ELECTRICAL POWERTRAIN HEALTH MONITORING FOR INCREASED SAFETY OF FEVs

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EMC Design Guidelines for manufacturers of vehicle electric drives

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Executive Summary

This Code of Practice is aimed at FEV electrical/electronics engineers and designers. Its purpose is to guide them in the design and installation of the components associated with electrical powertrains (such as inverters and cabling) to ensure good Electromagnetic Compatibility (EMC) of their finished products.

In section 1, an introduction of the issues of the Electromagnetic Interference (EMI) in FEVs is presented.

Section 2 concentrates on the noise considerations in inverters. It summarises the origins and reasons for the EMI and presents a typical solution to reduce the EMI in an ideal case for an inverter.

The EMC Design Guidelines are presented in section 3. These include details of good practice, which should be included in the design considerations for inverters to ensure good EMC of the finished product. Alco included is an investigation into the differing screening abilities of a variety of materials that might be used for vehicle bodyshells.

Section 4 describes the most effective mitigation techniques for reduction of magnetic fields generated by the power train (inverter, cables and motor) and protection of other circuits from the fields.

Finally, section 5 includes a study of cable types and configurations, which concludes that the current use of flat cables is not as effective at reducing radiated low frequency fields as trefoil cabling.

Contents

Acronyms

AC	Alternating Current
ALSE	Absorber Lined Shielded Enclosure
CEIT	Centro de Estudios e Investigaciones Técnicas
DC	Direct Current
FEV	Fully Electric Vehicle
EM	Electromagnetic
EMC	Electromagnetic Compatibility
EMF	Electromagnetic Field
EV	Electric Vehicle
FM	Frequency Modulated
HEMIS	Electrical Powertrain **He**alth **M**onitoring for **I**ncreased **S**afety of FEVs
HV	High Voltage
I	Current
ICNIRP	International Commission for Non-Ionizing Radiation Protection
IEC	International Electro-technical Commission
LV	Low Voltage
MIRA	Motor Industry Research Association
OATS	Open Area Test Site
PHMS	Prognostic Health Monitoring System
PM	Permanent Magnet
RF	Radio Frequency
SR	Switched Reluctance
UK	United Kingdom
UNECE	United Nations Economic Commission for Europe
V	Voltage
Y-EMC	York EMC Services

1. Introduction

The use of electric vehicles relies on a DC power supply supplied by a battery. However, the use of DC motors as traction motors has largely been superseded and the DC supply has to be used to power AC motors. Various motors are used or are under investigation for use in electric vehicles, but the power supply requirements for all are similar. The AC power supply is generated by an inverter from the DC battery power supply.

Inverters rely on the high speed switching of the battery power supply, using switching waveforms with fast rise and fall times. This fast switching produces harmonics and therefore can be a source of radio interference emissions. These emissions have the potential to interfere with radio and other communication services. Emissions can also be conducted back onto the power supply and hence to other devices. Within the vehicle the source of the emissions (inverter) is in relatively close proximity to the potential victims. Although it is possible to provide some screening between the source and victim it is always more cost effective in the longer term to design the source such that any potential emissions are minimised at source.

Various European directives are relevant for electric motor vehicles [1 to 5]. Vehicles have to pass stringent EMC tests (emissions and immunity) which are referred to by UNECE regulation 10 and its addendum [6]. This generally refers to CISPR 25 [7]. To help ensure that vehicles continue to conform to these regulations once new or replacement equipment is added to a vehicle further component immunity tests are specified in [8 to 11] as well as [7]. The inverter, as a high power device with fast switching of currents and voltages, can be a source of both conducted and radiated emissions. It is also potentially susceptible to external fields although this is less likely if it has self compatibility (ie its power switching does not interfere with its own control circuitry).

In addition to the international standards mentioned above, many vehicle manufacturers have their own internal standards for component parts of vehicles. These can be more stringent to ensure that the parts made by suppliers do not interfere with each other when assembled into the final vehicle.

This document discusses the sources of emissions with respect to inverters and describes some specific reduction techniques in Section 2. Section 3 is a more generic description of EMC mitigation techniques.

This document also describes the most effective mitigation techniques for reduction of magnetic fields generated by the power train (inverter, cables and motor) and protection of other circuits from the fields remaining in section 4.

A study of cable types and configurations is also included in Section 5, which concludes that the current use of flat cables is not as effective at reducing radiated low frequency fields as trefoil cabling.

It should be noted that none of the techniques described are new and these are all likely to be as relevant to new technology which may be included in electric vehicles (e.g. solar power which will require conversion of voltages from one level to another) as to existing technology.

2. Noise Considerations in Inverters

The main drawback of inverters is the production of electromagnetic interference, also known as radio frequency interference, EMI or RFI. By careful design, the problem of interference can be minimised to an acceptable level in most applications. Inverters are widely used for industrial electronics applications and in railway traction and the lessons from these applications can be adapted to the electric vehicle environment.

2.1 Noise Sources

To see how EMI can arise, consider the following simple switching circuit. Initially with the switch open, see Figure 1, there is an electric field only around the wire connected to the battery. This is a static field and does not induce interference in surrounding circuits.

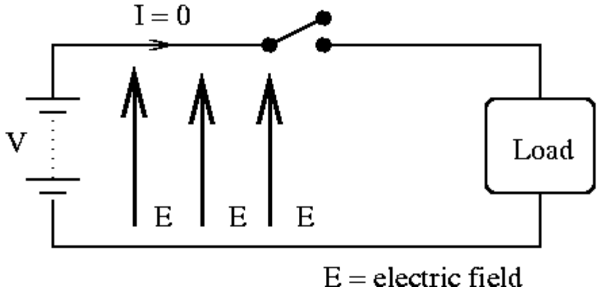


Figure 1 Simple switching circuit with switch open

When the switch is closed, see Figure 2, magnetic fields are established around the conductors and an electric field is established in the right hand half of the circuit.

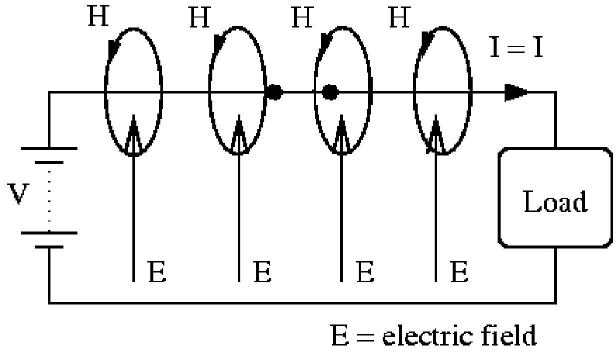


Figure 2 Simple switching circuit with switch closed

The establishment of the field flux in the space around the wires involves rapid changes of these fields. These changing or moving fields may intersect other conductors in nearby circuits, inducing unwanted voltages and currents, namely interference. The amount of interference produced by the circuit will depend on the rate of change of voltage and current in the circuit, in time and also upon the size or geometry of the circuit. A large, spread out, circuit will produce more interference than a small compact one for a given current or voltage change.

2.1.1 Electrical Noise Sources

Electrical noise arises in circuits carrying changing voltages and currents. Common sources of noise are relays, electric motor commutators, digital switching circuits and radio transmitting devices.

2.1.1.1 Accelerating charge

Electromagnetic interference is generated by the acceleration or deceleration of electrical charge in a circuit. A DC current consists of a steady flow of charge, which will produce static magnetic fields, but no radiated electromagnetic field. As soon as the flow of charge is interrupted or otherwise changed, electromagnetic energy is radiated from the circuit. Circuits carrying rapidly changing currents and voltages are therefore prolific sources of electromagnetic radiation and therefore, potentially prolific sources of interference.

2.1.1.2 Electrical Noise in Inverters

In the simple inverter circuit shown in Figure 3, it is possible to identify the areas that give rise to EMI by considering the rate of change of the voltages and currents at different points in the circuit. In the vicinity of the switching transistors, there are high values of dV/dt and the conductors connecting to the DC supply and motor have high dI/dt values. Both of these can provide severe EMI if preventative steps are not taken.

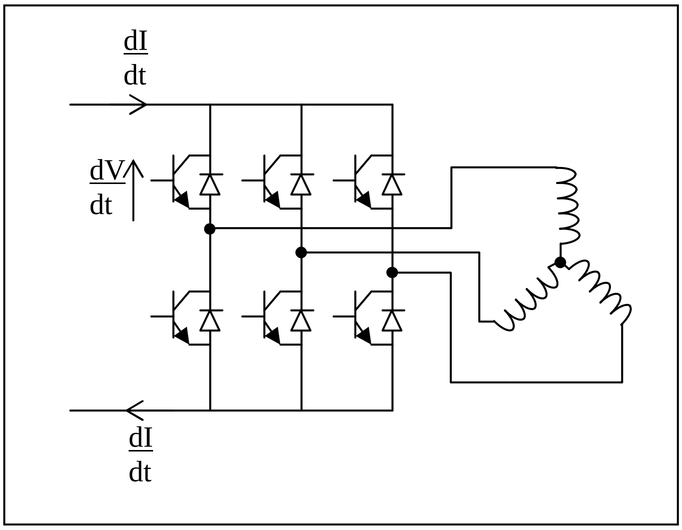


Figure 3 Simple Inverter circuit for AC motor drive

EMI can be conducted along both internal and external wiring to the power supply. It can also be coupled electrically (capacitively), magnetically (inductively) or radiated. Figure 4 illustrates the potential EMI problem areas in an inverter.

Figure 3 shows a typical star connection for a 3 phase induction motor. Other motor types might have different types of connection (e.g. 3 phases with individual returns) but the EMC principles are common for all types.

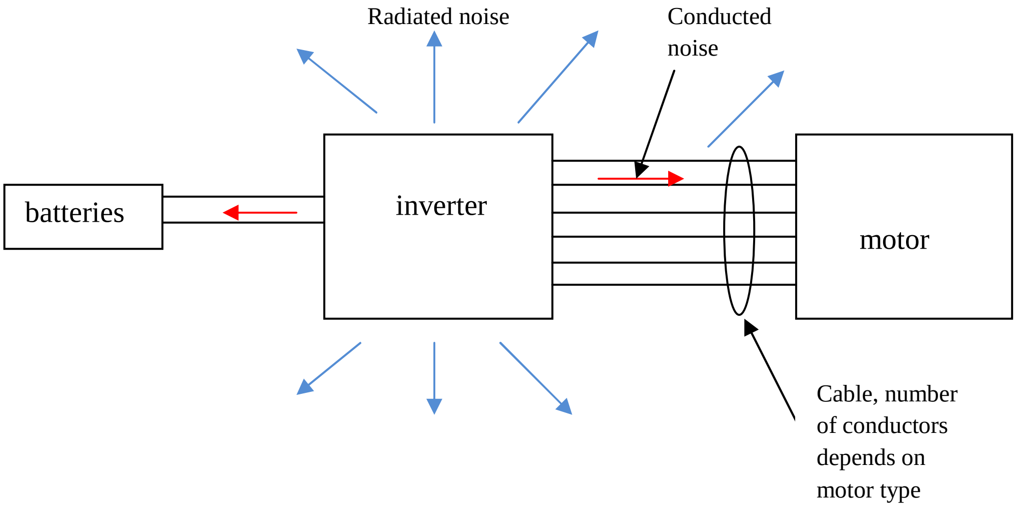


Figure 4 Potential EMI transmission routes in an inverter

The potential transmission routes of EMI in an inverter are:

- Conducted noise on the output connections to the motor.
- Conducted noise on the input power connections.
- Radiated noise from external cables.
- Direct free space radiation from the enclosure.

For EMI to be a problem in any electronic system there are three requirements:

- There must be a "source" of interference.
- There must be a transmission medium.
- There must be a susceptible receiver – a "victim".

Removing any one of these will prevent the problem, but ideally, all three should be eliminated to avoid unexpected problems when the equipment is in use.

In an inverter, there are two main areas, which require special attention:

- Conducted noise on the input power supply wiring and cabling. (This noise can also convert to radiated interference when the cable acts as an antenna).
- Radiated noise from the switching circuits (possibly via the attached cables).

2.1.2 Noise Reduction Techniques

2.1.2.1 Noise Reduction at Source

The requirement for efficient power conversion requires rapid switching of current and voltage by the main switching transistor. This gives rise to high dI/dt and dV/dt values that cause EMI. The major source of EMI in an inverter is around the main switching transistors. The abrupt transitions of switching current and voltage excite oscillations in the parasitic capacitances and inductance of transformers (chokes, wiring and motor windings). In order to reduce this interference at source, a slight trade-off with efficiency can be made by deliberately reducing the speed of the current changes, dI/dt, and voltage changes, dV/dt, at the switching devices. This can be achieved by the addition of small series inductors to limit dI/dt and small shunt capacitors to limit dV/dt as shown in Figure 5. Typical values are 500 nH and 100pF. Currents and voltages are dependent on the specific type of inverter being designed. Note the capacitor resistor network is often referred to as a 'snubber'.

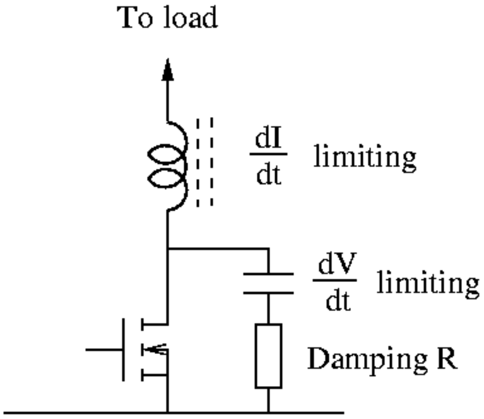


Figure 5: dI/dt and dV/dt limiting circuit

This solution will give rise to an increase in the power dissipated in the switching device.

Another source of interference is the fast fall time current spikes, which occur when diodes are reverse biased. Typically, a fast recovery diode will "snap off" in around 10 ns. This can result in ringing and radiation in the very high frequency region.

The fast fall time current spikes arising from diode snap-off can be controlled by the use of "soft recovery" diodes or by the incorporation of a low value ceramic capacitor connected across the diode. Again, a small trade-off can be made with efficiency by using small RF inductors in series with the main switching transistors to limit the switching edges, thereby giving a substantial reduction in EMI at source. Additionally, the circuitry should be contained in a grounded metal screening enclosure in order to prevent radiated interference. Usually effective suppression is only achieved by using both filtering and screening together, as neither is fully effective on its own.

2.1.2.2 Screening

Screening is used to prevent stray fields and radiated energy from inverters causing problems in nearby equipment. Screens for inverters are usually implemented using metal enclosures that reflect and absorb fields and radiation. See section 3.8 for more detail.

2.1.2.3 Filtering

Filtering is used to block the propagation of high frequency currents and voltages along cables and wiring. These are usually implemented in the form of low pass filter sections comprising suitable inductors and capacitors. The main problem areas in an inverter are at the power input and the output. These effects are often referred to as “conducted EMI”. A filter is best placed at the screen with minimal cable or track between the filter and screen or adjacent to the source (e.g. where the switching takes place). This reduces the level of signal which can couple between the cables or tracks on either side of the filter. Further details on filter components is provided in Section 3.6.

3. EMC Design Guidelines

3.1 Introduction

Within EMC standards, there are no requirements to design for EMC, although equipment, which is built without any consideration, is likely to fail testing to the relevant EMC standards. Testing failure leads to re-design and re-testing, which are often expensive and time consuming.

An FEV can be designed in many ways, and design for EMC compliance should be an integral part of the product design process. There are often various ways to prevent EMC problems, but at a late stage in the development, options for controlling the problems may be restricted and costly. Such issues can be avoided by following some “simple” guidelines. Some of these are summarised in the next few sections.

3.2 Nature of the Application

Inverters for use in FEV power trains will be in closer proximity to potentially susceptible equipment and radio receivers than power electronics used in many other situations. It is therefore necessary that they are designed with EMC requirements in mind.

It is important for the inverter manufacturer to ensure that the product is tested to the appropriate standards. Inverters are treated as apparatus under the EMC Directive so must carry CE marking: however, the manufacturer of the vehicle in which it is to be used is also likely to have their own EMC requirements to ensure that the inverter does not interfere with other parts of the vehicle. Specific considerations for the design may also be required to ensure compliance of the final vehicle (with the inverter installed) with the relevant regulations applicable to the vehicle.

3.3 “Internal” EMC and Signal Line Considerations

It is important that the inverter operates correctly and its operation does not suffer from self-generated noise. For example, the circuitry used to control and regulate the output voltage level for varying load currents is generally implemented as some form of feedback controller. This is usually implemented with low-level circuitry that can be prone to interference. For correct operation, it is important that this does not happen. Careful de-coupling of the control circuitry, and careful planning of the grounding within the inverter is essential.

3.4 PCB Considerations

The design of the printed circuit board (PCB) or boards, is crucial to the correct functioning of an inverter. The trend to ever-higher switching frequencies coupled with more stringent EMI specifications make the design of the PCB increasingly demanding.

Designers should follow good high frequency/radio frequency design practice in the design of PCBs. Connections should be kept as short as possible and tracks should be dimensioned to have as low an impedance as is feasible.

It is good practice to use a “ground” plane. This can be realised by the use of double-sided (or multi layer) PCBs. Consideration should also be given to the use of thicker copper than the normal ‘1oz’. Conductors should be made as wide as possible and this points to etching the minimum of copper from the board consistent with meeting insulation and clearance requirements. The ground plane works as a screen and helps to minimise radiation. It also provides a good low-impedance “zero-volts” connection.

The layout of components also requires thought at a top-down level. The low-level circuitry associated with the control and monitoring of the power supply unit (PSU) should be kept separate from the high dI/dt and dV/dt values associated with the main switching transistors and transformer. Grounds for analogue and digital circuits should be separated to reduce coupling between sources and susceptible parts of the inverter, further information is given later in this report (Section 3.7).

3.5 Component considerations

Filtering of the input and output leads to contain EMI within an inverter is an important aspect of interference control. The components available for this purpose are capacitors, inductors and feed-through capacitors and filters. These must be chosen with care and appropriate types picked for the frequencies at which the filtering is to be effective. The most important consideration for choosing a component for this application is the value of its “parasitics”. Take, for example, the capacitor shown in the equivalent circuit below in Figure 6:

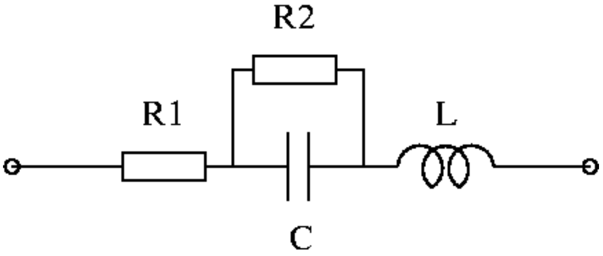


Figure 6 Capacitor equivalent circuit

The capacitor equivalent circuit has series inductance, L, arising from the leads and the physical construction of the component and resistances, R1 and R2, associated with its losses. It is important that the effects of the parasitics are small at the frequency of interest if the capacitor is to be effective at decoupling or bypassing.

Capacitors for EMI suppression and filtering should have good high frequency properties and a low series inductance. The most useful types are disc and plate ceramic components. These have excellent high frequency properties with good high voltage properties. It is important to consider the effect of lead length on the layout of the filter and the effectiveness of the bypass capacitors. The table below gives the self-resonant frequency for ceramic capacitors of different values with different lengths of leads.

Capacitance - pF	0.25in leads	0.5in leads
10,000	12	-
1,000	35	32
500	70	65
100	150	120
50	220	200
10	500	350

Table 1: Examples of self-resonant frequency for ceramic capacitors of different values with different lengths of leads (frequency in MHz)

It is important to use capacitors whose self-resonant frequency is well above the frequencies at which bypassing or decoupling is to be effective. At switching frequencies where a higher capacitance is required than is available from ceramic types, polycarbonate or polypropylene types are the most effective.

Figure 7 shows the effect of self-resonance on the impedance of a capacitor. Above resonance, the impedance rises and can become greater than that of an “ideal” capacitor, rendering it ineffective as a bypass or decoupling component.

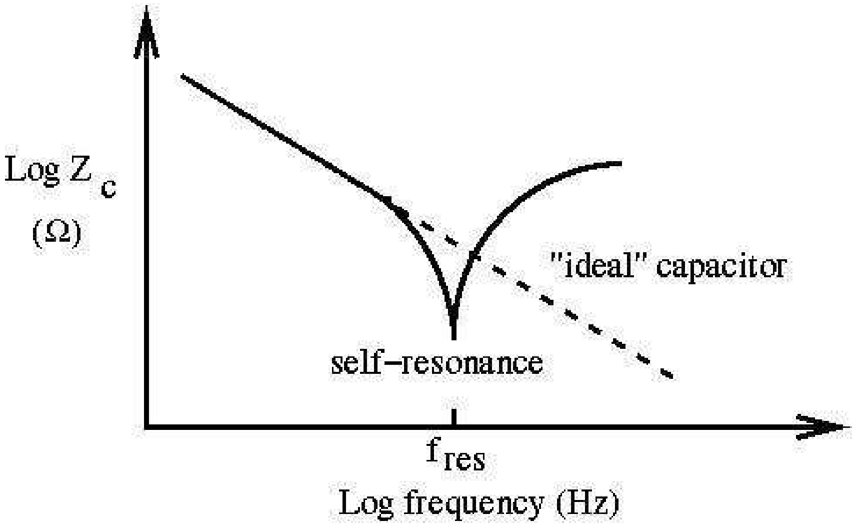


Figure 7 Plot showing the variation of capacitor impedance with frequency

Inductors also exhibit self-resonant effects arising from their parasitic inter-turn capacitance. This capacitance appears in parallel with the inductance, and above the resonant frequency, the reactance of the inductor will start to fall, making it less effective as a choke.

It should be noted that ‘super-caps’ should not be regarded as capacitors for EMC purposes. Their impedance is only capacitive up to a few hertz due to the mechanism by which they operate.

3.6 EMC Components

3.6.1 Ferrite Beads

Ferrite beads are a simple way to control EMI. They are formed from cylinders of ferrite material, with an axial hole through the centre. They can easily be slipped over the leads of components or over cables to provide attenuation of high frequency signals. They are most effective above 1MHz and when properly used can give effective high frequency decoupling and shielding. They are particularly useful in applications where a high current is flowing and it is not possible to insert a resistor in the circuit. Figure 8 shows the equivalent circuit of a ferrite bead at high frequencies.

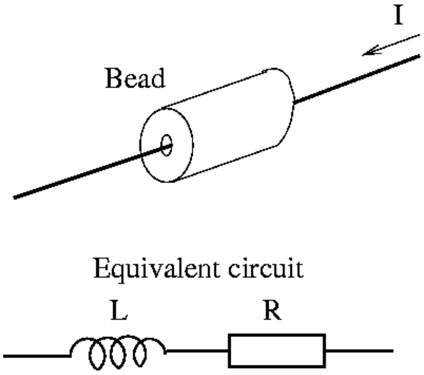


Figure 8 Ferrite bead

The resistive component arises from the loss component of the ferrite. Ferrite beads are most useful for damping out high frequency oscillations and "ringing" in switching circuits. They are also useful for blocking high frequency noise on power lines. The impedance of most beads is limited to around 100 ohms, making them most effective in low impedance lines, such as power supplies and switching circuits. Typically, ferrite beads are used in conjunction with shunt capacitors to form low pass filters to block EMI on lines. Care should be taken in their use not to introduce any spurious resonances into a circuit that could exacerbate an interference problem. Another point that is often overlooked is that the current flowing through the wire must not saturate the ferrite. A ferrite will saturate at a much lower DC current than with AC.

3.6.2 Feed-through filters

Feed-through filters are useful components for EMI suppression. They consist of a central ferrite bead to supply series inductance between two coaxial ceramic capacitors formed from a high dielectric ceramic material. These are manufactured by many companies and are available in a variety of voltage and current ratings, covering a range of frequencies. They are available as both L and Pi low-pass sections and are convenient to use. Figure 9 shows the construction of a typical feed-through filter.

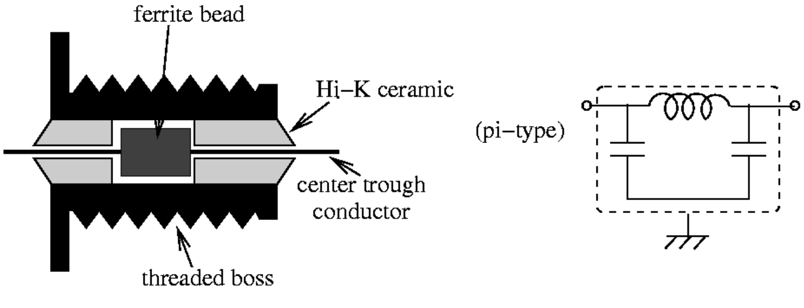


Figure 9 Feed-through filter construction and equivalent circuit

3.6.3 Inductors

Inductors may be classified by their core type. The most general types are the air-cored varieties and the magnetic core types. Magnetic core types can be further subdivided depending on whether the core is open or closed. Designing EMI filters would not be a problem if the inductors were ideal.

Unfortunately, they have stray capacitance arising from adjacent turns and stray resistance from the wire of which it is wound.

In a low pass filter configuration, the inductor will only be effective if it is operated well below its self-resonant frequency; thus, ideally, only the smallest inductance should be used that will give the necessary attenuation, at the lowest frequency which the filter has to reject. Another important consideration in the choice of an inductor is its stray magnetic field.

3.6.3.1 Toroid

Closed core types, for example toroids, have a much-reduced surrounding magnetic field as compared to air or the open cored types. Consequently, they are much less prone to radiate or receive signals by means of stray magnetic coupling. If a toroidal inductor cannot be used, it may be necessary to enclose the winding in a metal box providing magnetic shielding.

3.6.3.2 Air Cored

Air cored or self-supporting coils are only useful to obtain small inductance values, of the order of a few micro-Henries. They have the advantage that they do not have a core to saturate.

3.6.3.3 Ferrite Cores

Ferrite cored inductors are used to achieve compact inductors with a higher inductance value in the tens of micro-Henries to Henry range. Care must be taken to ensure that the current flowing in the winding does not saturate the core material. Care must also be taken to ensure that the stray capacitance of the winding does not resonate with its inductance to bypass the effect of the inductance. Open cored types also produce stray fringing fields from the ends of their cores.

3.6.4 Common Mode Chokes

A useful component for filtering power supply lines between equipments is the bifilar wound choke. It is especially useful when common mode or ground noise is a problem and finds almost universal use in switched mode power supplies. It consists of windings placed on a core to form a broadband transformer that allows equal and opposite currents to flow through its windings whilst suppressing common mode currents such as ground noise. Because of the bifilar winding no net flux is set up in the core when the currents are balanced and in flowing in opposite directions, therefore the balanced currents do not encounter any inductance. When balanced currents flow in the same direction there is a net flux giving an inductance and the choke opposes such currents. An additional advantage of the balanced configuration is that in normal operation the core is kept well away from saturation. Figure 10 below illustrates the use of a bifilar choke between a supply and a load.

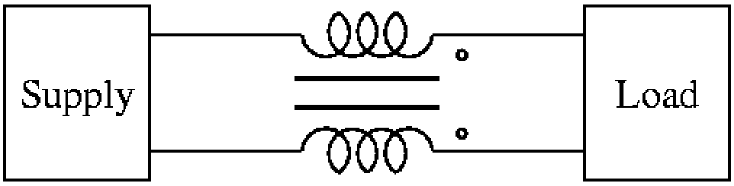


Figure 10 A bifilar choke used to block EMI between a supply and a load

Bifilar chokes are used to break ground loops as shown in Figure 11. This figure shows an equivalent circuit of a bifilar choke including an interfering ground potential.

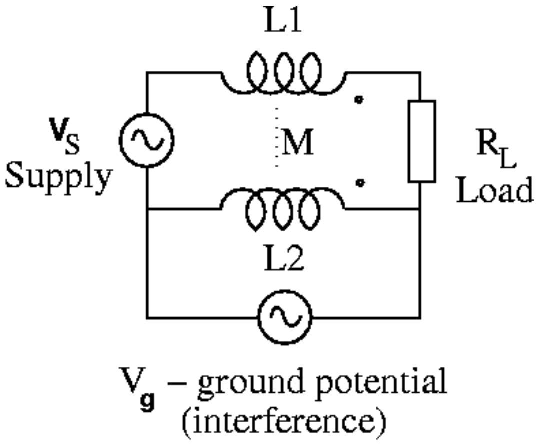


Figure 11: Equivalent circuit of a bifilar choke

To understand how the common mode choke operates consider each voltage generator in Figure 12 in turn. Firstly, neglecting Vg the equivalent circuit becomes:

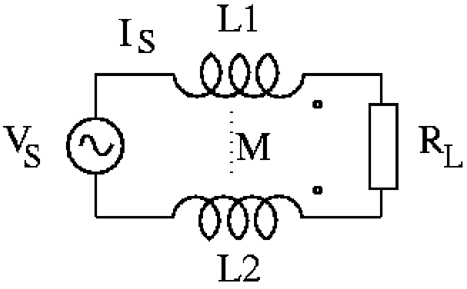


Figure 12: Equivalent circuit for a balanced supply only

The two windings are wound to have identical self-inductances and are closely coupled so that:

L1 = L2 = M **(Equation 1)**

Since the two windings are connected so that their fields arising from the current from Vg cancel, both the mutual and self-inductances will cancel causing the choke to have no effect in the ideal case. In practice, the windings have a small resistance and this may have to be taken into account.

For an unbalanced (ground) voltage the circuit becomes as in Figure 13:

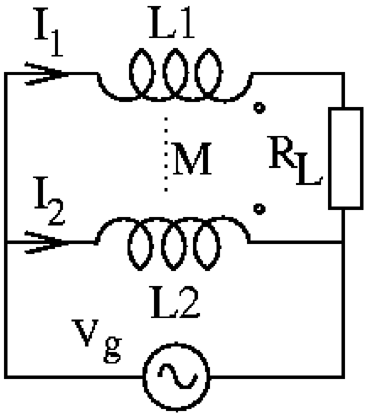


Figure 13: Equivalent circuit for an unbalanced supply only

In this case, the windings are in the same sense and the inductances oppose the currents I1 and I2, minimising the currents in the load caused by Vg.

3.6.5 Network Isolator

The interference problem is potentially severe at the input of an inverter where the currents have very high rates of change with time. There is unlikely to be other equipment using the same high voltage battery supply (other than any power recovery system used with regenerative braking) but the high speed current switching on the cables to the battery may interfere with other equipment and radiate if the cable lengths are not minimised. If filtering is used on the dc supply (bifilar common mode chokes and capacitors between the positive and negative supply) it is necessary to ensure that they are rated for the high dc voltage and high currents which will be drawn. The filtering at the input must be capable of blocking the switching frequency ripple and its harmonics well into the MHz region of the spectrum.

At the output there may also be a low pass filter section, to remove the switching frequency ripple, and this serves to attenuate high frequency noise. The inductive load provided by the motor stator windings will provide filtering to the output at low frequencies but the windings are likely to be self resonant at relatively low frequencies due to the capacitance between the windings, in this case separate filtering may be required.

3.7 Grounding

Grounding is an important aspect of interference control. One possible configuration is shown below in Figure 14.

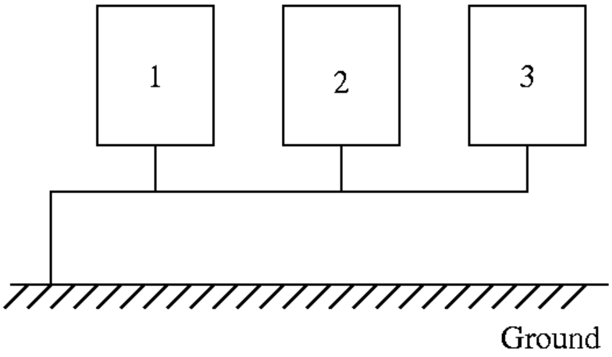


Figure 14: Series connection - single point

This will ground each unit 1, 2 and 3 but if the circuit is considered in more detail and the wiring impedances, which become significant at high frequencies, are added to circuit it is possible to see the potential pitfalls of this configuration.

Inclusion of these points gives a different appearance to the first of these two earth circuits (Figure 15).

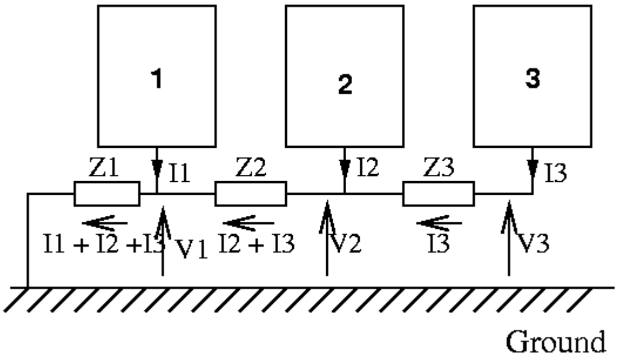


Figure 15: Series connection - single point, plus parasitic resistances

Two points should be borne in mind when discussing grounding:

- Separate ground points on a chassis are seldom at the same potential;
- All conductors and wires have finite impedance.

The first point dictates that a common single point earth is desirable; unfortunately, in practice this tends to mean that a number of common impedance paths are introduced into the earth returns for units 1, 2 and 3. A situation where this occurs commonly is in printed circuit boards, which pick up all their connections including ground through an edge connector. This can result in excessively noisy grounds especially if one of the stages is high-powered.

At low frequencies where wiring inductance is not a problem the solution is to use a single point grounding scheme, such as, that shown in Figure 16.

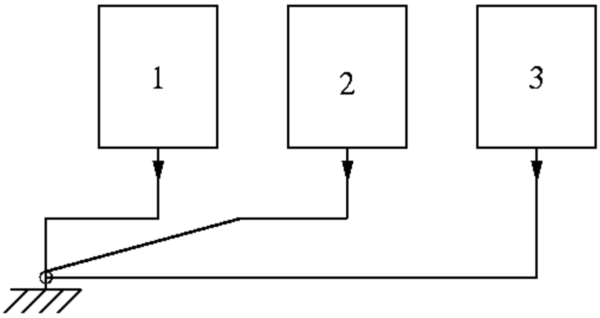


Figure 16: Parallel connection - single point

This scheme avoids the problems of common ground return paths and impedances however; it is cumbersome and can necessitate long ground connections. For frequencies above around 1MHz, a low impedance ground plane is good practice especially on printed circuit boards. Here multi-point grounding is the preferred method, as shown in Figure 17 provided the ground connections are kept short and direct.

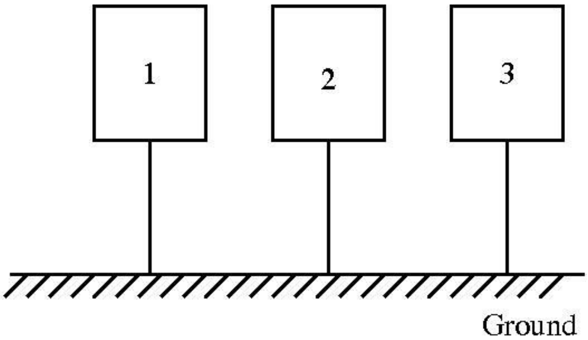


Figure 17: Multi-point grounding

The importance of choosing grounding points carefully can be illustrated in the following simple switching circuit (Figure 18) in which the gate of the transistor is driven from the secondary of a pulse transformer to provide isolation for the control electronics. In the first circuit, the lower connection from the secondary of the gate drive transformer includes a length of common wire connection, which carries the source current. At the switching frequencies in common use, this wire could have a significant inductance causing a voltage drop to occur along its length. This voltage could easily be large enough to cause faulty turn-on cycles in the Metal-Oxide-Silicon Field Effect Transistor (MOSFET). By making the transformer connection directly to the source of the transistor, this problem is avoided. The same principle applies if the switch on control is not via transformers.

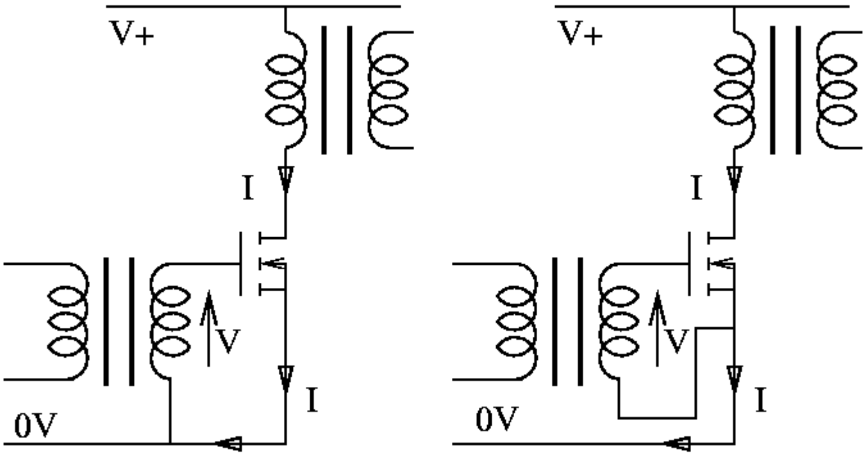


Figure 18: Method of avoiding faulty turn on cycles due to wiring inductance

In practice, it is often impossible to stick rigorously to one grounding scheme or another and the following guidelines and Figure 19 should prove useful.

- Never combine noisy, "high power" circuit grounds with ones for "low powered" signal circuitry.
- Group ground leads selectively, i.e. place high power grounds together and keep low power grounds together.
- Provide separate grounds for chassis, case and AC power ground when required for safety.
- Keep high power grounds as short as possible.

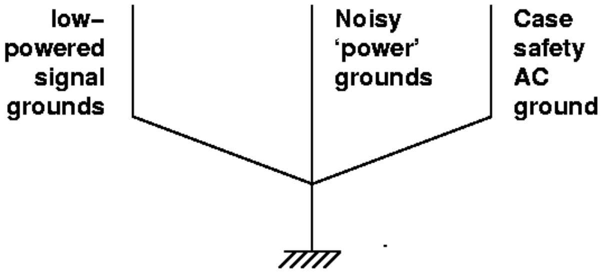


Figure 19: Grounding Guidelines

3.8 Screening

Another important consideration in the design of switched mode power supplies is the prevention of radiated interference from the supply entering into surrounding systems and wiring. This is achieved by paying careful attention to screening and grounding throughout the design. Switching regulators can generate noise up to frequencies in the VHF range (up to 300MHz). Cable radiation tends to dominate up to approximately 200MHz after that enclosure radiation takes over. These frequency components are easily radiated from packages that are not 'RF tight'; in other words, the circuitry of the supply should be fully enclosed in a grounded (theoretically the screened enclosure does not have to be grounded to function as a faraday screen), conducting case. In addition, all leads for input, output and control functions must be adequately filtered at the point of entry to the case. All lids and covers should be bonded onto the main chassis using fastening spaced less than one tenth of the minimum wavelength for the frequencies of interest, using suitable RF gasket material for addition screening if necessary. For optimum screening, the enclosure should be thought of as being electrically ‘watertight’.

3.8.1 Near/Far Field

When planning screening for a supply it is necessary to know the type of field that is being shielded against. The characteristics of the field are determined by the nature of the source and the proximity of the source. Near fields describe fields that are predominantly electric or magnetic with the dominant coupling mechanisms being capacitive or inductive. A source with a high current and low voltage will have a near field that is predominately magnetic, while one that has a high voltage and low current has a predominately electric field. The electric and magnetic fields must be considered separately. Far fields are those sufficiently far from the source to behave as an electromagnetic wave with a fixed ratio of electric and magnetic field components. Electromagnetic waves tend to decay at a much reduced rate with distance when compared to the near field cases.

Electric fields are relatively easy to shield against by using a metal sheet of good electrical conductivity, as the prime shielding mechanism is reflection.

At the frequencies which are generated by the electric power train (likely to be mostly under 1 kHz) the circuits are all within the near field of the source, in which the field will be predominantly magnetic. This is relatively hard to screen at low frequencies as the skin depth of non-magnetic screening materials is relatively high, and can be higher than the thickness of the enclosure walls. If it is necessary to provide a screening enclosure then it is recommended that this is made of a material with a relative permeability of at least 100. At these frequencies, providing good electrical contact is necessary between the enclosure and lid, although it is not necessary to have a large number of fastenings to reduce the slot length between the fastenings as is required in shielded enclosures used at higher frequencies.

3.8.2 Screening Mechanisms

An electromagnetic screen works in two ways. Firstly, it serves to reflect the unwanted field and, secondly, energy transmitted through the screen is absorbed and hence attenuated. The total attenuation provided by the screen is the sum of the absorption loss and the reflection loss:

Total attenuation = absorption loss + reflection loss (**Equation 2**)

Reflection loss can be calculated from knowledge of the wave impedances in the screen and the wave impedance of the surrounding medium. In order to maximise the loss through the screen, the amount of the signal reflected from the screen should be high and the amount of signal transmitted should be small. A useful analogy is to think of the matching at the junction of two transmission lines of different characteristic impedances. In the case of a screen, in order to maximise reflection, it is necessary to ensure that the wave impedance of the screen is radically different from that of the surrounding air. Figure 20 shows the relationship between the incident and transmitted fields at the boundary between two media.

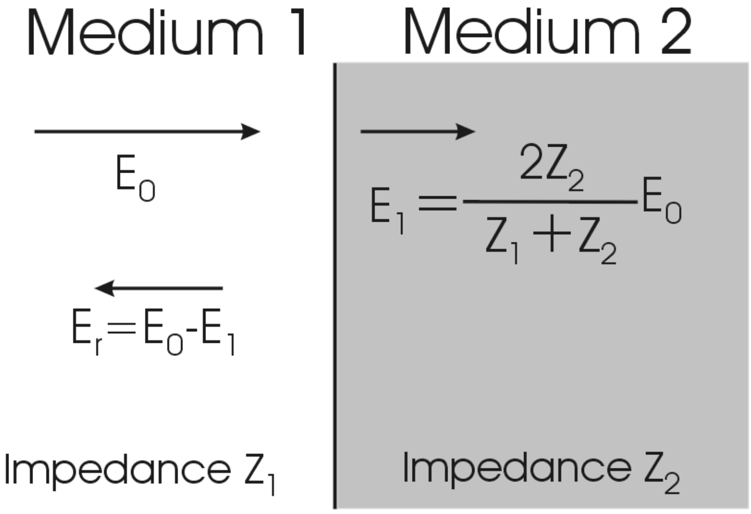


Figure 20: Transmission at the boundary between two media

3.8.3 Magnetic Fields

Magnetic fields are more difficult to contain. Reflection loss is generally low (<= 10 dB) as the near-field wave impedance is low and comparable to that of a metal sheet. The main mechanism has to be absorption, so it is necessary to use thick screens of a material with high relative permeability, μ_r. The commonest solution is to use mild steel, which has a relative permeability of around 1000. There are also special alloys such as mu-metal (that have permeabilities of around 10,000) which can be used to solve magnetic field problems. These have some drawbacks, however, as they tend to lose their magnetic properties when mechanically worked or subjected to vibrations, which are likely to be present in a vehicle. This data is not readily available in the public domain. Manufacturers of mu-metal anneal products after forming, to maximise the initial permeability by optimising the granular structure of the material, working the material changes this structure and reduces the permeability. They are also not as effective at frequencies in excess of approximately 1kHz. An alternative approach to dealing with magnetic screening at frequencies in the tens of kilohertz region is to enclose the field in a material with a band of metal of high conductivity. Provided the metal thickness is greater than the skin-depth at the minimum frequency of interest, it will enclose the magnetic field. This is often used to screen transformers and takes the form of a copper band placed around the core external to its magnetic circuit and is termed an “eddy-current band”.

3.8.4 Electric Fields

Electric fields are relatively easy to screen. The main mechanism is reflection. For good reflection, it is necessary to use a good conductor. Attenuation levels of around 150-200 dB are relatively easily obtained providing good electrical connection is obtained between enclosure and lid.

3.8.5 Radiated Fields

A useful general-purpose screen is provided by plated steel. Here, the high permeability of steel is available to combat magnetic fields, and a high conductivity plating such as copper, tin or zinc provides good electric field screening. In practice, it is difficult to fully enclose a unit such as a power supply in a metal box, as some provision must be made for cooling either by convection or forced air-cooling. This necessitates the provision of holes for the air to pass through. The shielding effectiveness of a square grid of side l, of round holes of diameter d, and pitch c is

$$S = 20\log\frac{c^2 l}{d^3} + 32\frac{l}{d} + 3.8dB$$ **(Equation 3)**

Where S, the shielding effectiveness, is the improvement in shielding over a square hole of side l. This assumes that the holes are acting as short waveguides below cut-off; i.e. d < $\frac{\lambda}{2\pi}$, where λ is the wavelength at the frequency of interest.

Other areas to pay particular attention to in the design of screens are the joints and seams in cases and the seating and electrical bonding of lids and covers. If a lid or joint is not tight fitting it is relatively easy for it to act as a slot antenna, making it an excellent radiator and receiver of interference. To avoid this, the use of multiple fixings or conducting gaskets is recommended in all joints and covers. Actual screening effectiveness obtained in practice is usually determined by the leakage at the seams and joints, not by the material itself.

The maximum dimension (not area) of a hole or gap determines the amount of leakage, e.g. slot radiator. A large number of small holes result in less leakage than a larger hole of the same total area.

3.8.6 Shielding at lower frequencies

The majority of the higher level electromagnetic emissions emanating from electrical vehicle drive trains are magnetic fields at the lower end of the frequency spectrum (from tens of hertz to, typically, one hundred kilohertz). If good layout of the cables etc. in the powertrain cannot bring the fields down to a required level, screening may be required as well. There are various materials which can be used with various properties. There is also a requirement to reduce the weight of the vehicle to increase efficiency of the vehicle (i.e. reduce energy used), but where low frequency magnetic fields are involved this can create a conflict as is demonstrated in the results discussed in this section. For additional clarity, a low frequency screening video has been created as part of this work.

3.8.6.1 Relative Orientation and separation

Measurements were carried out using two small multi-turn coils of wire to demonstrate the variation of coupling with relative orientation and to show the effect of various materials on coupling at low frequencies. The dimensions are different to those which would be obtained from loops formed by cables but the principles are the same.

The coils consist of many turns of wire on a Perspex former with maximum dimensions of the coils being 38mm length and diameter. The Perspex former is 6mm thick so the closest the coils can be positioned is 12mm end to end. The former is 60mm wide giving a closest position with a gap of 22mm side to side. Figure 21shows the orientation.

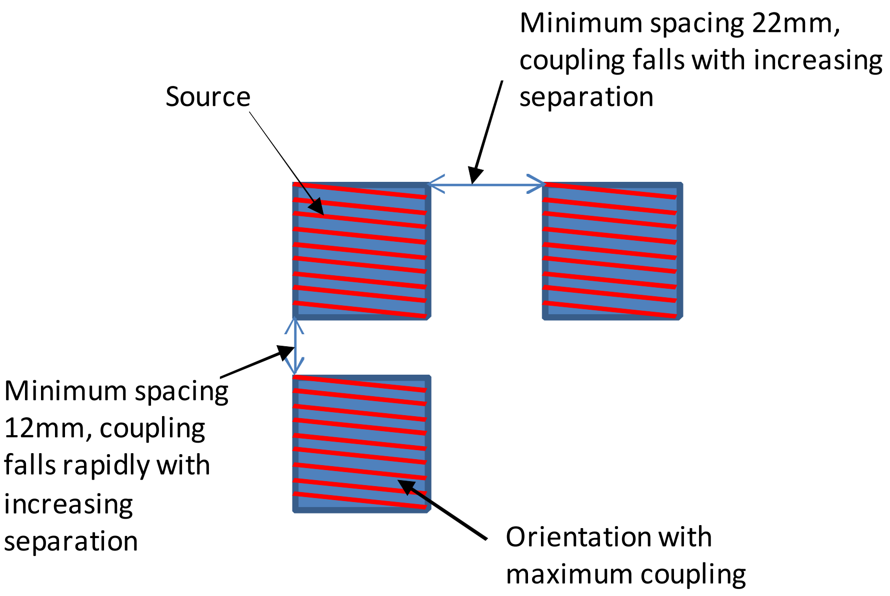


Figure 21: Orientation of coils, showing minimum spacing for measurements

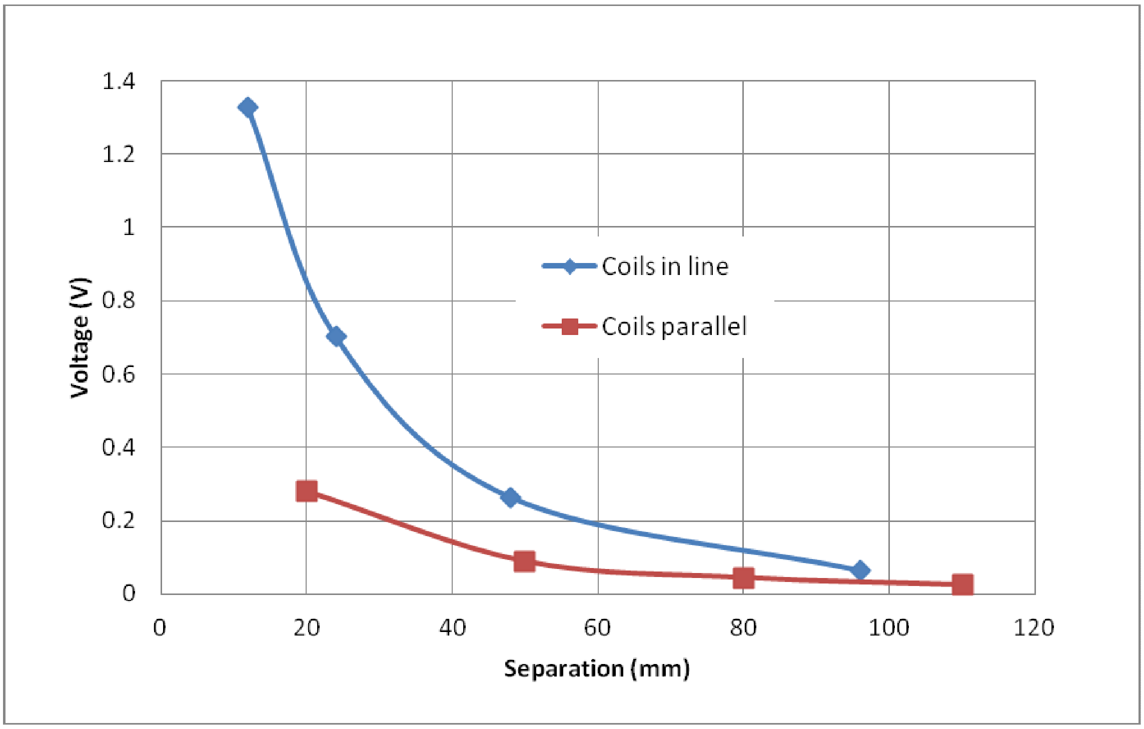


Figure 22 Variation of pickup with coil separation

Figure 22 shows the variation in coupled voltage between two coils with distance. The separation shown is the distance between the nearest points of the two coils.

Note that not all the coupling measured is due to the field generated by the coil. Some coupling is due to cross talk between the cables connecting the inductors to the signal source and the oscilloscope which does not fall at the same rate and generates a minimum below which the coupled signal does not fall.

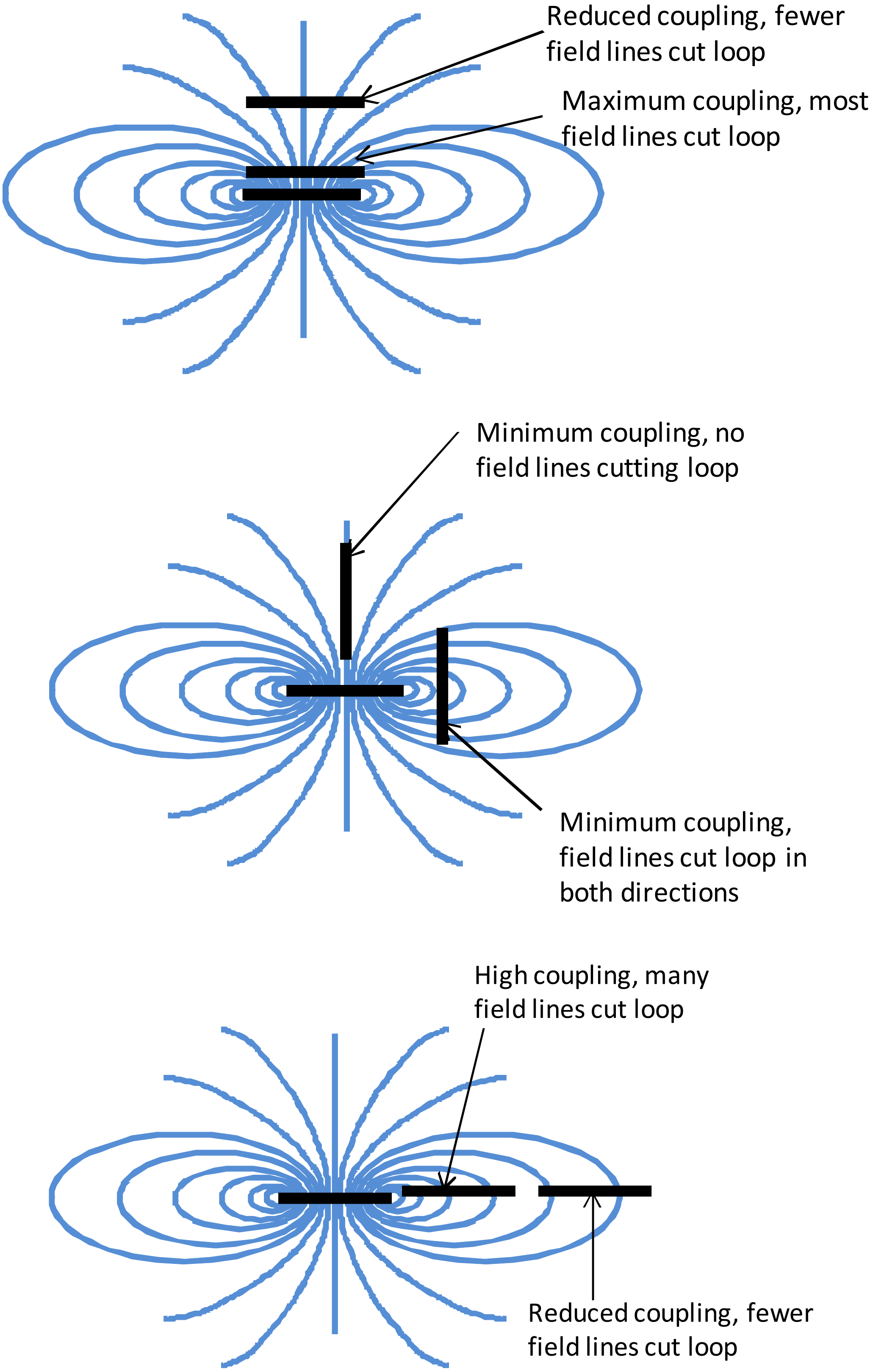


Figure 23 Relative orientations for maximum, minimum and reduced coupling

3.8.6.2 Materials

The degree of shielding that a material provides against low frequency magnetic fields depends upon the electrical conductivity, the magnetic permeability and the thickness of the material.

Four basic mechanisms can be considered to contribute to the magnetic field shielding provided by a planar sheet of material.

1. Absorption loss – is, as implied, a loss of energy within the shield material. Calculation of expected absorption loss in an infinite sheet of material gives $A(dB)=8.69(t/\delta)$ where t is the material thickness and δ the skin depth (determined by conductivity, permeability, permittivity and frequency).
2. Reflection loss – is associated with energy reflected owing to an impedance mismatch between the incident wave and the shield material. For low impedance (magnetic) fields close to their source the reflection loss is typically very small.
3. Eddy currents – currents induced into the shield material (acting in a similar way to a shorted transformer turn) generate magnetic fields in the opposite sense to the incident field. The net magnetic field is therefore reduced.
4. Leakage flux – for a finite sized shield some magnetic flux will leak around the material limiting the maximum level of shielding that can be achieved. This effect increases as frequency increases and leads to the need to consider enclosure design at higher frequencies.

The calculation of absorption loss relies on knowledge of all the relevant parameters. For spray type materials or fibre based materials (e.g. CFC and nickel fibre) the bulk conductivity is reduced from the conductivity of the basic conductive material by a proportion which depends on the volume of material within the structure. The thickness of the conductive material may also not be easily determined (e.g. spray or CFC). The conductivity and permeability of stainless steel vary depending on the exact composition of the material, as does the conductivity of brass. It should be noted that the permeability of ferrous materials is also dependent on the previous history of the material and the strength of the magnetic field in which the material is immersed. It is therefore difficult to accurately predict the absorption loss of many materials.

The permeability of magnetic materials falls with frequency so using the permeability measured at DC or very low frequencies will always overestimate the shielding which might be obtained. This is demonstrated in the table on the next page (note that the calculation is of theoretical attenuation only, there is not allowance for reflections).

				100 Hz			**1000 Hz**			**10000 Hz**			**100000 Hz**		
Material	thickness (mm)	relative conductivity (approx)	relative permeability	skin depth (mm)	theoretical attenuation (dB)	measured shielding (dB)	skin depth (mm)	theoretical attenuation (dB)	measured shielding (dB)	skin depth (mm)	theoretical attenuation (dB)	measured shielding (dB)	skin depth (mm)	theoretical attenuation (dB)	measured shielding (dB)
mild steel	1	0.1	800	0.74	11.8	10.5	0.23	37.3	15.5	0.07	117.8	<29.5	0.023	372.6	>26
mild steel x2	2	0.1	800	0.74	23.6	15.2	0.23	74.5	28.4	0.07	235.6	<29.6	0.023	745.1	>26
copper clad board	0.035	1	1	6.60	0.0	0.1	2.09	0.1	0.13	0.66	0.5	5.7	0.209	1.5	18
brass	1.6	0.26	1	12.94	1.1	0.5	4.09	3.4	7	1.29	10.7	21.9	0.409	34.0	>26
stainless steel (non magnetic)	1.6	0.1	1	20.86	0.7	0	6.60	2.1	0.1	2.09	6.7	4.7	0.660	21.1	19.9
carbon fibre (2 layer)	1	0.001	1	208.6	0.0	0	65.97	0.1	0	20.86	0.4	0	6.597	1.3	0.7
carbon fibre (6 layer)	4	0.001	1	208.6	0.2	0	65.97	0.5	0	20.86	1.7	0	6.597	5.3	2.4
nickel spray (on card)	0.001	0.1	100	2.09	0.0	0	0.66	0.1	0	0.21	0.4	0	0.066	1.3	0.6
aluminium	2	0.6	1	8.52	2.0	1.5	2.69	6.5	13.1	0.85	20.4	27.9	0.269	64.5	>26
aluminium grid	1	0.3	1	12.04	0.7	0.1	3.81	2.3	1.4	1.20	7.2	11.9	0.381	22.8	21.7
nickel fibre (40gsm)	0.5	0.001	10	65.97	0.1	0	20.86	0.2	0	6.60	0.7	0	2.086	2.1	0.3

Table 2: Screening comparisons

Notes: the conductivity is relative to that of copper; permeability and conductivity for non uniform conductors (ie nickel spray, nickel fibre and carbon fibre are estimates as these are not standard materials). The conductivity of the aluminium grid is reduced to account for the holes in the material

The measurements made on coupling between two coils at frequencies up 100 kHz demonstrate that at 100Hz the only materials tested which gave any attenuation was the mild steel. By 1 kHz good conductors such as aluminium and brass also give some attenuation. Brass is an expensive metal and its physical properties probably also make it unsuitable for use in a vehicle. Aluminium is also relatively expensive compared to mild steel although it is relatively light and with a strong subframe might be suitable for this purpose. Carbon fibre does not give any worthwhile screening at these frequencies. The samples tested are only starting to give some attenuation at 100 kHz. Likewise the spray on materials (such as nickel) and non woven conductive materials do not give any significant screening to low frequency magnetic fields.

3.8.6.3 Enclosures

At these low frequencies the contact between any lid and the body of the enclosure has little effect on the shielding. A 30cm brass cube gives as high shielding at frequencies below 10 kHz without the lid as with the lid. At higher frequencies any gaps between the lid and box can allow fields to propagate into (or out of) the enclosure. This can be observed in the measurement made at 100 kHz. Good electrical contact is required to give the highest level of screening at higher frequencies with slot length (eg between screws) being less than a quarter of a wavelength long.

The measurements on the aluminium grid demonstrate that an array of small holes has little effect on the screening at lower frequencies where the holes are small. If the array is large (as with the sample tested) the major effect of the holes will be to reduce the bulk conductivity of the material which may reduce any eddy currents induced in the material if the source is located close (and hence reduce the screening effect compared to material without holes).

3.8.6.4 Cables

At lower frequencies the dominant coupling between cables (or emissions via cables) is associated with inductive (or magnetic field) effects. It is important, therefore, that any shield is bonded to a return (or earth) at both ends.

At low frequencies where the cables are electrically short, the effects associated with shield structure, coverage and termination construction are substantially lower than at high frequencies. In these cases the conductivity of the shield material has the greatest effect on the level of shielding achieved.

4. Mitigation techniques for power train installation

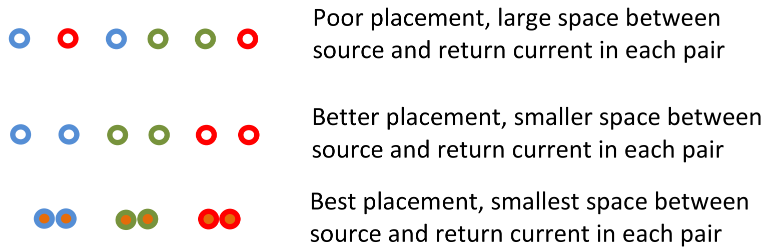
Current EMC mitigation techniques used in vehicles will be from threats from either electric fields (generated by the high voltage ignition system) or against higher frequency signals which are generated by the external environment (e.g. communications and systems). These are relatively easily screened using conducting enclosures, with signal pickup in lower frequency circuits being reduced with capacitors. Low frequency magnetic fields generated by the power train are more difficult to screen and the lower frequency signals are less easily decoupled using capacitors. The techniques discussed here will therefore be specific to the low frequency magnetic source. Existing techniques may still be required (e.g. for screening against electric fields generated by the ignition systems of range extenders).

4.1 Reduce at source

Magnetic fields are generated by currents flowing along a cable. The orientation of the field is determined by the direction of the current flow. Very close to the source (a single current element) the magnitude of the field falls with the square of the distance from the source. This means that the magnetic fields from a current which flows along one cable and returns down a second cable some distance away do not cancel each other out perfectly, with the magnitude of the resulting magnetic field depending on the separation of the cables). When a small current loop is considered, the magnetic field falls in proportion to the cube of the distance from the loop for small distances. In reality the conductors between the drive and motor are neither and the field pattern is more complex with the rate of fall at different distances depending on the exact layout of the cables and motor.

The first mitigation is to reduce the magnitude of the field being generated by reducing the area of the loops. This can be done by reducing the cable length (e.g. by mounting the inverter as close to the motor as possible) and by reducing the space between the current carrying conductors. Normally this is carried out by running the conductors in one cable with minimum spacing between the wires. The cable may then be screened if required to reduce higher frequency emissions. However, the currents required to deliver the power an electric vehicle requires mean that the conductors are relatively large and stiff. Putting two or more of these conductors into a (screened) cable means that the resulting cable is difficult to handle and install in a limited space. The conductors also need to have sufficient separation to allow thermal dissipation within the available space which again makes the resulting cable larger and stiffer. Running the cables from the motor drive to the motor within a section of steel trunking with a cover will help to reduce the fields. The permeability of the steel will help to reduce the magnetic fields as well as the trunking acting as a shorted turn around the source. This trunking should not be replaced with carbon fibre which has a lower conductivity and a relative permeability of 1.

The general principle applies however many cables are involved. For instance, some types of motor might be driven using 3 pairs of cables where each pair carries the same current but in opposing directions, other motors might be wired such that there is a common reference along which the return current flows. In the former case each pair of cables should be run as close as possible together (see Figure 24), in the latter the cables should be arranged in a symmetrical pattern (such as a trefoil with the return in the centre, as shown in Figure 25). More in depth detail is available in Section 5.



Poor placement, large space between source and return current in each pair

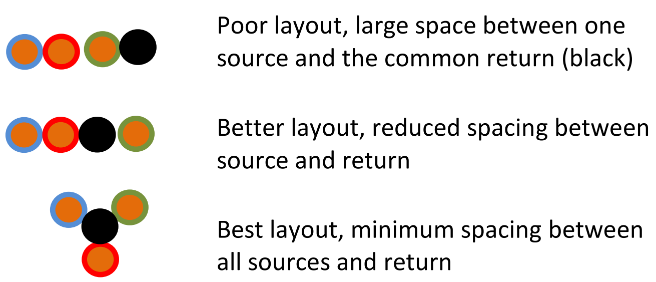
Better placement, smaller space between source and return current in each pair

Best placement, smallest space between source and return current in each pair

Figure 24: Poor and good layouts for 3 pairs of wires

Note that the two wires with the same colour are on the same circuit with currents flowing in opposite directions.

The common return might be omitted depending on how well balanced the currents are, a trefoil layout is best.



Poor layout, large space between one source and the common return (black)

Better layout, reduced spacing between source and return

Best layout, minimum spacing between all sources and return

Figure 25: Poor and good layouts for 3 wires with common return

In reducing the separation of the cables, it is also necessary to consider the separation of the motor and controller terminals to ensure that the loops at the ends of the cable runs are not larger than is necessary.

Reducing the magnetic fields at source will also help to reduce the potential problem of the magnetic fields generated by the electric vehicle interfering with roadside equipment (such as vehicle detection systems at traffic lights, and pedestrian crossings).

The connections between the batteries should not be ignored as these will generate a relatively high DC magnetic field if the loop formed by the connections and batteries is large. As with the AC magnetic fields the loop area should be minimised, particularly if it is situated adjacent to or just below the passenger cabin. Although the DC magnetic field is unlikely to induce any signal in any electronics within the vehicle there are some devices (satnavs or mobile phones) that may use the Earth’s magnetic field to determine their orientation. The steel structure of the vehicle itself can also interfere with this function, if sufficient steel is present. The load demands during driving may also mean that a large di/dt may be generated in the DC battery circuit e.g. switching from acceleration to regeneration modes.

4.2 Orientation

The coupling between the source and a victim circuit is proportional to the frequency and is determined by their relative orientations. A loop (that could be present on a circuit board) will have maximum pickup when the plane of the loop is perpendicular to the magnetic field. To minimise coupling orient loops (or circuit boards) so that the loop is aligned with the magnetic field (see Figure 26, and HEMIS Deliverable D7.1).

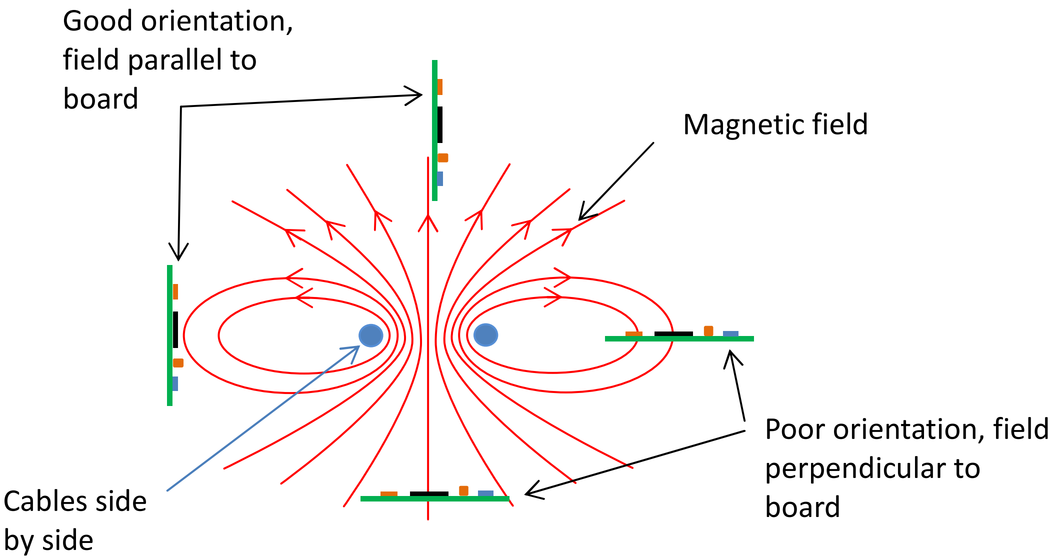


Figure 26: General magnetic field pattern around a pair of wires carrying currents in opposing directions, showing good and poor locations and orientations for circuit boards

4.3 Reduction of loop area of victim circuits

To minimise the pickup from a magnetic field by potential victim circuits (of which aspects of the inverter will be examples), the area of any loops on the circuit board should be minimised (see Figure 27). This can be done either by using multilayer circuit boards with a large area of ground plane or, at least, the tracks to individual device inputs/outputs being run above each other on opposite sides of the board.

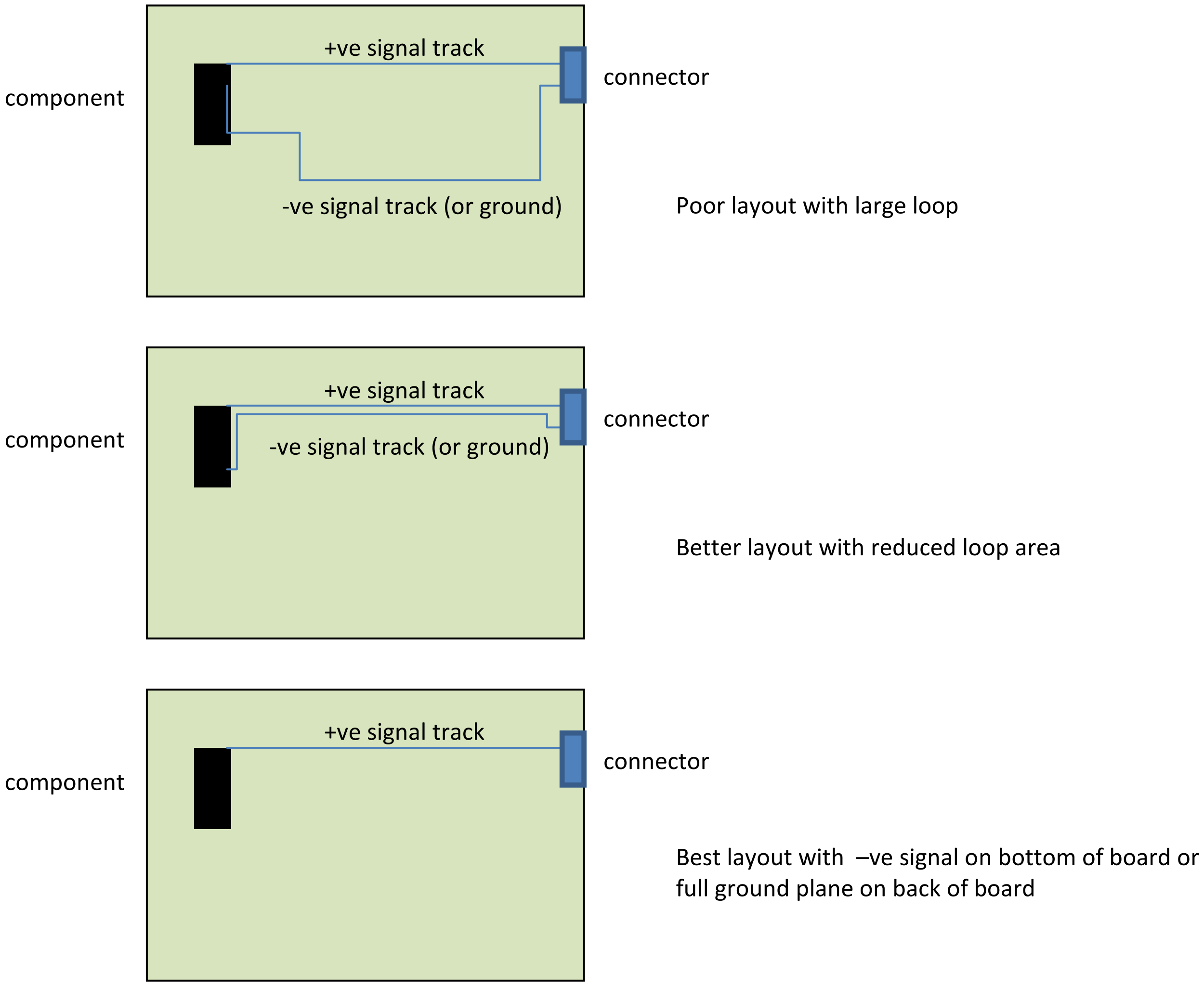


Figure 27: Poor, better and best track layouts on circuit boards

Place input devices/detectors at the edge of the circuit board with minimum length of track to connectors. If the circuit is likely to be susceptible, the cables to the input of the boards should be twisted pair wherever possible. The voltages generated within each loop of the twisted pair will have opposite polarity so will mostly cancel each other out (depending on the regularity of the twists). Depending on what the sensors/circuits are at the two ends of the cables it may be possible to filter (e.g. a high pass filter) or average the signals (for slowly changing inputs) over a period of time.

Modern vehicles often have light emitting diode (LED) lighting systems. The LEDs and associated circuitry can themselves be susceptible and can also rectify an AC signal that might be picked up on their own wiring loom. The LEDs and circuitry then generate a DC signal which can then cause incorrect operation of other devices (such as auto dimming lamps or automatic adjustment). Although the lamps themselves are generally at the extremities of the vehicle and as far from the power train as it is possible to get, the wiring to these devices is correspondingly long and can pick up a larger signal due to its length. It is therefore important for the cable to have as small a loop area as possible (for example, by twisting the wires) and ensuring that the twisted wire pair is run as far from the powertrain as possible.

4.4 Separation of power (threat) and control/low voltage (victim) circuits

Run wires to any devices which may be susceptible to the low frequency pickup as far from the source as possible (i.e. along the sides of the vehicle if the power cables are run along the centre of the vehicle). If wires have to cross each other, they should cross at right angles and any parallel element should then be as far from each other as possible. The following figures (Figure 28 and Figure 29) set out general design principles that should be followed.

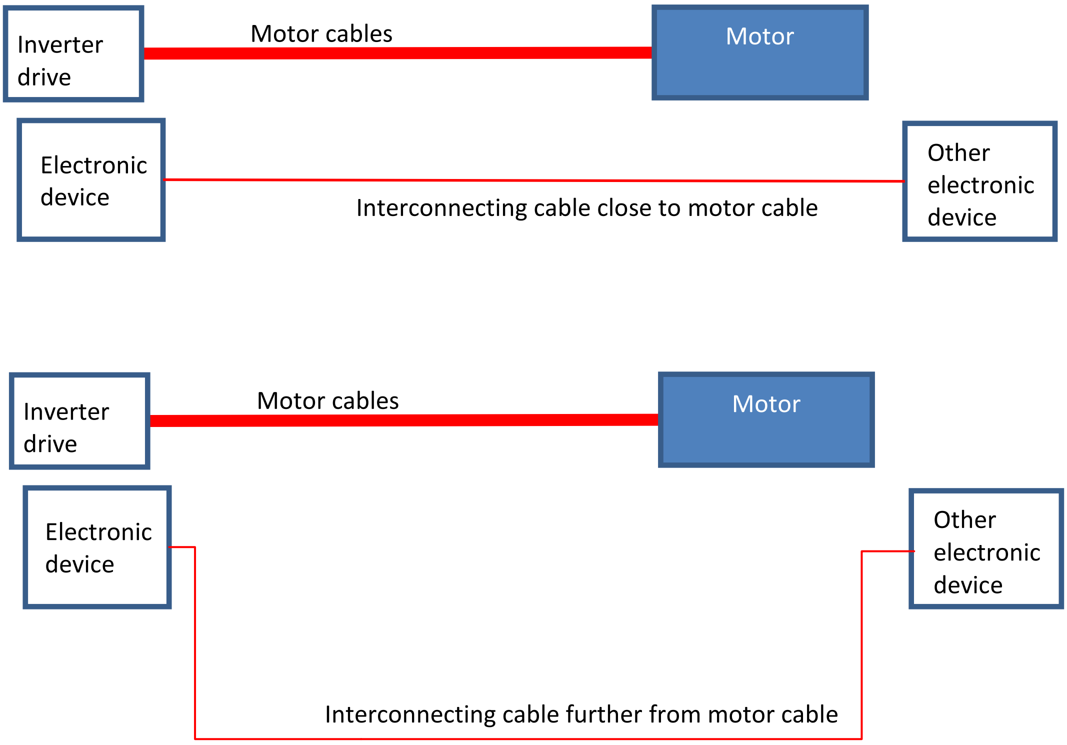


Figure 28: Parallel Cable run – the top diagram shows poor design and the bottom shows a better design.

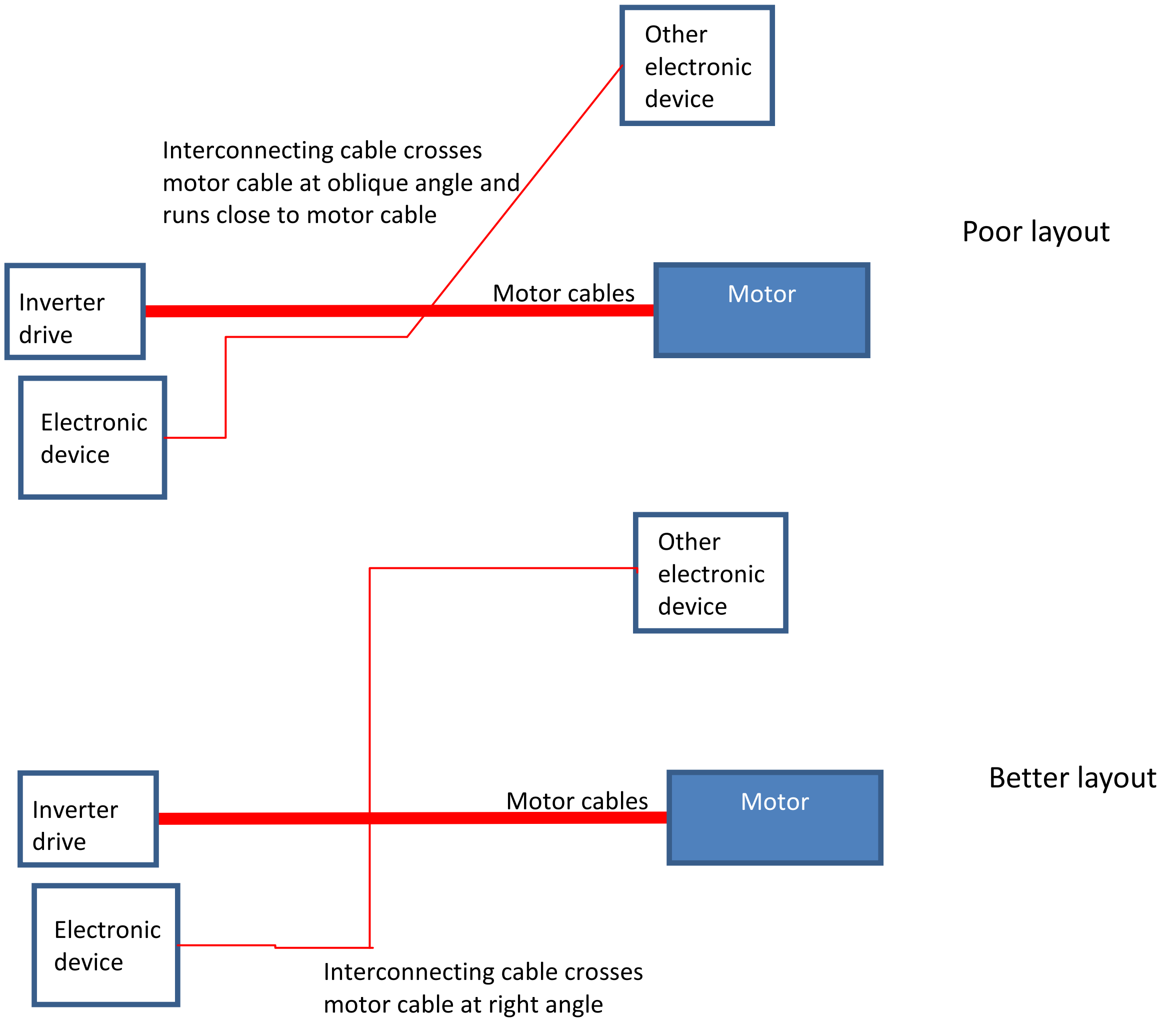


Figure 29: Poor and better routes for cables to cross each other

4.5 Cabling for multiple motor configurations

If the FEV is driven by multiple smaller motors (on each wheel or each axle) rather than a single larger motor, the cables to the motors should be arranged such that the cable to each motor is run in a star pattern from the controller/supply rather than in a daisy chain arrangement. This will reduce the currents on each section of the cables and hence reduce the field generated by each section.

5. Cable Configuration Considerations

For structures that are electrically small (relative to the wavelength), there is negligible phase variation and quasi-static approximations may be used to analyse their electromagnetic behaviour. To assess the magnetic field distribution around current carrying conductors, the current can then be assumed to be uniform at all points, allowing simpler models to be used. High voltage power cables in vehicles are unlikely to exceed the length of the vehicle, so the maximum is likely to be of the order of 5–10 m. For frequencies up to 100 kHz (motors are unlikely to be operated at frequencies this high) the wavelength is in excess of 3 km, so the quasi-static approximation is expected to be adequate over this frequency range.

The magnetic field due to a straight current filament of finite length at low frequency (under static and quasi-static conditions) can be obtained using the Biot-Savart law by integrating over appropriate limits. For an x-directed wire of length $2L$, centred on the origin of the coordinate system, the magnetic flux density $\mathbf{B}(\mathbf{r}, I, L)$ at a point $\mathbf{r}$ due to a current I is given by:

$$\mathbf{B}(\mathbf{r},I,L)=\frac{\mu_0 I}{4\pi\left[y^2+z^2\right]}\left\{\frac{L+x}{\sqrt{[L+x]^2+y^2+z^2}}+\frac{L-x}{\sqrt{[L-x]^2+y^2+z^2}}\right\}\left[-z\mathbf{y}+y\mathbf{z}\right] \quad \textbf{(Equation 4)}$$

where **x**, **y** and **z** represent unit vectors in the x, y and z directions, respectively. For an infinitely long current filament this reduces to:

$$\mathbf{B}_\infty(\mathbf{r},I)=\frac{\mu_0 I}{2\pi\left[y^2+z^2\right]}\left[-z\mathbf{y}+y\mathbf{z}\right] \quad \textbf{(Equation 5)}$$

The magnetic flux density due to a system of several such linear current elements (such as a straight single phase or three-phase cable bundle) can then be obtained by vector addition of their individual contributions at the point of interest.

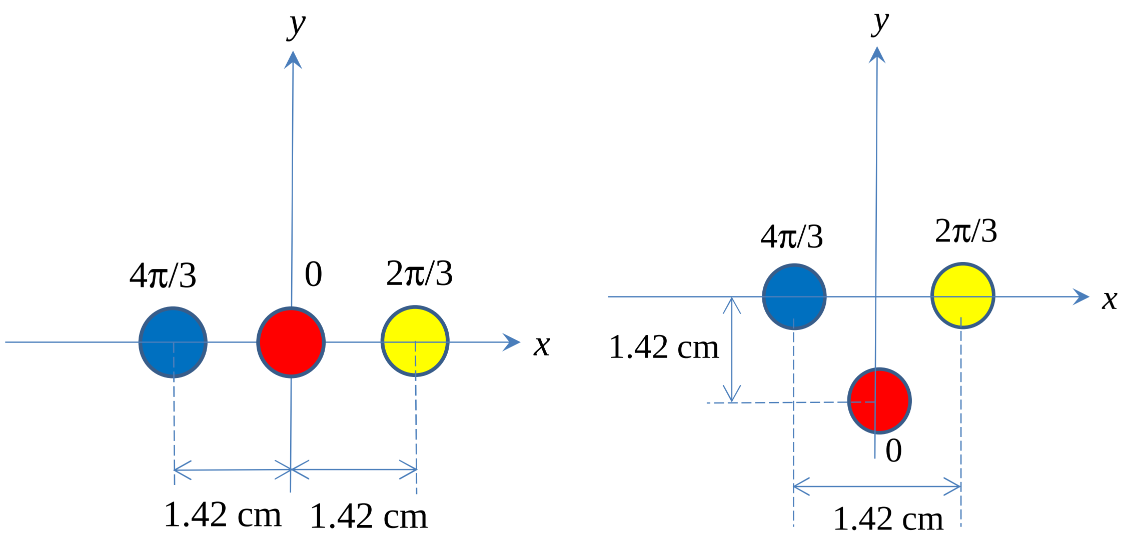
5.1 Three-phase cables

5.1.1 Untwisted three-phase cables

Three-phase high voltage power cables are commonly implemented in flat configurations in electric vehicles. In the Honda Insight, for example, a three-phase cable passes beneath the driver in order to link the electrical machine at the front of the vehicle with an inverter located with the traction battery in the rear of the vehicle. However, the trefoil configuration, in which the cable cores are located at the vertices of an equilateral triangle, is known to achieve lower stray magnetic field levels. In the three-phase cable it is assumed that the conductors carry currents with phases of 0, 2π/3 and 4π/3 radians, which are distributed as illustrated in Figure 31 for the purposes of illustration for flat and trefoil configurations.

The results of calculations carried out using both 3D numerical models and analytical methods (Tables 2–3) show excellent agreement between the 3D numerical model and the analytical models for finite length cables, while the analytical approximations based on infinitely long cables show good agreement with the finite length results at points that are closer to the cable path.

The results obtained for geometries that are representative of a cable passing through the transmission tunnel of a vehicle indicate that the trefoil arrangement produces lower stray magnetic field levels than an equivalent flat configuration. The maximum reduction achieved for the cases illustrated here is 54% in the vicinity of the ankle, which is the point with the highest field level in this case, falling to 21% at head height, where the field is lower.



(a) Flat configuration *(b) Trefoil configuration*

Figure 31: Three-phase cable – flat and trefoil configurations for comparison

Observation point	Observation point coordinates (mm)			Distance from cable axis (mm)	Net magnetic flux density (nT) at 1 A		
					Flux3D simulation	Analytical calculations	
	x	*y*	*z*			*Finite*[1]	*Infinite*[2]
Ankle	-762	-229	-522	235	135.51	135.5	129.6
Seat	25	-394	-386	403	44.46	44.47	42.26
Trunk	134	-374	-76	543	21.85	21.84	22.71
Head	241	-415	376	941	5.745	5.739	7.63

[1] For distances and angles as in Flux3D model

[2] For specified radial distances only

Table 3 Computed results for 1.96 m long cable in flat configuration with 1.42 cm spacing between current paths

Observation point	Observation point coordinates (mm)			Distance from cable axis (mm)	Net magnetic flux density (nT) at 1 A		
					Flux3D simulation	Analytical calculations	
	x	*y*	*z*			*Finite*[1]	*Infinite*[2]
Ankle	-762	-229	-522	235	88	88	89.12
Seat	25	-394	-386	403	29.99	29.95	30.29
Trunk	134	-374	-76	543	16.01	16	16.69
Head	241	-415	376	941	4.74	4.74	5.56

[1] For distances and angles as in Flux3D model

[2] For the specified radial distances only

Table 4: Computed results for 1.96 m long cable in trefoil configuration with 1.42 cm spacing between current paths

For a looser trefoil, with wider current separations, higher field levels are expected. In the example presented in Table 4, with a current spacing of 2.6 cm, the field levels are more like the flat configuration with 1.42 cm current separations.

Observation point	Observation point coordinates (mm)			Distance from cable axis (mm)	Net magnetic flux density (nT) at 1 A		
					Flux3D simulation	Analytical calculations	
	x	*y*	*z*			*Finite*[1]	*Infinite*[2]
Ankle	-762	-229	-522	235	161.08	159.4	163.4
Seat	25	-394	-386	403	56.29	55.27	55.49
Trunk	134	-374	-76	543	30.67	29.86	30.59
Head	241	-415	376	941	9.08	8.76	10.17

Table 5 Computed results for 1.96 m long cable in trefoil configuration with 2.6 cm spacing between current paths

For the straight trefoil configuration the magnetic field varies with angle around the current bundle depending on the proximity of the current filaments and the relative phases of the current that they represent. At sufficiently large distances, however, these effects become negligible and the radial and tangential field components become approximately equal. Thus, the field at large distances *R* from the cable axis can be approximated [13] using:

$$B_{S\_Far}(R) \approx \sqrt{\frac{3}{2}}\frac{\mu_0 Ia}{\pi R^2} \qquad \textbf{(Equation 6)}$$

where μ_0 is the permeability of free space and the individual current filaments are assumed to be mutually separated by a distance 2*a* and *I* is the current magnitude. This approximation is applicable for distances $R>>a$.

5.1.2 Twisted trefoil cables

The stray magnetic field levels of the trefoil configuration may be further reduced by twisting the cable such that the current paths follow three concentric helices. Analytical results for infinitely long cables suggest that very significant field improvements in field decay can be achieved as the twist pitch is reduced. For the twisted trefoil, the predicted asymptotic value is [13]

$$B_{T\_Far}(R) \approx \sqrt{3}\frac{\mu_0 \pi Ia}{R^2}\left(\frac{R}{p}\right)^{\frac{3}{2}} e^{-2\pi R/p} \qquad \textbf{(Equation 7)}$$

where *p* is the twist pitch length for a twisted trefoil with the individual current filaments separated by a distance 2*a* and *I* is the net current. This approximation is applicable for distances $R>>p$.

However, numerical Biot-Savart calculations on finite length twisted trefoils indicate that the expected benefits may not be achieved for cables that are short relative to the pitch length, and not at all distances for longer cables [13].

In order to determine the magnetic field distribution for a twisted trefoil of finite length the paths of the three helices were approximated using a sufficiently large number of short (linear) segments in order to achieve convergence when the Biot-Savart law was applied to calculate their individual contributions to the total field. The magnetic flux density contribution $\mathbf{bi}_{m,k}$ at a field observation point $\mathbf{Q}_k$ due to the m^{th} segment of helix *i* is:

$$\mathbf{bi}_{m,k} \cong \frac{\mu_0 sI \exp(j\phi_i)}{4\pi} \frac{\mathbf{vi}_m \times (\mathbf{Q}_k - \mathbf{ri}_m)}{\left|\mathbf{Q}_k - \mathbf{ri}_m\right|^3} \qquad \textbf{(Equation 8)}$$

where s is the segment length, I is the current magnitude, ϕ_i is the phase of the current on helix i, $\mathbf{vi}_m$ is the direction vector for the centre of segment m of helix i, and $\mathbf{ri}_m$ is the position vector for the centre of segment m of helix i, with $i \in \{1,2,3\}$ for a trefoil (comprising three cores). The total field is then assembled by summing the contributions over all segments of the helices.

These calculations indicate that the field close to a twisted trefoil is approximately the same as for the straight trefoil, and shorter pitch lengths give a more rapid decay rate. For short cables, with only a few twists, the enhanced decay rate expected for an infinitely long cable is not achieved, although the field is lower than that expected for the straight trefoil (see Figure 32 for 20cm twist, and Figure 33 for 6.6cm twist). For longer cables, with more than ~10 twists, the theoretical enhanced decay rate is achieved, but the distance that this effect persists is limited, depending on the trefoil radius, twist pitch, cable length, and position along the cable (see Figure 34– Figure 37). Very short cables with lengths that are comparable to the twist pitch are unlikely to yield much yield mitigation.

The results indicate that the field decay rate for twisted cables with odd-numbers of half-turns becomes like that of the straight trefoil at large distances (see Figure 38,Figure 39). For twisted cables with an even number of half-turns the field decay rate at large distances is more rapid than for the untwisted trefoil, but significantly lower than expected from theory for the infinitely long cable. However, having an even number of half-turns (i.e. an integer number of turns) appears to be an advantage.

However, as the magnetic field levels decay with distance from the cable, the fact that the enhanced field decay of longer twisted trefoils may not be maintained out to large distances may not be significantly detrimental to their use. For cables of the lengths and geometry that could be encountered in cars (i.e. ~1–5 m), the enhanced field decay rate due to twisting is expected to be achieved at distances of the order of 5–30 cm (depending on the length, twist pitch and cable cross-section). This could be sufficient to be of benefit for magnetic field mitigation in the close vicinity of high-voltage power cables in vehicles with electric powertrains.

Although the trefoil arrangement and twisting offer significant potential for reducing stray magnetic fields from traction currents, such cables are less flexible and may be more difficult to install in FEVs. Shorter twist pitches provide greater benefits over short distances, but such cable will be less flexible than those with a longer twist pitch. However, these disadvantages may be acceptable if this approach is more effective than other techniques that may be considered to achieve mitigation of low frequency magnetic fields due to traction currents.

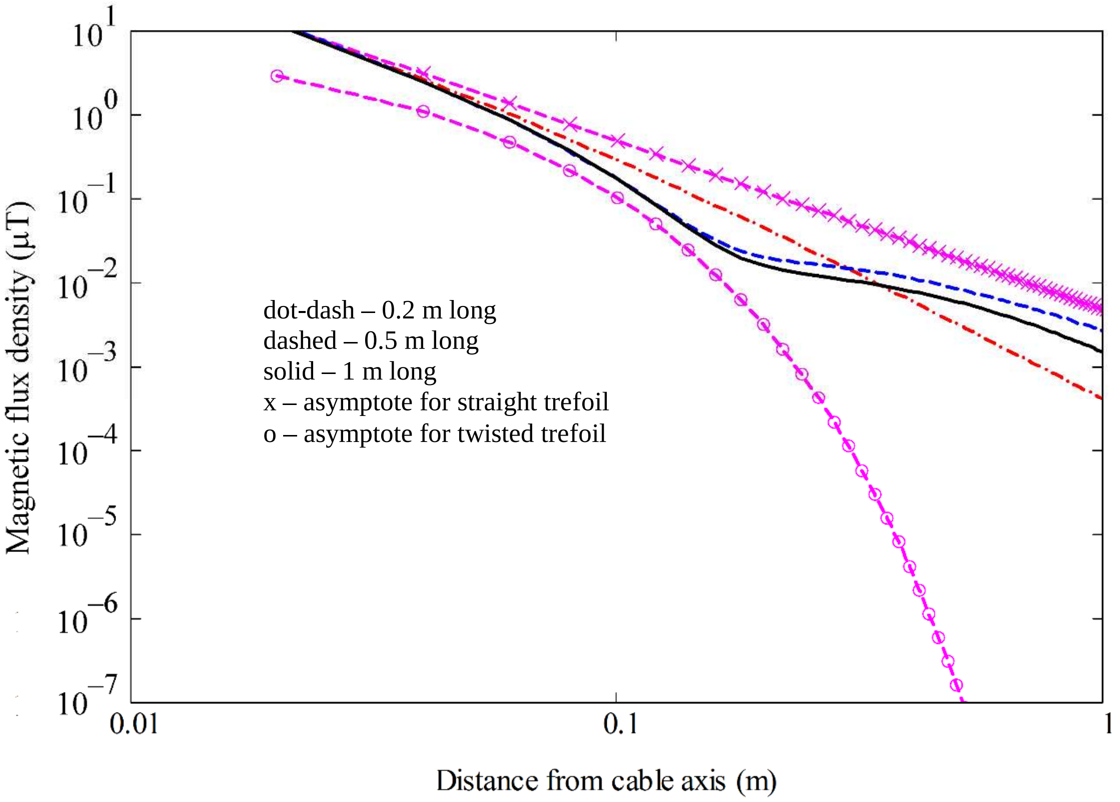


Figure 32 Computed magnetic field decay transverse to centre of twisted trefoil (20 cm pitch and 1 cm radius) at 1 A current: 0.2 m, 0.5 m and 1 m lengths

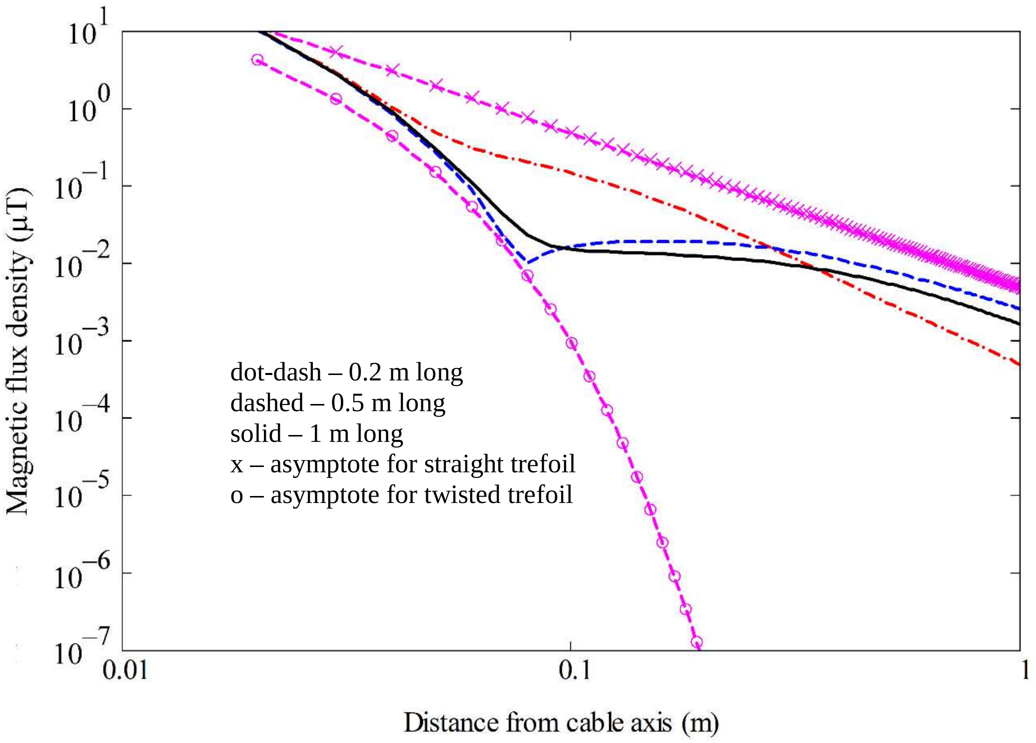


Figure 33 Computed magnetic field decay transverse to centre of twisted trefoil (6.6 cm pitch and 1 cm radius) at 1 A current: 0.2 m, 0.5 m and 1 m lengths

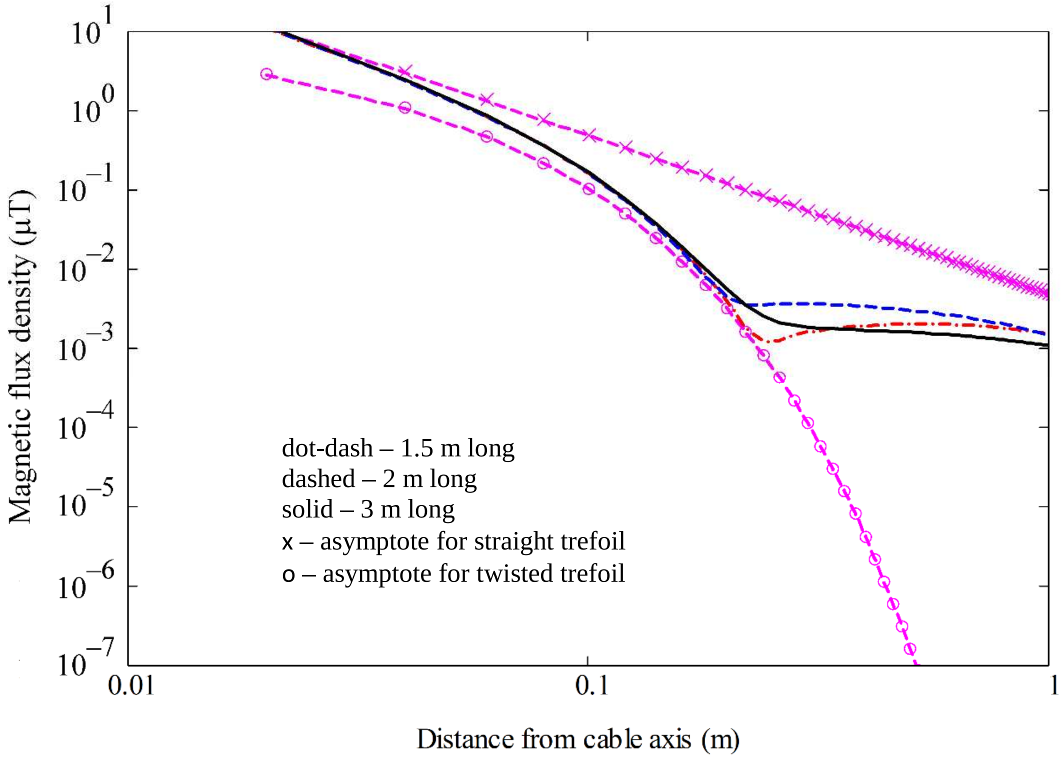


Figure 34: Computed magnetic field decay transverse to centre of twisted trefoil (20 cm pitch and 1 cm radius) at 1 A current: 1.5 m, 2 m and 3 m lengths

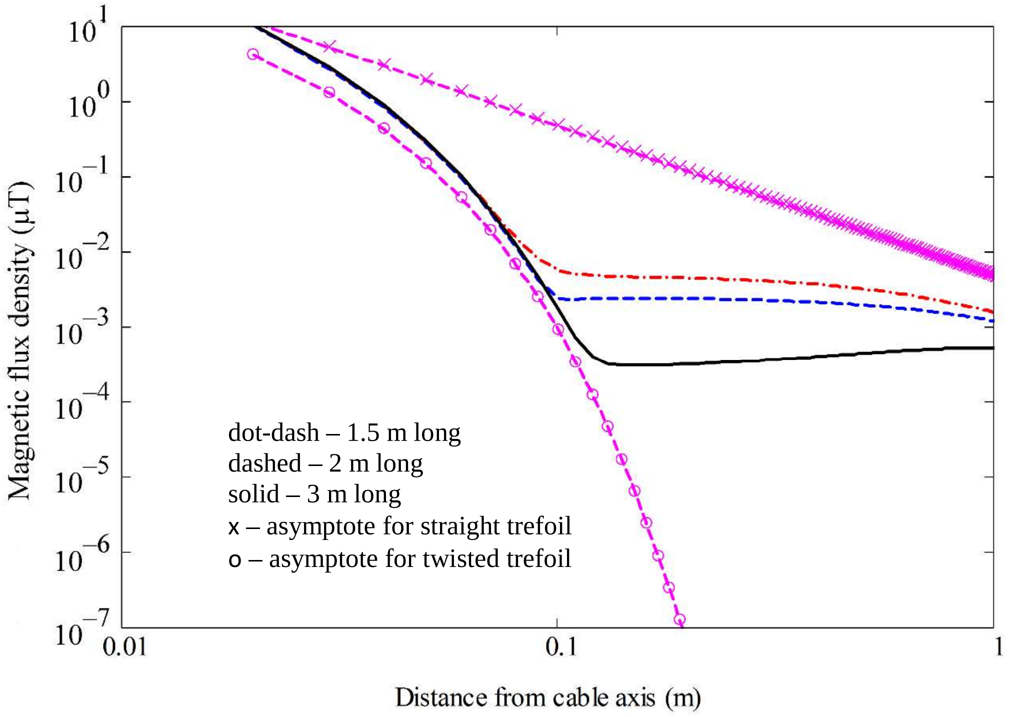


Figure 35: Computed magnetic field decay transverse to centre of twisted trefoil (6.6 cm pitch and 1 cm radius) at 1 A current: 1.5 m, 2 m and 3 m lengths

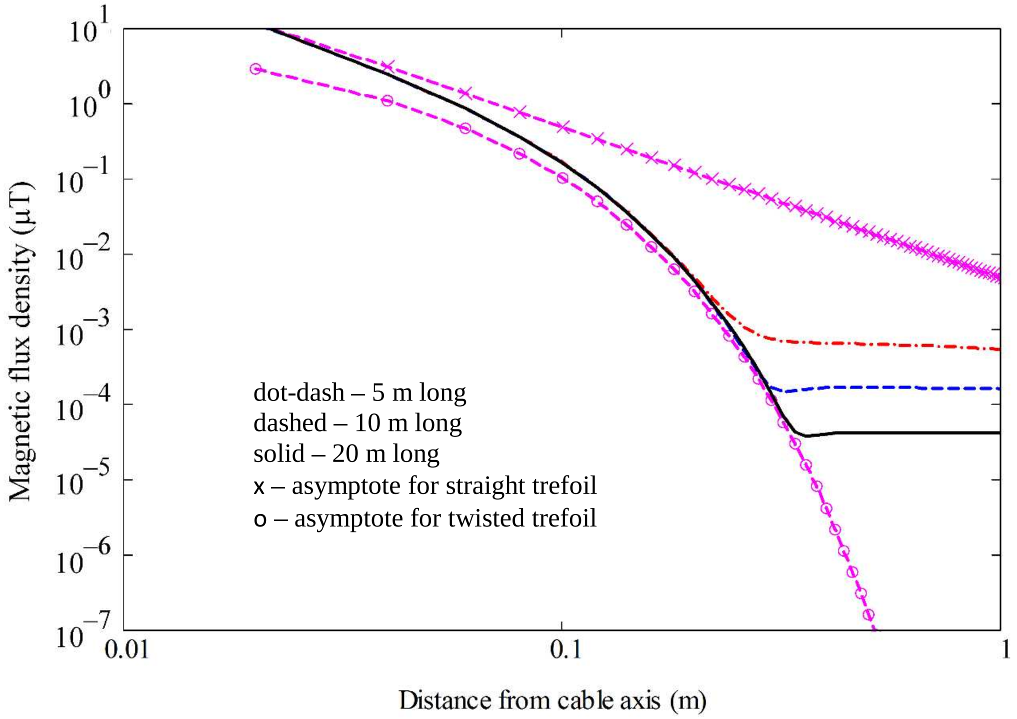


Figure 36: Computed magnetic field decay transverse to centre of twisted trefoil (20 cm pitch and 1 cm radius) at 1 A current: 5 m, 10 m and 20 m lengths

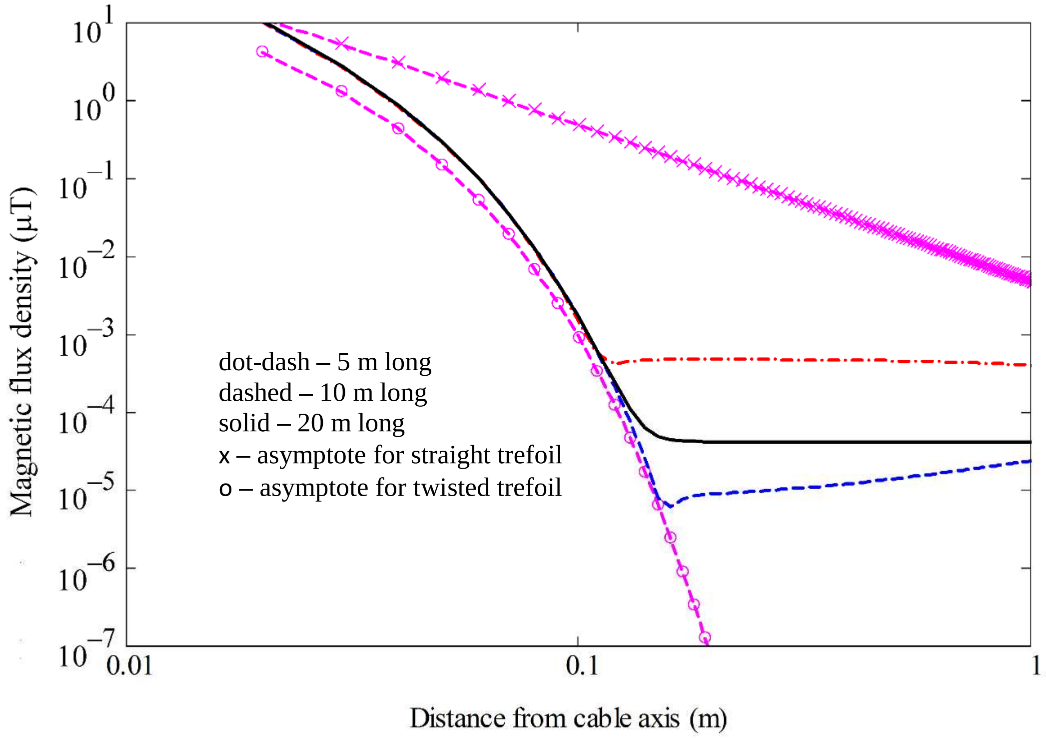


Figure 37 Computed magnetic field decay transverse to centre of twisted trefoil (6.6 cm pitch and 1 cm radius) at 1 A current: 5 m, 10 m and 20 m lengths

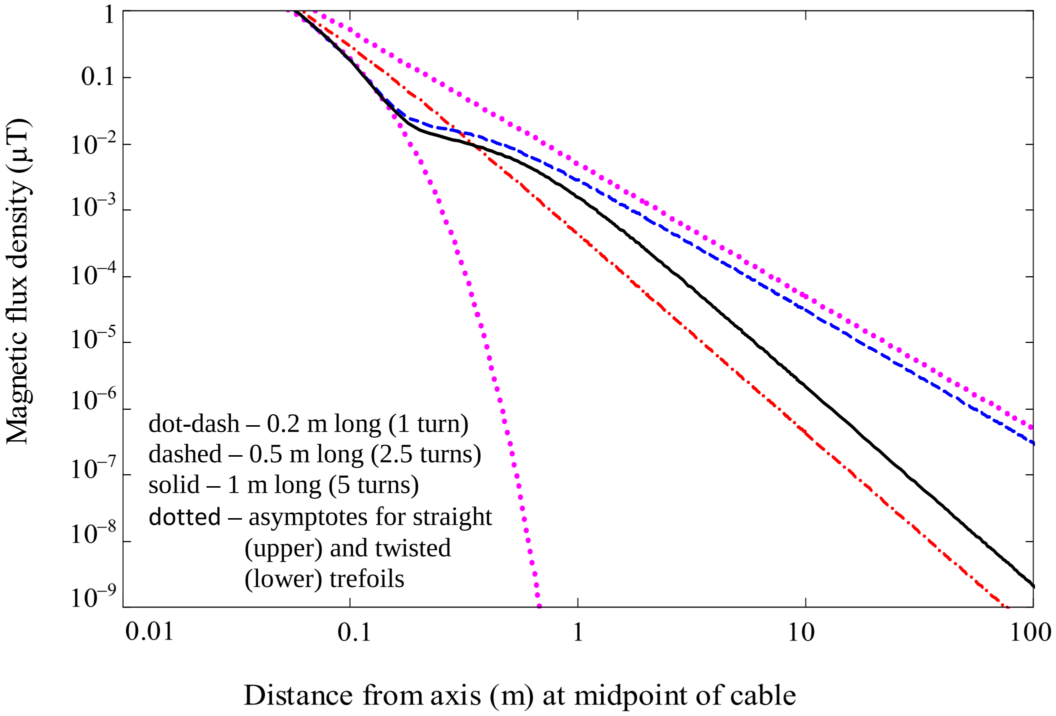


Figure 38: Computed magnetic field decay transverse to centre of twisted trefoil (20 cm pitch and 1 cm radius) at 1 A current: short cables, including lengths with non-integer turns, at large distances

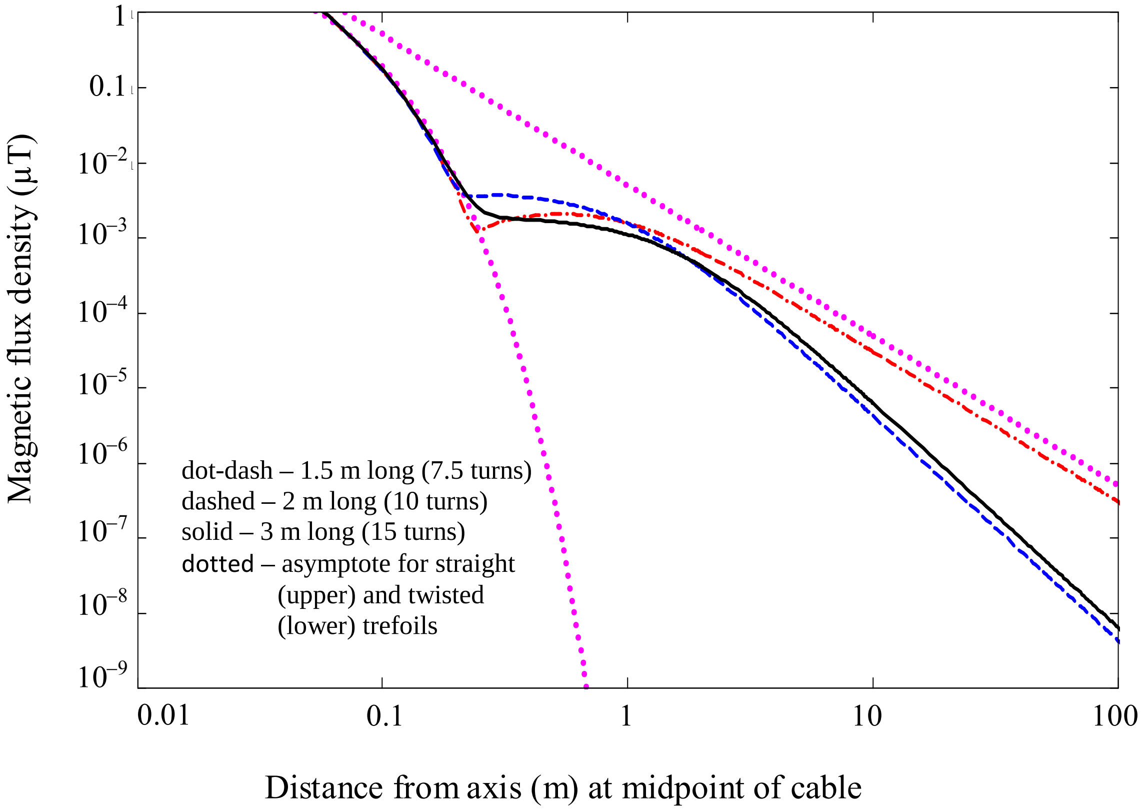
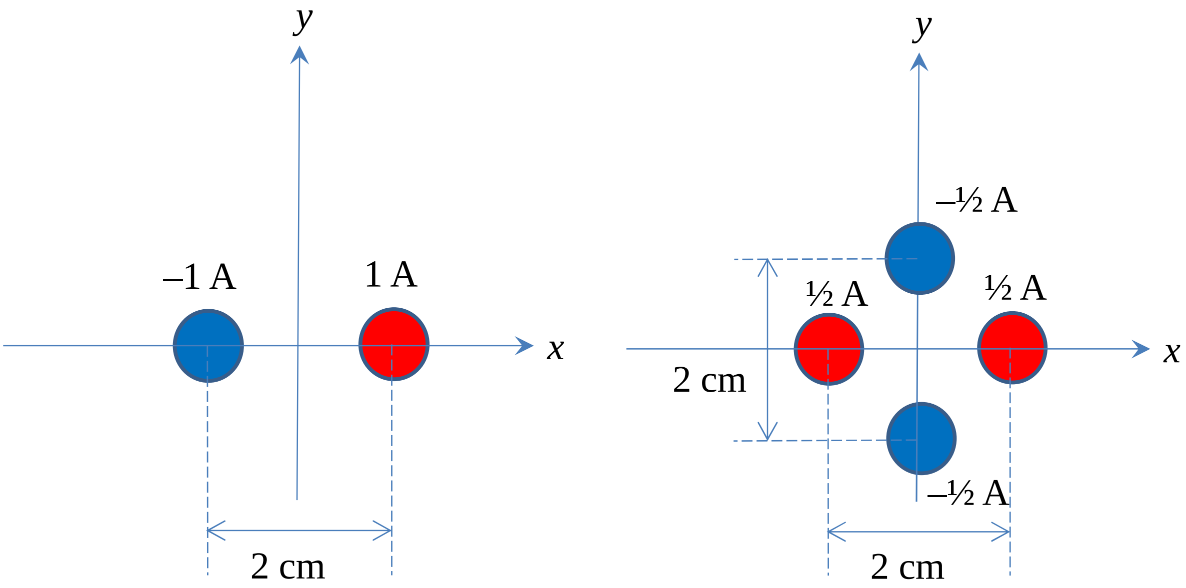


Figure 39: Computed magnetic field decay transverse to centre of twisted trefoil (20 cm pitch and 1 cm radius) at 1 A current: car-length cables, including lengths with non-integer turns, at large distances

5.2 Single-phase cables

Single-phase high voltage power cables are also often implemented in flat configurations in electric vehicles. In the Toyota Prius hybrid, for example, a single-phase cable passes beneath the driver in order to link the inverter, located with the electrical machine in the front of the vehicle, with the traction battery, which is located in the rear of the vehicle [14]. For single-phase cables, the stray magnetic field may be reduced splitting the currents and arranging them as shown in Figure 40 below. For the purposes of illustration it is assumed here that the currents are arranged on a 1 cm radius.



(a) Bifilar configuration **(b) Quadrifilar configuration**

Figure 40: Single-phase cable – bifilar and quadrifilar configurations for comparison

Twisting can also be used to further enhance the field decay rate of single-phase cables, although numerical Biot Savart calculations for cable lengths that might be expected in vehicles (see Figure 41–Figure 44) again predict similar behaviour to that seen for the three-phase case, where the enhanced decay is not maintained out to large distance for finite length cables.

The magnetic field decay rate of twisted bifilar cables with integer numbers of turns approach those of the corresponding straight bifilar cables at larger distances. However, for the bifilar case with an odd number of half-turns (see Figure 43) the predicted magnetic field at distances greater than 1 m is higher than for the straight cable. Thus, twisted bifilar cables with an integer number of turns again appear to offer an advantage. For the quadrifilar cases, the magnetic field decay rates of twisted cables with both even and odd numbers of half-turns become similar to those of the corresponding straight bifilar cables at larger distances.

Splitting the currents has a significant effect for the single-phase case, and is likely to be similarly beneficial for three-phase cables. However, these benefits are offset by increased complexity and component count. As with straight and twisted trefoils, the quadrifilar bundle is similarly less flexible and therefore more difficult to install in vehicles. Nonetheless, this may be justified if this is the best way to achieve mitigation of low frequency magnetic fields due to traction currents.

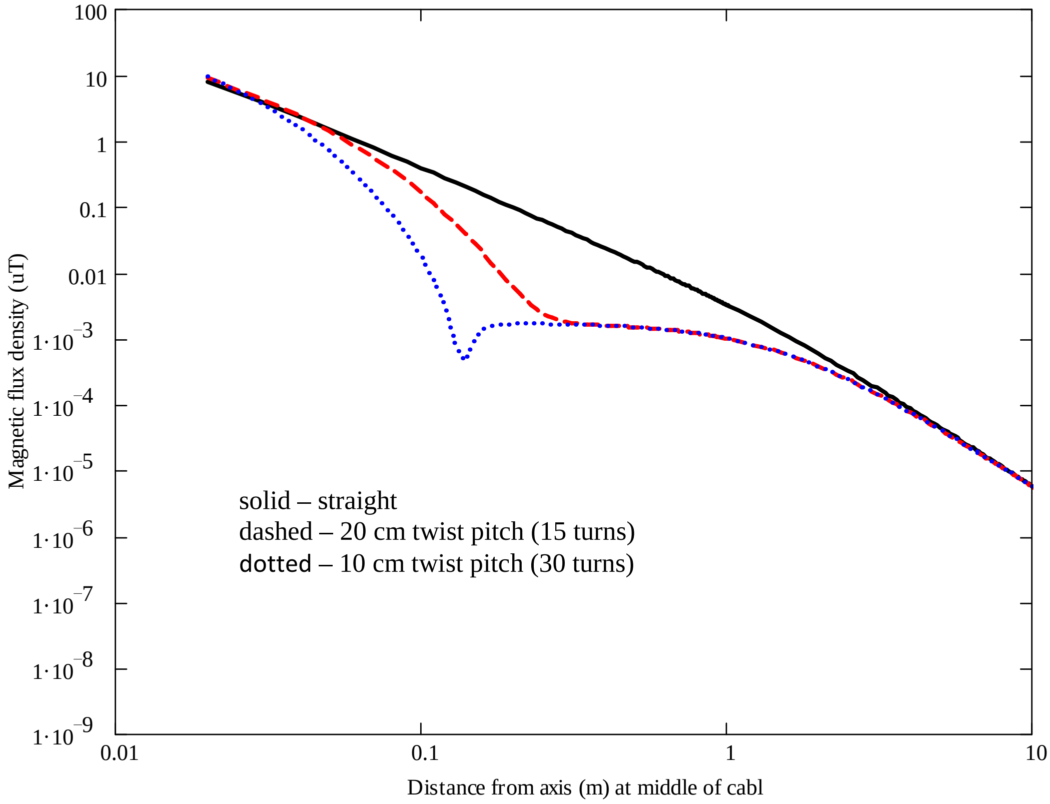


Figure 41: Computed magnetic field decay transverse to centre of 3 m bifilar single-phase cable (1 cm radius) at 1 A current: straight and twisted cases (integer numbers of turns)

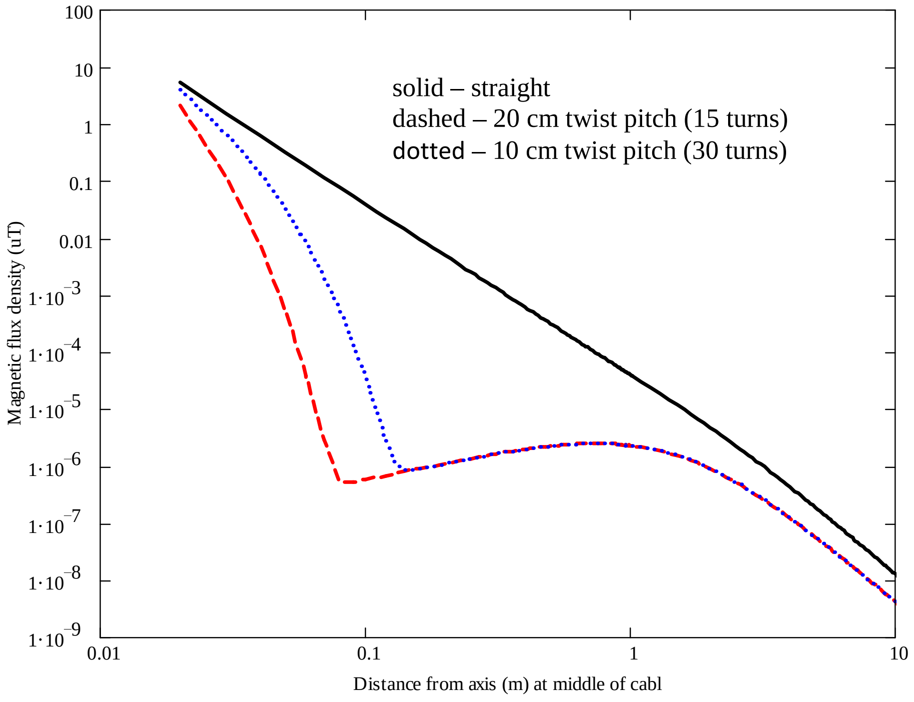


Figure 42: Computed magnetic field decay transverse to centre of 3 m quadrifilar single-phase cable (1 cm radius) at 1 A current: straight and twisted cases (integer numbers of turns)

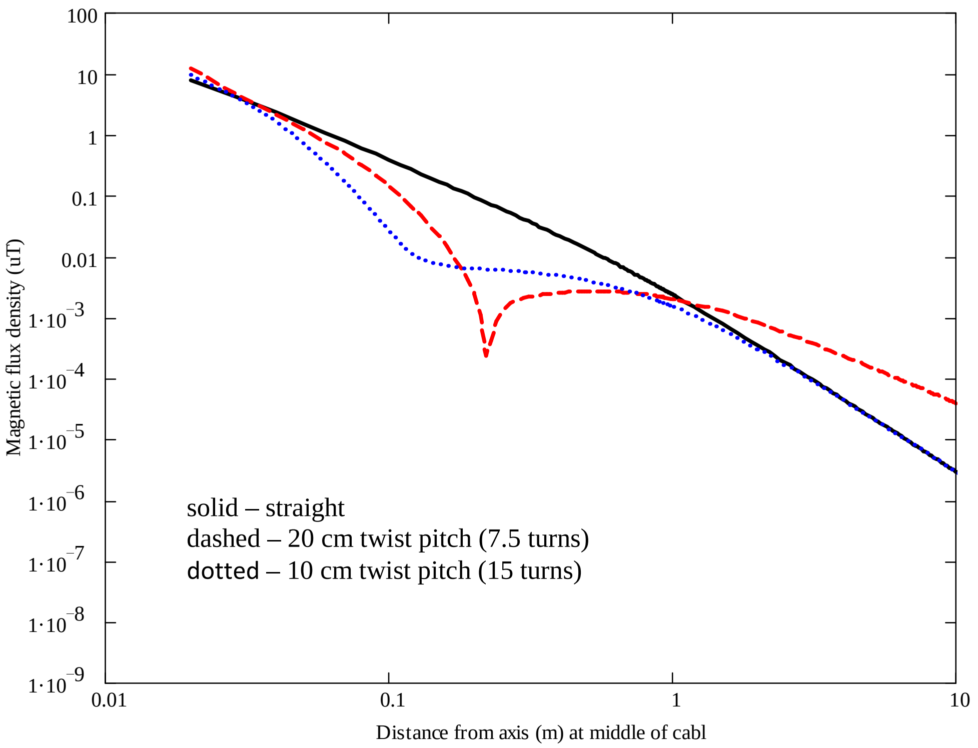


Figure 43: Computed magnetic field decay transverse to centre of 1.5 m bifilar single-phase cable (1 cm radius) at 1 A current: straight and twisted cases (integer and non-integer numbers of turns)

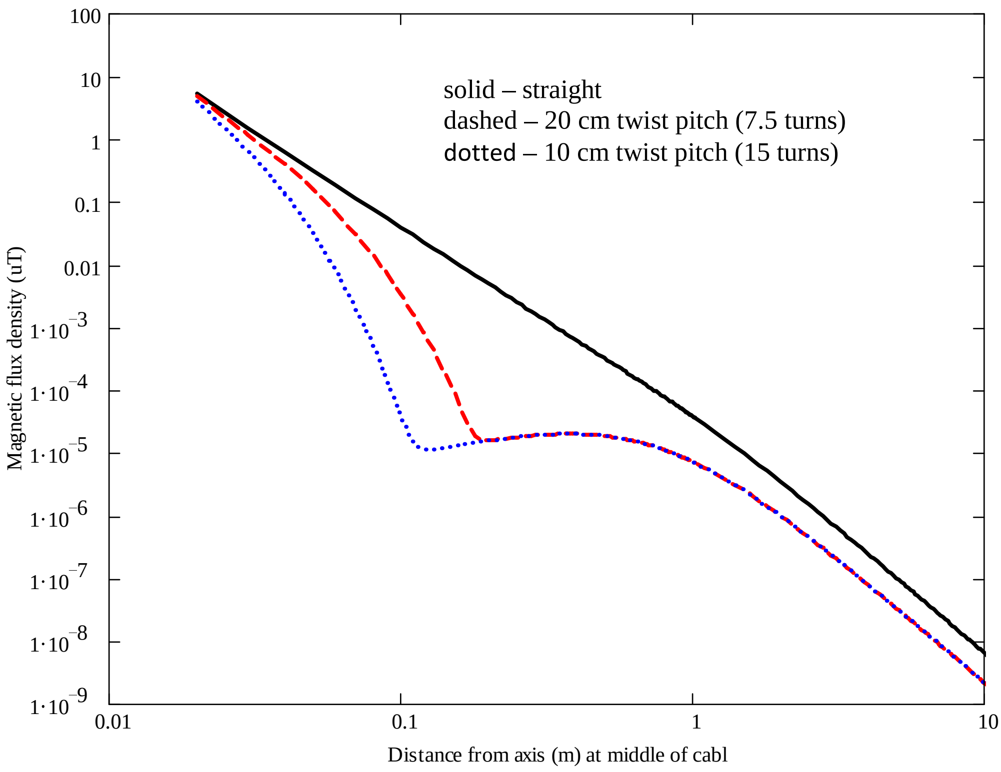


Figure 44: Computed magnetic field decay transverse to centre of 1.5 m quadrifilar single-phase cable (1 cm radius) at 1 A current: straight and twisted cases (integer and non-integer numbers of turns)

Conclusions

Considerations regarding good EMC practice are described in this deliverable. These cover considerations from circuit design to layout, shielding and installation practices which must be considered at the design stage to reduce the likelihood of EMC problems when the power train inverter is first installed in the vehicle. Redesign due to EMC problems which have not been considered at the design stage is always a more expensive option.

Particular consideration of the cables between the battery, inverter and motor assemblies has also been included. A study of the various cable layouts has been shown and the associated magnetic fields calculated. Also included are some ‘generic’ guidelines for the layout of the cables and the separation from other systems. It is worth noting that vehicle specific guidelines are not possible in the project timeframes due to the diversity employed in this sector (battery location, inverter location, cable runs and traction motor location being the main differences).

Although the trefoil cable arrangement and twisting offer significant potential for reducing stray magnetic fields from traction currents, such cables are less flexible and may be more difficult to install in vehicles. Shorter twist pitches provide greater benefits at short distances, but such cable will be less flexible than those with a longer twist pitch. However, these disadvantages may be acceptable if this approach is more effective than other techniques.

Splitting the currents has a significant effect for the single-phase case, and is likely to be similarly beneficial for three-phase cables. However, these benefits are offset by increased complexity and component count. As with straight and twisted trefoils, the quadrifilar bundle is similarly less flexible and therefore more difficult to install in vehicles. Nonetheless, this may be justified if this is the best way to achieve mitigation of low frequency magnetic fields due to traction currents.

A1. References

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