emission standards work by specifying a limit curve for the emission as a function of frequency. A measuring receiver is used with a coupling unit and antenna to measure voltage (usually up to 30MHz) or electric field (usually beyond 30MHz). The receiver is a standardised calibrated device, which simulates a conventional radio receiver.

Immunity standards are rather diverse because of the many different electromagnetic phenomena which can cause interference. The main phenomena tested for routinely are:

- → Electrostatic discharge (human body discharge)
- → Radio frequency field (radio transmitter)
- → Fast transient burst (electric spark effect)
- → Surge (lightning induced)
- → Supply dips and short interruptions

There are very many more tests available; those listed are the required tests under the CENELEC generic standards.

The most important standards for drive applications are the following, all of which have equivalent EN and IEC versions:

IEC 61800-3	Power Drive Systems (contains emission and immunity requirements)
IEC 61000-6-4	Generic emission standard for the industrial environment
IEC 61000-6-2	Generic immunity standard for the industrial environment



The product standard IEC 61800-3 applies in principle to variable speed drive modules where they are sold as end products. There are however many cases where the drive will be incorporated into an end product, which is not in itself a power drive system, and is more likely to fall into the scope of the generic standards. In this case it is the generic standards which are of interest. The permitted levels are generally similar, except that IEC 61800-3 defines a special environment where the low-voltage supply network is dedicated to non-residential power users, in which case relaxed emission limits apply. This can permit useful economies in input filters.

3 EMC behaviour of variable speed drives

3.1 Immunity

Most drives can be expected to meet the immunity requirements of the IEC generic standard IEC 61000-6-2. Control Techniques drives meet them without any special precautions such as shielded signal wires or filters except for particularly fast-responding inputs such as data links and incremental encoder ports.

The standard sets levels corresponding to a reasonably harsh industrial environment. However there are some occasions where actual levels exceed the standard levels, and interference may result. Specific situations, which have been encountered, are:

Situation	Effect	Cure
Very inductive d.c. loads such as electromagnetic brakes, without suppression, and with wiring running parallel to drive control wiring	Spurious drive trip when brake released or applied	Fit suppression to brake coil, or move wiring away from drive wiring
High radio frequency field from powerful radio transmitter (e.g. in airport facility adjacent to aircraft nose)	Drive malfunction when transmitter operates	Provide RF shielding, or move to a location further from the transmitter antenna
Severe lightning surges due to exposed low-voltage power lines	Drive trip or damage from over-voltage	Provide additional high-level surge suppression upstream of drive

3.2 Low frequency emission

Drives generate supply frequency harmonics in the same way as any equipment with a rectifier input stage. Supply harmonics are discussed in detail in *A Guide to Supply harmonics and other low-frequency disturbances*. Harmonics generated by an individual drive are unlikely to cause interference, but they are cumulative so that an installation containing a high proportion of drive loads may cause difficulties.



Apart from supply harmonics, emission also occurs as a result of the switching of the power output stage over a wide range of frequencies which are harmonics of the basic switching frequency – that is, size times the supply frequency for a 6-pulse d.c. drive, and the PWM carrier frequency for a PWM drive. This covers a range extending from 300Hz, for d.c. drives, up to many MHz for a.c. drives. Unwanted electromagnetic coupling is relatively unusual at frequencies below about 100kHz. Few standards set limits in that range, and interference problems are unusual.

3.3 High frequency emission

The power stage of a variable speed drive is a potentially powerful source of electromagnetic emission ("noise"), because of the high voltage and current which is subject to rapid switching. Thyristors are relatively slow switching devices, which limits the extent of the emission spectrum to about 1MHz, whereas with IGBTs it may extend to about 50MHz. If attention is not paid to installation guidelines then interference is likely to occur in the 100kHz-10MHz range where emission is strongest. Where conformity with an emission standard is required, it is not unusual to find excessive emission anywhere in the 150kHz – 30MHz range, where emission is measured by conduction, and occasionally in the 30MHz – 100MHz range, where emission is measured by radiation.

This frequency range is lower than that associated with personal computers and other IT equipment, which tend to cause direct radiated emission associated with the internal microprocessor clock and fast digital logic circuits. The drive itself is not an important source of direct emission, because its dimensions are much less than a half wavelength over the relevant frequency range. There may be strong electric and magnetic fields close to the drive housing, but they diminish rapidly, by an inverse cube law, with increased distance from the drive. However the wiring connected to the drive can be widespread and is likely to be long enough to form an effective antenna for the frequencies generated by the drive.

The power output connections of a drive carry the highest level of high frequency voltage. They can be a powerful source of electromagnetic emission. Since the cable connecting the drive to the motor is a dedicated part of the installation, its route can usually be controlled to avoid sensitive circuits, and it can be shielded. Provided the shield is connected correctly at both ends, emission from this route is then minimised.

Output filters can also be used, and are offered by specialist filter suppliers. Their design is quite difficult because they must offer high attenuation in both the common and series modes, whilst presenting an acceptable impedance to the drive output circuit and avoiding unacceptable voltage drop at the working frequency. They tend to be very costly, and they will usually only work with simple open-loop control because of their complex impedance within the drive closed-loop bandwidth. They may be justifiable in applications where it is not practicable to use a shielded motor cable.



The power input connections of a drive carry a high-frequency potential which is mainly caused by the current flowing from the drive output terminals to ground through the capacitance of the motor cable and motor windings to ground. Although the voltage level here is rather lower than at the output, control measures may be needed because these terminals are connected to the widespread mains supply network. Most commonly a radio frequency filter of some kind is installed here.

The control terminals of the drive carry some high-frequency potential because of stray capacitance coupling within the drive. This is usually of no consequence, but shielding of control wires may be required for conformity with some emission standards.



Figure 1 summarises the main emission routes for high-frequency emission. Note that the current paths are in the common mode, i.e. the current flows in the power conductors and returns through the ground. Series mode paths are relatively unimportant in high-frequency EMC.

Since the return currents in the common mode all flow in the ground (equipotential bonding) wiring, grounding details are particularly important for good EMC. Much of the installation detail is involved with controlling the ground return paths and minimising common inductances in the ground system, which cause unwanted coupling.



4 Installation rules

4.1 EMC risk assessment

When a drive is to be installed, a cost-effective approach to EMC is to initially assess the risk of interference problems arising. This is in addition to considering any legal constraints on emission levels. Most industrial electronic instrumentation and data processing equipment has good immunity, and can operate with drives with only modest precautions to control emission. Some specific types of equipment have been found to be susceptible to interference from drives. The list shows some product families which call for special attention:

- → Any equipment which uses radio communication at frequencies up to about 30MHz. (Note this includes AM broadcast and short wave radio, but not FM, TV or modern communications services which operate at much higher frequencies).
- → Analogue instrumentation using very low signal levels, such as thermocouples, resistance sensors, strain gauges and pH sensors.
- → Other analogue instrumentation using higher levels (e.g. 0-10V or 4-20mA) only if very high resolution is required or cable runs are long.
- → Wide-band/fast-responding analogue circuits such as audio or video systems (most industrial control systems are intentionally slow acting and therefore less susceptible to high-frequency disturbance).
- → Digital data links, only if the shielding is impaired, or not correctly terminated, or if there are unshielded runs such as rail pick-up systems.
- → Proximity sensors using high-frequency techniques, such as capacitance proximity sensors.

4.2 Basic rules

For installations where it is known that no particularly sensitive equipment is located nearby, and where no specific emission limits are in force, some simple rules can be applied to minimise the risk of interference caused by a drive. The aspects requiring attention are:

Cable segregation

The drive supply and output cables must be segregated from cables carrying small signals. Crossing at right angles is permitted, but no significant parallel runs should be allowed, and cables should not share cable trays, trunking or conduits unless they are separately shielded and the shields correctly terminated.



A practical rule of thumb has been found to be:

→ No parallel run to exceed 1m in length if spacing is less than 300mm.

Control of return paths, minimising loop areas

The power cables should include their corresponding ground wire, which should be connected at both ends. This minimises the area of the loop comprising power conductors and ground return, which is primarily responsible for high-frequency emission.

Grounding

By "grounding" we refer here to the process for connecting together exposed conductive parts in an installation, which is done primarily for electrical safety purposes but also can have the effect of minimising difference voltages between parts of the installation which might result in electrical interference. The more correct term is "equipotential bonding", which is desirable both at power frequencies, for safety, and at higher frequencies, to prevent interference. Whereas at power frequencies the impedance of the bond is dominated by its resistance, at high frequencies the inductance is dominant. The actual connection to the ground itself is generally not important for either safety or EMC within an installation, but becomes important for connections between installations with separate ground arrangements.

The main drive power circuit ground loop carries a high level of radio frequency current. As well as minimising its area as described above, these ground wires should not be shared with any signal-carrying functions. There are three possible methods for minimising shared grounding problems, depending on the nature of the installation:

1. Multiple grounding to a "ground plane"

If the installation comprises a large mass of metallic structure then this can be used to provide an equipotential "ground plane". All circuit items requiring ground are connected immediately to the metal structure by short conductors with large cross-sectional area, preferably flat, or by direct metal-to-metal assembly. Shielded cables have their shields clamped directly to the structure at both ends. Safety ground connections are still provided by copper wire where required by safety regulations, but this is in addition to the EMC ground plane.

2. Dedicated ground points, ground segregation

If a single grounded metallic structure does not extend throughout the installation, then more attention must be given to the allocation and arrangement of ground connections. The concept of separate "power ground" and "signal ground" or "clean ground" has been discredited in EMC circles recently, but it is valid in widely spread installations where a good equipotential ground structure is not available. It is not necessary to provide separate connections to the ground itself, but to allocate a specific single point in the ground network as the "reference ground" to which signal and power circuits are separately connected.



Figure 2 Ground potentials and their effect on signal circuits



Figure 2 illustrates how two "grounded" circuits in a system may have different noise potentials. Local circuits grounded to either point will work correctly (circuits 1 and 2), but if a single circuit is grounded at both points then it will experience a noise potential which might cause disturbance (circuit 3).

Figure 3 Use of single "signal ground"





The solution is to nominate one ground point as the "signal ground" and use it as the sole reference point for shared signal circuits, as illustrated in Figure 3. This prevents creating loops for the noise current. Circuit 3 must now be provided with signal isolation means if it is to communicate with the motor environment. The disadvantage is that this situation is difficult to manage in a large complex installation, and sneak paths can easily arise which cause problems and are difficult to trace.

3. Common bonded network, correct use of shielded cables

An extension of the "ground plane" principle for a large installation where a solid ground plane cannot be realised, is to use a network of ground or equipotential bonding conductors. These conductors are selected to have sufficiently low resistance to ensure safety during electrical faults and to minimise low-frequency circulating current, but it has to be accepted that their inductance is too high to prevent differential potentials over their area at high frequencies. High frequency differential potentials are prevented from affecting signal circuits by the correct usage of shielded cables. The explanations given in section 6 should assist in understanding it.

4.3 Simple precautions and "fixes"

There are some simple techniques which can be used to reduce high frequency emission from a drive at modest cost. These techniques should preferably be applied in conjunction with the basic rules given above, but they may also be useful as a retrospective cure for an interference problem.



The single most effective measure which can be taken is to fit capacitors between the power input lines and ground, as illustrated in Figure 4. This forms a simple RFI filter, giving a reduction of typically 30dB in overall emission into the supply network, sufficient to cure most practical problems unless exceptionally sensitive equipment is involved. Emission from the motor cable is not affected by this measure, so strict cable segregation must still be observed. The capacitors must be safety types with voltage rating suited to the supply voltage with respect to ground. Ground leakage current will be high, so a fixed ground connection must be provided. The values shown represent a compromise between effectiveness at lower frequencies, and ground leakage current. Values in the range 100nF to 2.2μ F can be used. The length of the motor cable affects emission into the power line, because of its capacitance to ground. If the motor cable length exceeds about 50m then it is strongly recommended that these capacitors should be fitted as a minimum precaution.



A further measure, which reduces emission into both supply and motor circuits, is to fit a ferrite ring around the output cable power conductors, also illustrated in Figure 4. The ring fits around the power cores but not the ground, and is most effective if the conductors pass through the ring 3 times (a single pass is shown, for clarity). Section 5.4 gives an explanation of the effect of the ferrite core. The ferrite should be a manganese-zinc "power grade". Care must be taken to allow for the temperature rise of the ferrite, which is a function of motor cable length; the surface temperature can reach 100°C.

4.4 Full precautions

If there is known sensitive equipment in the vicinity of the drive or its connections (see list in section 4.1), or if it is necessary to meet specific emission standards, then full precautions must be observed. The drive installation guide should give these precautions in full detail for specific drives. The following outlines the essential principles.

- → A suitable input filter must be fitted. The filter specified by the drive manufacturer should be used, and any limits on motor cable length or capacitance and on PWM switching frequency adhered to. Many filters which are not specifically designed for this application have very little benefit when used with a drive.
- → The filter must be mounted on the same metal plate as the drive, and make direct metal-to-metal contact, to minimise stray inductance. Any paint or passivation coating must be removed to ensure contact. A back-plate of galvanised steel, or other corrosion-resistant bare metal, is strongly recommended.
- → The motor cable must be shielded. A copper braid shield with 100% coverage works best, but steel wire armour is also very effective, and steel braid is adequate.
- → The motor cable shield must be terminated to the drive heat sink or mounting plate, and to the motor frame, by a very low inductance arrangement. A gland giving 360° contact is ideal, a clamp is also effective, and a very short "pigtail" is usually tolerable but the drive instructions must be adhered to.
- → The input connections to the filter must be segregated from the drive itself, the motor cable, and any other power connections to the drive.
- → Interruptions to the motor cable should be avoided if possible. If they are unavoidable then the shield connections should be made with glands or clamps to a grounded metal plate or bar to give a minimum inductance between shields. The unshielded wires should be kept as short as possible, and run close to the grounded plate. Figure 5 illustrates an example where an isolator switch has been incorporated.



With some drives, the control wiring needs to be shielded with the shield clamped to the heat sink or back-plate. The installation instructions should be adhered to in this respect. Omitting this is unlikely to cause interference problems, but may cause standard limits for radiated emission to be exceeded.



5 Theoretical background

5.1 Emission modes

Although the digital control circuits, switch-mode power supplies and other fast-switching circuits in a modern digital drive can all contribute to the radio frequency emission, their suppression is a matter for the drive designer, and suitable internal measures can keep such emission under control. It is the main power stage, especially the inverter of a PWM drive, which is an exceptionally strong source of emission because the fast-changing PWM output is connected directly to the external environment (i.e. the motor and motor cable). This is also the reason for the installation details having a major effect on the overall EMC behaviour.



Figure 6 Main elements of an a.c. inverter drive



Figure 6 shows the main circuit elements of an a.c. inverter variable speed drive. The output PWM waveform has fast-changing pulse edges with typical rise times of the order of 50-100ns, containing significant energy up to about 30MHz. This voltage is present both between output phases and also as a common-mode voltage between phases and ground. It is the common-mode voltage which is primarily responsible for emission effects, because it results in high-frequency current flowing to ground through the stray capacitances of the motor windings to the motor frame, and the motor cable power cores to the ground core and/or shield.

High frequency current causes unexpected voltage drops in wiring because of the wiring self-inductance. The significance of this can be illustrated by a simple example. A 1m length of wire has a typical inductance of about 0.8μ H – the true value of course depends upon the current return path, but this is a typical value. The output current from a drive to charge the stray capacitance of a motor winding would be typically 2A peak with a rise-time of 100ns. This current would cause a voltage pulse of 16V with duration 100ns in the 1m of wire. Whether this causes interference with associated circuits depends on their design, but certainly a 16V 100ns pulse is sufficient to cause a serious error in a digital circuit or a fast-acting analogue one.

Figure 1 shows the main emission paths. Due to the high voltage in the motor cable it is the main potential source of emission. It will be an effective transmitting antenna at a frequency where the motor cable length is an odd number of quarter wave-lengths. For example, a 20m cable will be particularly effective at about 3.75MHz and also at 11.25MHz and 18.75MHz. This will be modified somewhat by the presence of the motor and by the distance of the cable from surrounding grounded objects. In order to prevent this emission, the cable is usually shielded.



Figure 1 also shows how the high-frequency voltage in the motor and cable causes current to flow into the ground, because of their capacitance. The capacitance of a motor winding to its frame may be in the range 1nF to 100nF, depending on its rating and insulation design, and the capacitance from the cable power cores to ground is generally between 100pF and 500pF per metre. These values are insignificant in normal sinusoidal supply applications, but cause significant current pulses at the edges of the PWM voltage wave. The current returns through a variety of paths, which are difficult to control. In particular, current may find its way from the motor frame back to the supply through any part of the machinery, and if it passes through ground wires in sensitive measuring circuits it may disturb them. Also, a major return route to the drive is through the supply wiring, so any equipment sharing the supply may be disturbed.



Figure 7 shows the effect of using a shielded motor cable and an input filter. Fields emitted from the motor cable are suppressed by the shield. It is essential that both ends of the shield are correctly connected to the grounded metal structure at the motor and the drive, in order that the magnetic field cancellation property of the cable can give its benefit. The shielded cable also minimises the ground current flowing from the motor frame into the machinery structure, because of its mutual inductance effect. This subject is generally not well understood outside the EMC profession (see section 6.1 and the references for a fuller explanation).

The input filter provides a low impedance path from the ground to the drive input lines, so that the high frequency current returning from the motor cable shield has an easy local return route and does not flow into the power network.

The primary role of the filter is to suppress common-mode high-frequency emission from the drive. There is also some series-mode emission because of the non-zero impedance of the d.c. smoothing capacitor in the drive. The filter provides some series-mode attenuation to control this.



5.2 Principles of input filters

Figure 8 Basic input filter



Figure 8 shows the circuit of a typical input filter. The capacitors between lines provide the series-mode attenuation, in conjunction with the leakage inductance of the inductance. The capacitors to ground and the inductance provide the common-mode attenuation. The inductance is constructed as a common-mode component, which is not magnetised by the main power current, therefore minimising its physical dimensions. It uses a high permeability core, which can accept only a very limited unbalance (common-mode) current.

Filters for voltage source drives are carefully optimised for the application. The drive presents an exceptionally low impedance source to the filter, which means that conventional general purpose filters may have little benefit. The usual method for specifying a filter is in terms of its insertion loss in a test set-up with 50Ω source and load impedance. An alternative test attempts to be more realistic by using 0.1Ω source and 100Ω load. Neither of these tests correctly represents a drive application, and neither can be used as any more than a very rough guide to the suitability of a filter.

5.3 Shielded motor cables

The shielding capability of shielded cable is generally measured by the parameter Z_T , the transfer impedance per unit length. In an ideal cable, any current flowing in the internal circuit produces no voltage between the ends of the cable shield, and conversely current flowing in the shield from an external source produces no voltage in the inner circuit. These two aspects minimise the emission from the cable and the immunity of inner signal circuits to external disturbance, respectively. In practice the resistance of the shield, its imperfect coverage and other details cause a departure from the ideal and a non-zero value of Z_T .

The transfer impedance is not however the only factor involved. Since it is not terminated in its characteristic impedance, the cable exhibits strong internal resonances, which cause high currents to flow internally. The current is limited by the natural damping caused by electrical losses in the cable. Steel sheaths have a higher resistance and therefore give better damping than copper sheaths. Steel gives an inferior transfer impedance to copper, but the two factors largely cancel so that a steel wire armoured cable gives no greater emission with a drive than a good quality copper braided shielded cable.

5.4 Ferrite ring suppressors

The use of a ferrite ring as an output suppressor was introduced in section 4.3. The ferrite ring introduces impedance at radio frequencies into the circuit which it surrounds, thereby reducing the current. Because of its high permeability the ring will not work if it surrounds a conductor carrying power current, due to magnetic saturation, but if it surrounds a three phase set then the magnetic field is only caused by the common-mode current, and saturation is avoided. The manganese-zinc ferrite exhibits high loss in the 1-10MHz frequency range where motor cable resonance occurs, and this gives useful damping of the resonance and a substantial reduction in the peak current. The loss in the ferrite does cause a temperature rise, and with long motor cables the temperature of the ferrite rises until its losses stabilise, close to the Curie temperature.

The recommendation for using three turns on the ring is based on experience. The number of turns obviously affects the inserted impedance, nominally by a square law relationship, but the inter-turn capacitance limits the benefit and it is rarely effective to exceed three.

5.5 Filter ground leakage current

Because of the low source impedance presented by the drive, suitable filters generally have unusually high values of capacitance between lines and ground. This results in a leakage current (or touch current) to ground at supply frequency exceeding the 3.5mA which is generally accepted as permissible for equipment which derives its safety ground through a flexible connection and/or plug/socket. Most filters require the provision of a permanent fixed ground connection with sufficient dimensions to make the risk of fracture negligible. Alternative versions of filter with low leakage current may be available, which will have more severe restrictions on the permissible motor cable length.

5.6 Filter magnetic saturation

With long motor cables the common-mode current in the filter may rise to a level where the high-permeability core of the filter inductor becomes magnetically saturated. The filter then becomes largely ineffective. Filters for drive applications therefore have limits on motor cable length.

The capacitance of the cable causes additional current loading on the drive and the filter. Shielded cables with an insulating jacket between the inner cores and the shield present a

tolerable capacitance. Some cables have the shield directly wrapped around the inner cores. This causes abnormally high capacitance, which reduces the permissible cable length. This also applies to mineral insulated copper clad cables.

6 Additional guidance on cable shielding for sensitive circuits

The subject of signal circuit cable shielding is often misunderstood. It is quite common for such circuits to be incorrectly installed. This applies particularly to critical signal circuits for drives, such as analogue speed references and position feedback encoders, and also to circuits in other equipment in the same installation as the drive. This section outlines the principles, in order to assist readers in avoiding and trouble-shooting EMC problems in complete installations.

6.1 Cable shielding action

Correctly used, a cable shield provides protection against both electric and magnetic fields, I.e. against disturbance from both induced current and induced voltage.

Electric field shielding is relatively easy to understand. The shield forms an equipotential surface connected to ground, which drains away incident charge and prevents current from being induced into the inner conductor.

Magnetic field shielding is more subtle. An incident alternating magnetic field, which corresponds to a potential difference between the cable ends, causes EMF to be induced in both the shield and the inner conductor. Since the shield totally surrounds the inner conductor, any magnetic field linking the shield also links the inner conductor, so an identical EMF is induced into the inner. The voltage differential between the inner and the shield is then zero. This is illustrated in Figure 9.

In order for this benefit to be realised, it is essential that the shield be connected at both ends. Whereas high-frequency engineers routinely observe this practice, it is common in industrial control applications for the shield to be left unconnected at one end. The reason for this to is to prevent the shield from creating a "ground loop", or an alternative ground path for powerfrequency current.

The problem of the "ground loop" is specifically a low-frequency effect. If the impedance of the cable shield is predominantly resistance, as is the case at low frequencies, then any unwanted current flowing in the shield causes a voltage drop which appears in series with the wanted signal.

This is illustrated in Figure 10 At higher frequencies the cable shield impedance is predominantly inductive. Then the mutual inductance effect takes over from resistance, and the voltage induced in the internal circuit falls. A further factor is that the skin effect in the shield causes the external current to flow in the outer surface so that the mutual resistance between inner and outer circuits falls. The net result is that at high frequencies the cable shield is highly

effective. A cut-off frequency is defined at the point where the injected voltage is 3dB less than at d.c., and is typically in the order of 1-10kHz. Where disturbing frequencies exceed the cable cutoff frequency, the shield should be connected at both ends.

6.2 Cable shield connections

Figure 11 Correct shielded cable connection for high frequency shielding effect

The conclusion of this is that for all but low-frequency interference, the shield should be used as the return path for data, as shown in Figure 11. Whether the shield is connected to ground at each end, or to the equipment metalwork, is less important than that it be connected to the circuit common terminals. The recommendations

of the equipment manufacturer should be followed. It is usual to clamp the shield to a metallic structural part because this gives the least parasitic common inductance in the connection. A "pigtail" causes a loss of shielding benefit, but a short one (up to 20mm) may be acceptable for drive applications where shielding is not critical.

The shielded cable should ideally not be interrupted throughout its run. If intermediate terminal arrangements are included with "pigtails" for the shield connections, every pigtail will contribute additional injection of electrical noise into the signal circuit. If interruptions are inevitable, either a suitable connector with surrounding shielding shell should be used, or a low inductance bar or plate should be used for the shield connection as in Figure 5. Suitable hardware is available from suppliers of terminal blocks.

Low frequency interference associated with "ground loops" is not important for digital data networks, digital encoder signals or similar arrangements using large, coarsely quantised signals. It is an issue with analogue circuits if the bandwidth is wide enough for errors to be

significant at the relevant frequencies, which are primarily the 50/60Hz power line frequency. Many industrial control systems have much lower bandwidths than this and are not affected by power frequency disturbance. Very high performance/servo drives however do respond at power line frequency, and can suffer from noise and vibration as a result of power frequency pick-up. The cable shield should not be used as the signal return conductor in this case. The correct solution for wide-band systems is to use a differential input. Analogue differential inputs give very good rejection of moderate levels of common-mode voltage at power line frequency. This rejection falls off with increasing frequency, but then the shielding effect of the cable takes over. The combination of differential connection and correct cable shielding gives good immunity over the entire frequency range. A typical arrangement is illustrated in Figure 12.

Figure 12 Correct shielded cable connection for high frequency shielding and low frequency interference rejection

There are electrical safety issues associated with grounding decisions.

A galvanically isolated port with the shield connected only to the isolated common rail prevents low frequency circulating current, but carries the risk that a fault elsewhere might make it electrically live and a hazard to maintenance staff. Cable shields should be grounded in at least one place for every disconnectable length, to prevent a length becoming isolated and live. This approach is used in the Interbus industrial data network, where each link is grounded at one end and isolated at the other.

Grounding at both ends carries the risk that an electrical fault might cause excessive power current to flow in the cable shield and over heat the cable. This is only a realistic risk in large scale plant where ground impedances limit power fault current levels. The correct solution is to provide a parallel power ground cable rated for the prospective fault current. An alternative is to provide galvanic isolation, though this carries the risk of a transiently high touch potential at the isolated end during a fault.

Some galvanically isolated inputs include a capacitor to ground, which provides a high frequency return path but blocks power frequency fault current. This is actually a requirement of certain serial data bus systems. The capacitor will exhibit parallel resonance with the inductance of the cable shield, and will only be effective for frequencies above resonance. In principle such a capacitor should not be necessary, but it may be required to ensure immunity of the isolated input to very fast transients, or to suppress radio frequency emission from

microprocessors etc. The capacitor must be rated at the mains voltage. It is usual to provide a parallel bleed resistor to prevent accumulated static charge. Figure 13 illustrates this capacitor arrangement.

Figure 13 Use of capacitor for high frequency grounding whilst blocking power fault current

6.3 Recommended cable arrangements

Figure 14 summarises the recommended connection methods for the following cases:

Figure 14 Preferred connection methods

(a) Low speed digital circuit - no special precautions, open wiring

(b) Low bandwidth low precision analogue circuit - shielded

distutrbance at power frequency!

(c) Wide bandwidth and/or high precision analogue circuit - shielded, differential

(d) Wide bandwidth digital data circuit – shielded, differential

7 References

This document contains material taken, with permission, from the 2nd edition of **"The Control Techniques Drives and Controls Handbook"** published in 2009 by The Institution of Engineering and Technology.

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	Unidrive SP Free Standing	Higher power performance AC drive	400V 575V 690V	90kW to 675kW
	Unidrive SP Modular	High power modular AC drive	200V 400V 575V 690V	45kW to 1.9MW
	Mentor MP	High performance DC drive	400V / 575V / 690V	25A to 7400A
	Digitax ST	Intelligent, compact and dynamic servo drive	200V / 400V	0.72Nm to 19.3Nm (57.7Nm Peak)
	Affinity	Dedicated HVAC/R drive for building automation and refrigeration	200V 400V 575V 690V	0.75kW to 132kW
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