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EMI EMISSIONS
of MODERN PWM AC DRIVES

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Electromagnetic Interference (EMI) noise is defined as an unwanted electrical signal that produces undesirable effects in a control system, such as communication errors, degraded equipment performance and malfunction or non-operation. References on the general principles of EMI are available [1]-[3], as well as methodologies on calculating radiated emissions [4]. IEEE Standard 518 applied these principles to slow switching Silicon Controlled Rectifier (SCR) dc drives in 1982 [5]. All ac Pulse Width Modulation (PWM) drives have the potential to cause EMI with adjacent sensitive equipment, when large quantities of drives are assembled in a concentrated area [6]-[11]. However, faster switching speeds of new converter/inverter topologies require an updated study of new system EMI issues created.

Market studies show the quantity of Adjustable Speed Drive (ASD)-Motor combinations that are replacing traditional across the line 60 Hz motor applications is increasing yearly. As the proliferation of the industrial and residential drives industry continues, there will be a "critical EMI mass". At this juncture the sheer quantity of power electronic converter drives, combined with the ever more sophisticated communication, sensor and computer technology of the future, may reach unpredictable performance levels. A case in point is the Switch Mode Power Supply (SMPS) industry, which integrated the high frequency power electronic converters into the expanding Personal Computer (PC) computer industry. Federal Communications Commission (FCC) regulations on allowable EMI emissions became the "Defacto Standard" for all SMPS manufacturers wishing to sell product.

At present there is not a North American EMI Standard enforced for ASDs. There is a European CE standard proposed. Whether the proposed limits are too stringent for an industrial application needs to be discussed with general industry consensus. Without government regulations, industry standards, or non-operating penalties imposed, the EMI responsibility for large systems becomes one shared between user, integrator, and ASD manufacturer. This article provides a common understanding of the EMI issues and provides simple pre-installation and post installation guidelines useful for all interested parties involved in industry application of adjustable speed PWM ac drives.

What is Common Mode Noise?

Common Mode (CM) noise is a type of EMI noise induced on signals with respect to a reference ground. CM noise problems imply a *source of noise*, a *means of coupling noise* by conduction or radiation and *circuits / equipment susceptible* to the magnitude, frequency, and repetition rate of the noise impressed. Each aspect of the noise investigation is covered in detail, starting with the effect of CM noise on susceptible circuits.

Susceptible Equipment, Circuits & Systems

Fig. 1 shows potential CM noise issues increase with susceptible equipment present, high system-input voltage, large quantity of system drives, and long length of motor leads. Other factors are type of ground system and cabinet layout.

Susceptible equipment may be computer systems, communication links, ultrasonic sensors, weighing and temperature sensors, bar code/vision systems, and capacitive proximity or photoelectric sensors. Control interfaces include encoder feedback, 0-10 Vdc, and 4-20 mA signals. Past experience has shown unknown conducted noise in the plant ground grid as the predominant EMI issue for susceptible equipment. Past experience has shown equipment susceptible to ASD radiated noise has solely been confined to AM radio

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reception in the Radio Frequency (RF) band of 535 kHz to 1.7 MHz. This is because the drive output voltage transition time and typical conducted noise oscillation frequency is mostly concentrated in the AM band.

Fig. 1 risk factors are briefly discussed as they are covered in more detail throughout the article. Higher system ac line voltages have higher dc bus voltages (V_{bus}). The higher output switching *dv/dt* (change in voltage with time) increases peak CM ground current (i = Cstray $*$ *dv/dt)*. Increasing drive quantity increases the sum total of transient CM noise current to ground. Higher drive carrier frequency (f_C), increases the number of switch transitions and sum total of CM noise current. Motor cable lengths < 20 ft (6.5m) exhibit low cable line to ground capacitance and low CM noise risk from capacitive *dv/dt* ground currents. As cable lengths increase, cable capacitance increases and CM charging current to ground increases. At long cable lengths, the high frequency oscillations of reflected wave voltage transients (~2 V_{bus}) also appear on motor terminals, to create CM ground noise current through the stator winding and cable capacitance [8]. EMI mitigation must also involve a discussion of safety equipment ground, signal grounding and the effect of grounding system type on CM noise.

The main topics of discussion are segmented into the following sections.

- **GENERATION OF EMI**
- **EMI COUPLING MECHANISMS**
- **MITIGATION OF EMI**
- **EFFECT OF EMI ON EQUIPMENT**
- **MODELING OF EMI**
- **EMI STANDARDS AND TEST METHODS**

GENERATION OF EMI

This section determines the noise frequency characteristic of the normal mode and common mode voltage at the ASD output. It shows why these voltages may be viewed as EMI noise generators and how they couple EMI into an industrial application. The following topics are covered in detail.

- ***ASD Normal Mode Output Voltage***
- ***ASD Common Mode Noise Current Path***
- ***Common Mode Voltage as EMI Noise Source***
- ***Frequency Characteristics of Noise Source***

ASD Normal Mode Output Voltage

Fig. 2 shows a typical ASD line-to-line output voltage waveform (V_{uv}) consisting of a series of pulses controlled by a PWM with peak pulse voltage equal to (V_{bus}). Pulse width (τ) and dwell time at zero are PWM controlled so a fundamental sinewave output voltage component at a desired variable output frequency (f_o) is obtained. Pulse spacing is controlled to maintain a constant Volts per Hertz (V/Hz) ratio (460V @ 60 Hz or 7.6 V/Hz) to maximize torque production over the output frequency range.

Pulse rise and fall time between pulses of Fig. 2 is further detailed in Fig. 3. Abrupt output voltage transitions are dictated by ASD semiconductor switching times. Present generation ASDs use Insulated Gate Bipolar Transistors (IGBT) semiconductors with rise/fall times t_{rise} < 200 ns and are inherent sources of radiated and conducted EMI. Pulse repetition rate is called carrier frequency (f_c) and for IGBT ASDs is user selectable with f_c = 1-2 kHz on high hp drives and f_c over 12 kHz possible on low hp drives.

Fig. 4 shows a simplified representation of a drive, output conduit and motor system. Line-to-line output voltage waveform of Fig. 2 applied to the motor and power leads in the conduit will result in (I_{motor}) phase current. The I_{motor} waveform consists of four components. A sinewave current component at the fundamental operating frequency selected, ripple current due to the carrier frequency selected, a transient line-to-line cable charge current (I_{ll}) during the *dv/dt* voltage transition and a line-to-ground transient current (I_{lg}) during the *dv/dt* voltage transition. The I_{motor} waveform in Fig. 5 is for a 2 hp motor load and shows that I_{ll} and I_{lg} transient current spikes may be higher than the fundamental current.

Transient line-to-line cable charge current is determined by the bus voltage magnitude and surge impedance of the cable parameters around the loop, such as cable resistance (R_{o1}), self inductance (L_{o1}), line-to line capacitance (C_{ll}), (R_{o2}) and (L_{o2}). I_{ll} is confined to the drive terminals and cable loop area shown in Fig. 4. As such it does not interfere with other plant equipment, other than possible radiated noise from the power leads. However, transient I_{ll} current may reach 12 Apk and become problems for small hp drives and the current sensors used within them.

Transient line-to-ground current in Fig. 4 is determined by the bus voltage magnitude and surge impedance of the cable parameters around the loop, such as R_{o1}, L_{o1}, line-to-Power Equipment (PE) ground wire capacitance (C_{lg}), line-to-conduit ground capacitance (C_{lg-c}), and motor stator winding capacitance to ground (C_{lg-m}). I_{lg} is sourced from drive output terminals but does not have a return path directly back to the output terminals in Fig. 4. As such it can interfere with other plant equipment referenced to ground. A current probe (CT) encircling ASD output (U,V,W) wires in Fig. 4 would normally measure zero current, since the instantaneous sum of the fundamental frequency components of each phase sum to zero. Also the I_{ll} component sums to zero, since it is sourced and returned through the same current probe window, but in opposite current polarity directions. However, the current probe placement described does measure the transient I_{lg} waveform that occurs during every *dv/dt* edge of Fig. 2 and Fig. 3. I_{lg} is sometimes called zero sequence current or Common Mode (CM) current. Transient I_{lg} current may reach 20 Apk and is a predominant EMI generator.

ASD Common Mode Noise Current Path

Fig. 6 is a detailed representation of the transient I_{lg} current path in a solidly grounded ASD system. Transformer secondary (A,B,C) is connected to ASD (R,S,T) ac input. An ASD input diode bridge converts the ac input voltage to a dc bus voltage (V_{bus}). The ASD uses six IGBTs semiconductor switches to connect V_{dc_bus} to the line-to-line (U,V,W) output terminals. The motor frame is grounded to a plant ground grid at *Potential #3* and a motor *Power Equipment (PE)* ground wire is also connected back to ASD PE frame ground and plant grid ground at *Potential #1*. The typical ASD system of Fig. 6 is earth grounded at a steel girder or ground rod arrangement at *Potential #4*, where the transformer neutral is solidly grounded.

Transient line-to-ground capacitive current I_{lg} is sourced from the ASD U, V or W outputs of Fig. 6 during every *dv/dt* pulse edge of Fig. 3. The *dv/dt* magnitude ($\sim V_{dc\_bus} / t_{rise}$) is between 5,000 V/µs to 15,000 V/µs, depending on system voltage and IGBT risetime (t_{rise}). Two I_{lg} system paths exist in Fig. 6, one through line-to-ground cable capacitance ($C_{lg\text{-}c}$) and another through line-to-ground capacitance ($C_{lg\text{-}m}$) of the motor stator winding. Since the line-to-ground system impedance is predominantly capacitive, then I_{lg} magnitude in general terms is proportional to $I_{lg} \sim (C_{lg\text{-}c} + C_{lg\text{-}m})(dv/dt)$. Thus, I_{lg} magnitudes are highest for:

- ASDs with long output cables ($C_{lg\text{-}c}$ is greater)
- High hp ASD with higher motor capacitance ($C_{lg\text{-}m}$ is greater)
- ASDs with faster output voltage risetimes (*dv/dt* is greater)
- ASDs with higher system voltages (*dv/dt* is greater)

The rms magnitude of I_{lg} CM noise current increases with higher carrier frequency selected, since the repetition rate in Fig. 3 is faster. Higher quantities of ASD may increase the rms magnitude of CM noise and EMI, due to increased I_{lg} in the ground circuit.

I_{lg} current returns to ASD ground *Potential #1* either by the PE ground wire or through the motor-ASD ground grid, depending on which is the lower impedance at the I_{lg} transient oscillation frequency. No physical connection exists between PE ground *Potential #1* and the ASD dc bus. Thus, the only remaining path to complete the I_{lg} route back to the ASD is through the feeder transformer neutral and drive input phase wires (R,S,T).

Fig. 6 is a possible wiring installation that might have been implemented with previous generation ASD drives in which the 3 output wires or unshielded tray cable were randomly laid in cable tray. National Electric Code (NEC) motor grounding requirements were met with a separate wire taken to the closest ground pole of the plant ground grid. Due to the slower switching speed of the Bipolar Junction Transistors (BJTs) in previous ASDs, the system may not have had a system ground noise problem. However, the output *dv/dt* of the new IGBT drive technology is *10* to *20* times greater and will capacitively couple greater noise current magnitudes into the ground grid. The motor ground wire as shown in Fig.6 permits noise current to flow into and across the full ground grid. Fig. 6 shows the CM noise voltage developed in the ground grid elevates drive logic ground *Potential #1* from building steel ground *Potential #4.* Thus, this wiring method is not recommended for new installations, since drive interface signals to susceptible equipment, which is grounded at a quieter True Earth (TE) Ground *Potential #4*, will see a CM voltage impressed on it and may malfunction.

Common Mode Voltage as EMI Noise Source

A convenient way of investigating all three ASD line-to-ground outputs simultaneously is by establishing a *virtual neutral* reference node to ground (V_{ng}). V_{ng} voltage in Fig. 6 is the voltage generator behind the I_{lg} current sourced from the ASD and is measured from a wye connected node of three 1 Meg-ohm resistors to ground. As seen in Fig. 7**,** the V_{ng} waveform is comprised of a low frequency 180 Hz amplitude modulated ripple component that is further modulated by the PWM high frequency switching. The (+) 180 Hz ripple waveform is due to the 3 pulse ripple voltage measured at the input diode bridge (+) terminal to true earth ground [12]. Likewise, (-) 180 Hz ripple is due to 3 pulse ripple voltage measured at the input diode bridge (-) terminal to ground.

Fig. 8 is a time-expanded scale of Fig. 7, showing the higher frequency, step-like, PWM voltage component. Fig. 8 I_{lg} current waveform is the combined zero sequence or common mode line-to-ground current from all ASD phases. The 8 Apk I_{lg} current spike of Fig. 8 is typical of systems using solidly grounded transformers. Exact calculation of I_{lg} magnitude is discussed in [13]. Although f_c = 4 kHz in Fig. 8, current spike repetition rate into the ground circuit is closer to 20 kHz, because every phase switching contributes line-to-ground current transients. Thus, I_{lg} repetition rate is estimated as 4 f_c to 6 f_c depending on PWM modulator duty cycle.

Zero sequence voltage can be generated from the eight basic switching states of a PWM modulator. The eight basic switching states of the zero sequence pattern result in the six zero sequence, or common mode, voltage levels. These six levels are demonstrated in Table 1 and Fig. 9. The states refer to the IGBT device switch states of ON (1=conducting) or OFF (0=blocking). There are three states with two phases tied to the positive bus and one phase tied to the negative bus. There are another three states with one phase tied to the positive bus and two phases tied to the negative bus. Lastly, there are two states that have all three phases tied together, one to the positive bus, and one to the negative bus. A majority of the states (six of the eight) have two phases tied together and voltage applied between them and the third phase. In the remaining two states all three phases are tied together.

The zero sequence switching states can be measured from the stator neutral point of the motor winding to frame ground. In most wye-configured motors, the true neutral point isn't available, while delta wound motors have no physically available neutral point. Therefore, the stator neutral point must be artificially duplicated, by connecting a wye-configured resistor network across the motor terminals. The center point is the artificial neutral, which will approximate the true neutral of the motor. The motor neutral voltage on a balanced 60 Hz utility sinewave system is near zero. The motor neutral on an ASD will not be zero but dynamic and described by the term "neutral shift voltage" [14]. Fig. 9 motor neutral waveform is determined by realizing upper IGBTs in an ON state have a drive output phase-to-ground value of (V_{bus} /2), assuming a virtual midpoint ground reference of the ASD dc bus voltage. Lower IGBTs in an ON state have a ASD output phase-to-ground value of (-V_{bus} /2). The resultant neutral-to-ground voltage of the wye resistor network for each of the given switching states is thus determined by using superposition of the phase-to-ground voltages applied to each impedance *R* of the three phase network. Thus, all three phases tied together at the positive dc bus rail have a neutral-to-ground voltage of (V_{bus} /2), while all three phases tied together at the negative dc bus rail have a neutral-to-ground voltage of (-V_{bus} /2). Associated intermediate states have values of plus / minus (V_{bus} /6).

Table 1. Zero Sequence Switching Pattern

Upper IGBT Switching Pattern			*Common Mode Voltage*
U	**V**	**W**	
0	0	0	**- Vbus / 2**
0	0	1	**- Vbus / 6**
0	1	1	**Vbus / 6**
0	1	0	**- Vbus / 6**
1	1	0	**Vbus / 6**
1	0	0	**- Vbus / 6**
1	0	1	**Vbus / 6**
1	1	1	**Vbus / 2**

Frequency Characteristics of Noise Source

Frequency characteristics of the DM voltage spectrum are shown in Fig. 10 for a 50% duty cycle in Fig. 3 with a f_c = 500 Hz and pulse risetime = 200 ns. The spectrum is normalized to the dc bus value. EMI components centered at drive f_c and harmonics of the f_c are seen. High frequency harmonics decay at a -20 dB/decade rate above f_c until the Fourier frequency component corresponding to the pulse rise / fall time in Fig. 3 is reached. Spectrum analysis indicates a risetime frequency component at f_r = (1 / π t_{rise}) = 0.318/t_{rise}, decaying at -40 dB/decade above f_r in Fig. 10. Voltage transition time determines an equivalent "noise coupling frequency", f_n=f_r = 0.318 / t_{rise}. IGBT risetimes (t_{rise}) range from 0.05μs to 0.2 μs, while BJTs (t_{rise}) range from 1 to 2 μs, corresponding to noise coupling frequencies of 6.4 MHz to 1.6 MHz for IGBTs and 320 kHz to 160 kHz for BJTs, respectively. Thus, a slow pulse risetime has a significant effect on the total noise energy coupled into a circuit, because the –40 dB/decade attenuation factor is occurring at a lower frequency. Pulse width (t) and duty cycle constantly change over a given fundamental frequency cycle in Fig. 2. Pulse width variance is constantly shifting the spectrum (f_t) to the left and right over a wide frequency range. Thus, measured data from a spectrum analyzer will have a non-stationary "smearing" of the spectrum displayed.

Logic board SMPSs powered from drive dc bus power, also have differential mode PWM voltage waveforms similar to Fig. 3. Thus, f_r, f_t , and f_c (10 kHz to 100 kHz) noise frequency components may also exit drive input and output power leads.

Frequency characteristics of the CM voltage spectrum are shown in Fig. 11 for a six step waveform in Fig. 9 with a f_c = 500 Hz and pulse risetime = 200 ns. The spectrum is normalized to the dc bus value. EMI components centered at drive f_c and harmonics of f_c are seen. High frequency harmonics decay at a -20 dB/decade rate above f_c until the Fourier frequency component corresponding to the pulse rise / fall time is reached at f_r = (1 / t t_{rise}) = 0.318/t_{rise} and starts decaying at -40 dB/decade above f_r in Fig. 11. Pulse width (t) and duty cycle constantly change over a given fundamental frequency cycle in Fig. 2 cycle. Thus, the ideal six step waveform of Fig. 9 may not have as many steps as actually measured in Fig. 8.

Conducted and radiated emissions are thus expected to follow the general waveshape of the DM and CM "Voltage vs. Frequency" spectrums discussed.

EMI COUPLING MECHANISMS

This section determines the various paths by which the noise frequency spectrum defined is coupled into signals and equipment. The topics covered in detail are:

- ***Conducted CM Current Inducing CM Ground***
- ***Critical Distance vs. CM Current Risetime***
- ***CM Current Capacitively Coupled to Signal Voltage***
- ***CM Current Capacitively Coupled to Interface Power***
- ***Noisy Shield Ground***
- ***Noisy Source Ground***
- ***Conducted CM Current & Radiated Emissions***
- ***Noise Coupling Paths in a Drive System***

Conducted CM Current Inducing CM Ground

A transient high frequency CM current path exists in Fig. 12 from each drive output phase during switching, thru stray cable and motor C_{lg} capacitance, into ground *Potential #1* (V_1) and thru the ground grid to ground *Potential #2* (V_2). Ground grids are high impedance to CM high frequency noise current, so an instantaneous voltage difference V_{1-2}, known as common mode noise voltage exists across the ground grid.

A (*Send / Receive*) susceptible interface circuit, with source and return signal current (i_{signal}), is referenced to TE zero voltage ground (via building structure steel) at V_2, while the *Send* end is referenced to noisy V_1 ground. Thus, CM noise voltage impressed on both *HI* and *LO* signal lines, allows a CM noise current (i_{1-2}) to appear in the same direction on both lines and circulate back through ground. The signal may develop a noise voltage due to i_{1-2}. The interface equipment's ability to function in the presence of high frequency noise depends on it's Common Mode noise Rejection Ratio (CMRR) threshold tested at noise frequency (f_n).

Critical Distance vs. CM Current Risetime

If both V_1 and V_2 of Fig. 12 were maintained at TE potential, then $V_1 = V_2 = 0$ and $V_{1-2} = 0$, thus eliminating the signal noise. Susceptible circuits may function with I_{lg} ground noise present, if both V_1 and V_2 are approximately equal in magnitude and phase. In this case both V_1 and V_2 are not = 0, but $V_{1-2} \sim 0$, so that the minimal noise remaining is rejected by the circuit CMRR. Thus, high peak I_{lg} ground current with slow risetime noise may still have $V_{1-2} \sim 0$, depending on distance separation. Low peak I_{lg} but with fast 50 ns risetimes may have large instantaneous voltage differences at either end, even for short ground distance separation.

Wavelength (λ) in meters is calculated as $\lambda = c / f_n$, where the speed of light (c) is $c = 3 \cdot 10^8$ m/s and f_n is in Hz. The term ($\lambda/8$) defines a maximum critical distance (l_c) where magnitude and phase relationships are equal, such that $V_{1-2} \sim 0$ between two separated single ended interface circuit grounds. Fig. 13 shows the critical length chart for various PWM voltage risetimes.

Consider an IGBT drive with t_{rise} = 100 ns, logic common to noisy PE, connected to a 0-10 Vdc single ended two wire interface circuit of 200 ft (60m) length, and with receive end referenced to a different TE ground. Fig. 13 shows there is a possibility for CM noise voltage interference with these conditions after 40 ft (12m). In contrast, a BJT drive with t_{rise} of 2 µs has $V_{1-2} \sim 0$ and minimal CM noise up to 900 ft (90m) of interface length.

This chart applies to single ended systems and does not imply equipment will not operate properly above the critical length if systems containing CM filters, galvanic or optically isolation, or differential circuits are used.

CM Current Capacitively Coupled to Signal Voltage

High *dv/dt* from a drive unshielded output lead in Fig. 14 will capacitively couple I_{lg} through stray capacitance (C_{ls}) onto both signal lines in close proximity and produce an error voltage depending on load impedance balance. In the worst case, $I_{lg} \sim (C_{ls})\ (V_{l-g}\ /\ D\, t_{rise})$, where C_{ls} is proportional to the length of parallel power and signal leads and separation distance. Standard noise reduction solutions available are:

- Twist signal leads together to provide balanced capacitive coupling C_{ls} to each signal lead.
- Shield signals so electrostatic coupled noise current flow on shield-to-ground instead of signal leads.
- Separate control from power wires in open air, conduit or cable trays.
- Use shielded power cables.

CM Current Capacitively Coupled to Interface Power

In Fig. 15, unshielded 120 Vac power leads in a conduit or cable tray with unshielded drive power leads cause EMI problems when *dv/dts* of 10,000 V/µs or greater are present. High *dv/dt* from drive power leads capacitively couple to 120 Vac power leads and through susceptible load power supply capacitance, to impress noise voltage on *HI* and *LO* signal lines at TE.

Noisy Shield Ground

Signal shields reduce external electrostatic coupling but *may introduce* EMI, if the shield is connected to a noisy ground potential. As discussed, drive *dv/dt* at "noisy" V_1 creates a transient CM I_{1-2} path to "quiet" V_2 and induces a V_{1-2} CM noise voltage.

Shield connections to noisy V_1 potential in Fig. 16 cause a CM current i_{1-2} path through shield capacitance (C_{s-HI} & C_{s-LO}) creating susceptible load noise. Current i_{1-2} continues through zero voltage ground V_2 and back to V_1. Load noise due to shield induced noise is verified by removing the shield ground. Solutions include:

- Galvanic or optical signal isolation modules.
- Inductance on power leads to reduce I_{lg} risetime to ground, so noisy V_1 is closer to quiet V_2 potential and $V_{1-2} \sim 0$,
- CM choke on both signals and shield at *SEND* end. CM choke inductance in the i_{1-2} ground path reduces the effect of V_{1-2} *dv/dt* reducing i_{1-2} coupling through C_{s-HI} & C_{s-LO} , reducing susceptible load noise. CM cores do not affect line to line signal quality.

Noisy Source Ground

Signal shields reduce external electrostatic coupling but still *may introduce* EMI, if the shield is connected to TE ground potential, while interface equipment source is referenced to noisy ground at *Potential #1* in Fig. 17. The fast *di/dt* edges (change in current with time) of CM I_{lg} current set up a high *dv/dt* V_{1-2} *voltage as demonstrated before*. The i_{1-2} paths due to non-zero V_{1-2} are shown in Fig. 17. Noisy V_1 end in the previous section (Noisy Shield Ground) had a metallic shield path to couple noise in the entire length of signal cable. In this case, noisy V_1 end must first go through the *Send* end power supply ground impedance, thus noise levels will be lower with this configuration.

Previous solutions also apply in this case. Signal quality may be improved by grounding the shield at both ends in cases of CM noise with fast rising edges or high frequency ringing. The shields low impedance co-axial braid parallels the high ground impedance between V_{1-2}, but forces $V_1 \sim V_2$, so CM noise voltage $V_{1-2} \sim 0$. However, interface grounds ride up and down with identical noise voltage, so coupled noise into differential signal leads is minimal.

Disadvantages of multi-point ground schemes are V_1 to V_2 ground loops that may produce high shield current limited by shield resistance and "quiet" zero voltage ground V_2 becomes polluted with "noisy" V_1 ground voltage and affects other sensitive equipment tied to V_2.

Conducted CM Current & Radiated Emission

Unshielded drive wires act as antennas for the electric fields set by the steep *dv/dt* of the PWM output voltage. Efficient radiated emissions occur at $f_n = 1/\pi t_{rise}$ and its higher harmonics. Unshielded drive input / output cables carrying CM I_{lg} may act as loop antennas for radiated emissions, due to the current path in these wires returning via the ground grid in Fig. 18. Drive CM output cores and conduit, armor or shielded cable solutions substantially reduce radiated noise, but full compliance to FCC/European CE regulations may require EMI filters.

The normal mode I_{ll} charging current path may also function as an antenna with loop area, if the phase wires are not bundled closely as shown in Fig. 18**.**

Noise Coupling Paths in a Drive System

Fig. 6 shows system CM noise current paths taken when poor wiring practice using three unshielded phase output wires, randomly laid in cable tray, and a local motor ground wire to the ground grid is used.

The ground grid is a high impedance to high frequency ground noise current I_{lg}, so that an instantaneous CM noise voltage is created across the ground grid *Potential #1* through *Potential #3*. CM voltage is impressed on susceptible interface equipment between drive logic ground *Potential #1* (which is noisy compared to structure steel) and interface ground *Potential #4* (referenced at zero voltage TE potential). Common mode voltage is also impressed between the encoder/tach case at *Potential #3* and drive PE logic ground *Potential #1*. Successful encoder/tach operation depends on how much CM voltage is capacitively coupled into the encoder/tach circuitry from the encoder/tach case, which is mounted to noisy motor frame ground. The chart of Fig.13 may help determine probability of CM problems. Additional equipment users referencing to ground grid *Potential #1*, *Potential #2*, *and Potential #3* may also experience CM voltage problems. Ability of interface equipment to function in the presence of noise is ultimately determined by it's CMRR threshold tested at noise f_n. Poor wiring practice (shown in Fig. 6) also exemplifies the radiated emissions problem. A large system noise loop antenna is formed between both drive output / input wires and return ground grid, as in Fig. 18. Thus, a better wiring practice is desired prior to drive installation.

MITIGATION of EMI

Four philosophical steps to ASD noise mitigation and abatement are discussed. Any method used alone may minimize but not necessarily eliminate ASD CM noise currents and its effect on industrial equipment. Successful drive installation is assured as more methods are incorporated.

- ***Proper low and high frequency grounding***
- ***Attenuating the noise source***
- ***Shielding noise away from sensitive equipment***
- ***Capturing and returning noise to the source (ASD)***

Low & High Frequency Equipment Grounds

The importance of system ground philosophy selection, single point signal grounding, and drive / equipment panel layouts, as related to proper low frequency grounding practices and acceptable high frequency grounding practices that reduce the effect of EMI noise from ASD*s* is discussed.

System Grounding Philosophy: System grounding philosophy for process industry applications has historically been based on low frequency concerns of providing safe and reliable power distribution, while insuring maximum protection against transient voltages and maintaining uptime availability during ground faults [15]. However, system ground philosophy as applied to ASD's does influence the magnitude and coupling path of EMI generated from a PWM ac drive.

The *Un-grounded System* of Fig. 19 has an advantage in that a single line-to-ground fault does not require immediate interruption of power flow. A disadvantage is that primary line-to-ground voltage transients are passed to the secondary without attenuation. Another disadvantage is that transformer neutral point (*Xo*) is capacitively coupled to ground, allowing *Xo* voltage to float toward the line voltage during transients and overstress the line-to-neutral insulation system. The principal problem with an ungrounded neutral system is that an arcing ground fault can cause escalation of the system line-to-ground voltages to several times normal line-to-ground voltage [16],[17]. However with respect to EMI from ASD*s*, the open transformer *Xo* circuit does beneficially break the return path of CM EMI noise current back to the ASD input in Fig. 6**.** Thus, *CM noise has substantially reduced* current in the ground grid to only that which can pass through the stray capacitance between the transformer *Xo* and earth ground.

The *Solidly Grounded System* of Fig.19 provides greater attenuation of transformer primary line-to-ground voltage transients, reduces the possibility of overstressing line-to-neutral insulation and eliminates the problem of line-to-ground voltage escalation due to an arcing ground fault, since the neutral is held to ground potential. A disadvantage is that a line-to-ground fault will interrupt power to the process line without warning and that a high ground fault must now be immediately interrupted, which has the possibility to inflict more damage due to the higher energy to be dissipated. With respect to EMI from ASDs, the solidly ground *Xo* neutral circuit of the transformer detrimentally *completes* a transient CM noise current conductive return path from the ASD output to the ground grid and back to ASD by the ac input leads in Fig. 6. Thus, *CM noise current is highest* in the ground grid with solidly grounded systems. However, the CM noise loop is contained at the transformer neutral (*Xo*) and noise does not progress into the ground grid on the transformer primary side.

The *High Resistance Ground (HRG) system* of Fig. 19 adds sufficient neutral-to-ground resistance to limit ground fault current to the one to five ampere range. Although the neutral is not held at earth ground, this value of resistance will limit the voltage to ground during an arcing ground fault to levels sufficiently low to avoid insulation failures. Secondary attenuation of primary line-to-ground voltage transients depends on the resistor value chosen.

The HRG method has become standard practice in many process industries due to the fact that a line-to-ground fault does not require immediate shutdown of the affected equipment. With respect to EMI from ASD*s*, the *HRG resistor significantly reduces peak CM ground current and provides additional circuit damping resistance* since the resistor is now in series with the CM noise current return path back to the ASD [13]. Thus, high-frequency CM potential voltage differences across the ground grid *Potential #1* to *Potential #3* in Fig. 6 are minimized. However, the current flowing through the HRG resistor corrupts the sense voltage for the Ground Fault Indicator (GFI) and may require a HRG filter to prevent false alarms [16].

Safety Grounds: Equipment safety grounds insure that safe touch potential voltages exist between operator extremities under ground fault conditions. Safety grounds also insure that under ASD operation, no exposed metal accumulates electrical charge by leakage current or from the high frequency EMI current traveling through the ground grid. The ASD frame, cabinet, enclosure steel mounting panels and doors are typically bonded to a system PE copper bus at the bottom of the cabinet which is connected via a ground conductor, sized per NEC code, to the dedicated zero voltage ground point. Incoming and outgoing conduit/armor or cable trays are inherently bonded to the cabinet structure. The conduit/armor bonds are important since it is shown these structures may carry high frequency noise currents.

The NEC requirement of grounding the motor is fulfilled by bonding a ground wire within the motor junction box and returning it to the ASD PE terminal, where a separate PE wire to the cabinet PE bus insures a metallic conductive path to ground. This grounding method insures a solid ground connection over the life of the equipment, while providing a possible ground return path, other than the ground grid, for the induced high frequency CM current from stator winding capacitance to frame ground during ASD switching.

Large hp motors (> 500 hp) have significant stator winding-to-frame capacitance resulting in appreciable CM currents. Installations with long motor cables (> 600 ft or 180m) and large hp motors may have the motor frame transiently elevated above zero potential during ASD switching due to the green ground safety wire appearing as a large inductance to the high frequency CM currents. In this case or when wet conditions around the motor frame exist, an additional bond wire from motor frame to the nearest building structure steel ground is sometimes used in practice to insure a safe touch potential voltage on the frame with respect to local ground**.**

Dedicated System Ground: Fig. 20 shows a dedicated grounding system buses and electrodes. Where practical, the resistance to ground should be on the order of one ohm or less, although NEC Section 250-84 will allow a resistance up to 25 ohms. Ground resistance is affected by soil resistivity, which is dependent on moisture content. Multiple ground rods in low resistivity soil may provide an adequate low impedance path for 60 Hz safety and signal ground for high frequency EMI noise current until summer, when ground water tables dry up. One installation using ground rods driven into a plant floor exhibited a high (1,000 to 5,000 ohms) resistance between ground rods and building steel, due to dry rocky soil under the building.

One suggested grounding practice description [18] for steel frame buildings is shown in Fig. 20. The ground bus should be connected to each outside building column. In large buildings, a network should be provided to include internal building columns. The ground bus should be connected to electrodes at intervals of 200 feet (60m) or less. If the building consists of more than one floor, each floor should have its own ground, which in turn, must be connected by a number of conductors to the main ground bus on the first floor. The steel girder grid connections provide multiple paths to ground and provide both a low and high frequency power grid connection, similar to the raised floor ground grid network used for mainframe computers.

A ground equivalent network, equivalent to the above, should be provided when a building does not have steel framework (see NEC Section 250-51).

A good ground system is essential for both safety and noise free signal grounds.

Single Point vs. Multi-point Signal Grounds: Fig. 21 shows four ASDs connected to earth ground building structure steel (potential V_o) along with a remote ground site with earth ground (potential V_6) relative to V_o. ASD-1 and ASD-2 have their logic board grounded to the drive PE frame, while ASD-3 and ASD-4 have their logic board grounded connected to a True Earth (TE) terminal , which can be bussed together and single point connected to earth ground building steel (potential V_o). Also shown are the hidden high frequency CM noise currents flowing through the ground buses I_{1-2}, I_{3-4} and ground system I_{6-0}. Depending on the high frequency inductance and resistance seen in the path of these CM currents, CM voltages V_{1-2}, V_{3-4} and V_{6-0} of Fig. 21 are respectively developed. The trend of increasingly faster output voltage risetimes of modern PWM ASDs have correspondingly increased the system CM voltage magnitudes seen. Transient common mode voltage peaks of 100 Vpk measured end to end across a 100 foot (30m) PE ground bus in a cabinet lineup may exist, unless steps to attenuate the ASD CM current magnitude and risetime are taken.

Control, communication and analog interface issues between ASD-3, ASD-4 and other cabinet electronics may be reduced with the single point TE logic board connection of Fig. 21. The effects of PE CM noise voltage V_{3-4} between multiple drives on drive-to-drive logic / communication operation in a multi-drive lineup is minimized. Single point connection of TE logic ground to the PE power ground bus and steel panel at the cabinet power entry, maintains drive logic ground and the grounds of any susceptible interface equipment grounded to the PE panel closer in magnitude for reduced noise interference. Connecting the bussed TE logic ground to a point other than the immediate cabinet PE ground may actually increase system interference, if the selected ground point is itself a noisy ground. In real sites, finding the best ground point, with drives located across a plant, may be difficult without a good ground matrix.

Interface issues between any drive (ASD-1 through ASD-4) in the cabinet and remote electronics located a long distance away may also occur. This is due to transient CM current I_{6-0} creating a CM voltage V_{6-0} different than V_{2-0} or V_{5-0} in Fig. 21. CM voltage difference between sites may be minimized in a similar manner by bonding node V_2, V_4, and V_5 to V_6 with a low inductance jumper or multi-point terminating signal shields at both ends of the nodes. If grounding solutions are ineffective, then signal isolators with appropriate CMRR must be used.

Fig. 22 is a drive cabinet grounding scheme attempting to incorporate concerns of safety grounds, system grounds, dedicated grounds and the need for single or multi point ground systems.

Cabinet Layout for Drives & Electronic Equipment: Trouble free operation of drives and electronics can be accomplished, even in the presence of noise, once the CM noise current path is understood and the drive system panel is intelligently laid out to re-route CM noise away from the sensitive electronics. Fig. 23, Fig. 24 and Fig. 25 show that much of the high frequency CM noise current sourced from the ASD output returns on both the conduit/armor and motor ground wire back to the drive frame. Without high frequency bypass means internal to the drive, the same CM current will flow on the input conduit/armor and input PE ground wire back to the source transformer ground, where the CM current may find a metallic path back to the drive by any of the ASD ac input wires.

Fig. 26 shows a proper cabinet layout done by grouping input and output conduit/armor to one side of the cabinet and separating Programmable Logic Controller (PLC) and susceptible equipment to the opposite side. CM current (A) in the output conduit enters the enclosure wall and is routed back to the input conduit, away from the sensitive electronics ground (potential V_1). CM current (B) in the output PE ground wire has a metallic connection back to the input PE wire, which also does not affect the sensitive electronics ground (potential V_1).

Fig. 27 shows an improper cabinet layout which, by design, forces the return CM current path on the output armor and output PE ground wire to generate transient voltage disturbances in the backplane of the sensitive electronics ground V_1, on its way to finding the possible low impedance ground taken off the left of the cabinet PE bus.

Attenuating the Noise Source

System noise is best eliminated by attenuating it at the drive source, before it enters the system ground grid and takes multiple high frequency "sneak" paths which are difficult to find in installations. Field experience has shown that CM current attenuation alone ensures successful installations for Fig. 1 medium to high-risk installations. Methods to reduce the rms and peak magnitude of CM current are discussed.

Semiconductor Risetime Selection: A typical high frequency line-to-ground CM current magnitude of 20 Apk for IGBT ASDs is shown in Fig. 28. Modern PWM ASDs using IGBT semiconductors have output *dv/dt* voltage transitions 10x to 20x faster than previous generation BJT ac drives. This has beneficially reduced drive switching losses, package size and phase current Total Harmonic Distortion (THD). Drive CM output impedance has remained unchanged and is primarily dominated by line-to-ground capacitance of the cable (C_{lg}) and motor (C_{lg-m}). Thus, peak CM current, which is proportional to C_{lg} (*dv/dt*), is also 10x to 20x higher than previous generation BJT ac drives. While IGBT risetime can be varied from 100 ns to 300 ns to reduce peak CM current, further increases in risetime will negate any benefits derived from the new technology.

Decrease Carrier Frequency (f_c) Selection: A lower f_c doesn't change the peak CM current but does reduce the CM rms noise current magnitude in the ground grid as shown in Fig. 3. Field experience has proven this mitigation technique effective in reducing CM system noise below equipment noise thresholds.

CM Choke on Drive Output: A CM choke on the drive output leads of Fig. 29 is highly effective in reducing CM noise below equipment noise thresholds. *A* CM choke is an inductor with ASD output phase (U,V,W) conductors wound in the same direction with one or more turns through a common magnetic core. The fast line-to-line *dv/dt* voltage transitions of the PWM output pulses of Fig. 6 do not change when a CM choke is added to the output. Thus, line-to-line cable charging current spikes are unaltered. However, magnitude and *di/dt* risetime of line-to-ground CM noise current is substantially reduced as shown in Fig. 28, due to the CM choke acting as a high inductance (high impedance) to any line-to-ground *dv/dt* voltage transitions. Fig. 28 shows peak ground current may occur at 5 µs and a *di/dt* rate = 1 A/µs with a CM choke versus 100 ns and *di/dt* = 200 A/µs without a CM choke.

Without a CM choke, large instantaneous CM voltage differences may occur across the ground grid, due to the high *di/dt* and high peak magnitude of CM current interacting with parasitic inductance and skin effect ac resistance of the system ground grid.

With a CM choke, the lower ground current magnitude and lower *di/dt* rate reduce potential voltage differences across the ground grid to near earth ground potential. As a result, error free system operation of widely separated ASD, interface, and sensitive equipment is possible, since CM voltages between them are reduced. A CM choke is physically smaller than a three phase line reactor, which may be used on the ASD output.

CM Choke on 120 Vac and Drive Signal Interfaces: CM cores are also beneficial in reducing noise on signal level voltages of drive interface equipment. CM chokes around drive *HI-LO* signal interface lead and shield in Fig. 30 reduces instantaneous CM noise current induced on signal leads due to instantaneous CM voltages differences between ground *Potential #1* and ground *Potential #2.* CM chokes around the 120 Vac power feeding susceptible interface equipment may also reduce EMI interference, if lead separation from unshielded drive output leads is not possible.

Passive Filters: Adding output line reactors (3-5% impedance) to each drive will reduce peak I_{lg} transient current to lower levels, but at substantial size, cost, weight and fundamental output voltage drop penalty. However, output line reactors reduce both line-to-ground and line-to-line capacitive coupled currents, so that all the phase current transient spikes of Fig. 5 are removed.

Active CM Voltage Cancellation: Recent efforts in active cancellation provide an alternative to passive mitigation techniques. One approach senses the CM voltage and actively cancels it by transformer coupling to each phase [19]-[21]. Although intuitive and understandable, the disclosed embodiment suggests isolation hurdles to overcome. Furthermore, the transformer secondary conducts full drive phase current in each winding.

Another approach is to add additional inverter poles [22]. The drive now consists of a total of 7 poles with 2 poles per motor phase isolated by inter-phase reactors and the 7th pole connected to the neutral point of a three-phase capacitor bank. Significant attenuation of the CM voltage occurs. Reported testing did not include the active 7th leg, but incorporated a CM choke and 2nd order dc link filter.

Shielding Noise from Sensitive Equipment

After high frequency CM noise current is attenuated with CM chokes, the third mitigation step is to control the conducted noise path taken. This is done by diverting noise away from the referenced ground of sensitive equipment.

Electro-magnetic emissions of the ASD output power leads contain several frequency components. There is a high electric field component emitted radially from the wires, which is due to the PWM risetime *dv/dt* and carrier frequency voltage components. There is a circular low-frequency magnetic field component around the wires due to the ASD fundamental output frequency, a mid-frequency magnetic field component due to the carrier frequency current and a high-frequency electric and magnetic field due to the transient *di/dt* CM current conducted on the power leads. In addition, there are also DM and CM traveling wave currents present on the cables. Carrier frequency and switching *dv/dt* components from the SMPS, connected to the ASD dc bus, may also exit from these leads.

Electric and magnetic field emissions for input power leads connected to the ASD three phase diode bridge input are not as severe as the ASD power output leads. Field emissions are limited to 60 Hz and 5th, 7th, 11th, 13th, etc harmonic frequency components for six pulse input phase currents, transient *di/dt* CM current conducted on the input power leads, and drive SMPS emissions which escape out the input leads to ground.

Basic noise reduction rules such as bundling output leads and ground to reduce external electric and magnetic coupling to other equipment and spacing control wires from the high *dv/dt* output power wires is a good practice to reduce the capacitive coupling problem [5]. Beyond this, the impact of cable selection to obtain predictable noise control is further investigated in terms of conducted emissions, radiated emissions and shielding effectiveness.

Fig. 31 shows different method of cable construction. Various reports have analyzed these cables for ASD use [23-26]. The cable tray with randomly isolated wires suffers from the possibility of stray capacitive current into the grounded tray and repeating the noise scenario of Fig. 6. Also being unbundled, there is higher electric and magnetic fields radiated. The extreme unsymmetrical case of cables in a tray is also shown. This un-symmetry may cause phase current unbalance on large hp machines > 250 hp used with long cables. This is due to the unbalanced mutual inductance between phases.

Tray cable is an improvement, since it is bundled with a ground to minimize field emissions and unbalanced impedance. The PE ground assists in returning some low frequency noise back to the drive and providing a conductor for motor grounding.

Interlocked armor cable is a good wiring practice for ASDs and is similar to conduit. It can reduce EMI field emissions due to the metallic sheath. It also has the possibility to contain the high frequency noise current out of the ground grid with a low inductance coaxial sheath. Interlocked armor cable may be available with insulated Poly Vinyl Chloride (PVC) jackets to prevent noise current on the sheath from accidentally going to ground. The single PE ground conductor assists in low frequency noise containment and safety grounding issues. The importance of having three symmetrical grounds is not an issue with up to #2 American Wire Guage (AWG) wire, since impedance imbalance in these wire sizes is not discernable.

Continuous welded aluminum armor or braided shield tray cable represents the best technical choice for ASDs and is discussed further.

Reduction of Conducted Ground Noise Current

This section investigates which conventional wiring practices may reduce ASD I_{lg} high frequency zero sequence noise current conducted in the *ground grid* circuit. Each method has a Good to Best performance vs. cost expense associated with it that must be evaluated.

Good Wiring Practice: *3 Wire plus GND in Conduit*

Fig. 23 shows the new transient I_{lg} line-to-ground CM high-frequency noise current path taken during PWM switching when using three output wires and insulated Power Earth (PE) ground wire in a steel conduit. Conduit ends are bonded to the drive cabinet and motor junction box. The PE ground wire meets NEC Article 250 motor ground requirement and is bonded at both ends, at the ASD PE bus and the motor ground stud. An additional motor ground wire to closest pole ground is sometimes used on large hp motors to insure the motor frame is grounded.

Part of I_{lg} flows through cable capacitance to the grounded conduit wall and part through motor stator winding capacitance ($C_{lg\text{-}m}$) to frame ground. The green wire/conduit combination collects most of the transient capacitive current in Fig. 23 and returns it back to the drive, thereby reducing "*ground grid noise*" in the drive to motor cable. The conduit PE ground wire provides a low resistance path back to the drive for the lower frequency CM noise current, which hopefully is lower than the ground grid impedance. However, at high noise frequencies the ground wire skin effect resistance increases ten to fifty-fold, and ground wire inductance at high frequencies contributes to high ground impedance, especially for long cable runs. Thus, CM current tends to flow on the conduit tube, which acts as a coaxial return of CM noise current. Fig. 23 shows that control of the CM high frequency noise path is not guaranteed with conduit and system ground noise problems may or may not occur.

The first problem is that conduit CM impedance is variable, due to low conductivity of steel at high frequencies and the fact that conduit-coupling joints may corrode over time or not be in proper contact. Also, ac resistance characteristics of earth ground are generally variable as discussed. Thus, it is unpredictable how noise current divides between the wire, conduit wall or ground grid.

The second problem is that CM noise flowing on the conduit may return to the user ground grid via conduit straps or conduit inadvertent contact with ground grid structures as at *Potential #2* in Fig. 23. Thus, inadvertent conduit grounding at *Potential #2* will induce CM voltages for users referencing this node in Fig. 23. A computer network malfunction problem in the field was traced to conduit mounting straps, which accidentally grounded the ASD output conduit to the same pole ground where a computer network was grounded. The CM noise found a lower return impedance path via a computer ground wire that was connected back to plant system ground, and injected high frequency ground noise into the computer network.

The third problem is that CM voltage problems may still exist for susceptible interface equipment referenced between *Potential #1* (which is noisy) and Earth Ground *Potential #4*. This is due to CM currents returning back from the motor conduit/ground that may re-enter the ground grid at *Potential #1*, through feed transformer *Xo* and back to the drive through input phase conductors as shown in Fig. 23. The amount of CM interference is dependent on the "*CM Current Risetime vs. Critical Interface Distance*" chart of Fig. 13. Thus, *3 Wire plus Ground Wire in a Conduit* is also recommended from the feed transformer source to the ASD input, with conduit and green wire bonded to secondary *Xo* neutral and another wire from transformer *Xo* to the ground grid structure. This provides a low impedance and predictable metallic return path out of the ground grid for the CM noise current. Locating the drive isolation transformer closer to drive cabinet will also shorten ground noise current paths and contain noise.

Overall, the conduit system has improved high frequency noise rejection characteristics as compared to the random wiring method of Fig. 6. The use of conduit and CM chokes has been successfully used in thousands of high-risk industrial applications.

Better Wiring: Shielded Output- Insulated PVC Jacket

The shielded tray cable or continuous aluminum sheath armor cable with a PVC jacket of Fig. 24 is one viable solution to control the drive's high frequency noise current in a predictable metallic path and divert it from conducting into the plant system ground. Shield and ground wires are bonded at both drive and motor grounds to prevent motor winding CM noise entering the ground grid. The low resistance full rated ground wire meets motor grounding requirements, while conducting some of the lower frequency components of the CM noise current. The armor or copper braid shield is the predominant CM noise return path, since it possesses both a low resistance and low coaxial inductance return for the higher frequency CM noise currents. The insulated PVC jacket insures most of the CM noise current returns back to the drive on the shield and out of accidental contact with the ground grid. Very little noise goes into the customer PE ground grid between *Potential #1* and *Potential #3*. Thus, ground grid potential voltage differences between *Potential #3 and #1* are minimized.

However, if the drive feed transformer is far away, then CM currents returning back from the motor shield or armor may re-enter the ground grid at *Potential #1* as discussed for conduit.

Best Wiring Practice: Shielded Input /Shielded Output

Shielded or armor cables with insulated outer jackets on both output and input sides, as in Fig. 25, prevent interference with other sensitive equipment by providing an isolated predictable metallic CM noise current path to and from the drive. Thus, noise is not re-introduced back into the ground grid by accidental ground contact or by grounding the drive metal. Shield and ground wires are bonded at both drive and motor grounds to prevent motor winding CM noise entering the ground grid between the drive and motor. Shield and ground wires are bonded at both drive PE and input transformer PE grounds to prevent drive CM noise entering the ground grid between drive PE and transformer PE ground. Shielded input wires are recommended for installations where AM radio interference is not acceptable, when the drive input transformer is physically located far away from the drive or when a large amount of sensitive equipment referenced to ground exists at the application site.

However, shielded cable will not solve GFI noise problems, since the grounded shield and PE wire at the HRG unit must allow I_{lg} current to re-enter the neutral *Xo* circuit and transformer secondary as shown in Fig. 25.

Radiated Noise Reduction with Shielded Cables

Difficulties with radiated magnetic or electric field EMI noise can be resolved by using appropriate equipment spacing and shielded power cables and instrumentation cables.

Magnetic Field: Drives generate balanced phase voltages resulting in fundamental frequency phase currents which are also a balanced set, $I_u + I_v + I_w = 0$. Also, 95% of the transient high frequency zero sequence currents sourced by the drive, return in opposite direction on the shield. External magnetic field emission radiated from a bundled shielded cable is not severe, since fundamental frequency currents sum to zero. This is verified with Amperes law as applied to the circular circumference around a three phase bundled cable,

$$\oint H \bullet dl = \sum N\left(I_a + I_b + I_c\right) = 0 .$$

Thus, the use of galvanized steel or aluminum armor selection is not critical for this magnetic field condition, since cable currents are almost balanced. Magnetic field emission efficiency at high frequency is also reduced with shield or conduit systems, since most drive output CM current returns in a small loop area, from phase wire to either the green wire or armor/conduit wall.

Radiated Field: Electric field emissions radiate perpendicular from phase conductors. There is a large radiating loop antenna area formed between the unshielded phase leads and ground of Fig. 18, with CM noise current frequency as the driving source. The large loop antenna occurs on both output as well as input leads.

The conduit system of Fig. 23 is better in terms of radiated emission area due to the internal ground wire return reducing the effective loop area and the attenuation properties of steel conduit. However, the CM noise exiting to ground at incidental ground contact in Fig. 18 may allow Radio Frequency (RF) emissions to escape.

Fig. 24 and Fig. 25 shielded cable solutions use an internal PE ground wire and continuous coaxial high conductivity shield to form a tight closed loop area that minimizes external RF emissions. Electric field noise is substantially attenuated with galvanized steel or continuous welded aluminum armor type Metal Clad (MC) cable for frequencies from the ASD carrier frequency up to the 6 MHz noise current frequency f_n. Thus, the capacitive coupling noise from power cable to adjacent signal and control interface is substantially reduced.

Fig. 32 shows relative low frequency shielding effectiveness of standard unshielded tray cable compared to shielded cable using copper braid with 85% area coverage. Test results are shown in Fig. 32 of the voltage induced on a loop antenna that is in direct contact to both cables for one complete 10 kHz PWM cycle. The unshielded cable couples a direct square wave voltage replica of the 10 kHz PWM pulses onto the pickup coil antenna, while the braided shielded cable substantially attenuates the low carrier frequency components and most other frequencies by 30 dB. There is some shielded cable high frequency emissions during the rising and falling edges of the PWM waveform, probably due to CM currents on the shield developing shield voltages.

High frequency shielding effectiveness of shielded cables that is associated with the steep *dv/dt* voltage switching edge (~1 MHz to 10 MHz for IGBT risetimes), was investigated by passing the ASD output cable through a RFI chamber, lined with absorption tiles, and returning the cable to a motor connected outside the RF measurement chamber. Reference [23] showed a relative 30 dB attenuation between shielded and unshielded cables when using a high gain dipole antenna which measured 10 MHz to 50 MHz RF emissions at 10 ft (3m) from the output cable.

Effectiveness of Shielded Cables

Most sensitive electronic equipment malfunction is caused by high magnitudes of CM noise current present in the system ground plane. Equipment is designed to operate with a solid zero potential ground reference, and this is not the case when high frequency noise exists on the ground grid.

Properly designed ASD cables can reduce the effect of CM noise by having a shield and ground conductors that can carry the noise back to the drive with an impedance that is several orders of magnitude smaller than the ground grid impedance. Fig. 24 shows that CM noise exiting at the motor winding to ground will take the path of least resistance back to the drive. CM current magnitude flowing in the ground grid is determined by impedance divider rule between cable ground/ shield impedance and ground grid resistance. The ideal cable should have a common mode surge impedance, at both low frequency and high frequency, that is less than the typical 1 to 25 ohms impedance of the ground grid system.

Fig. 33 determined the CM surge impedance of various cable constructions at two critical noise frequencies of interest. First, is the equivalent noise frequency corresponding to PWM pulse risetime at (1/ π t_{rise}) in 1 MHz to 10 MHz range for 50 ns to 400 ns IGBT risetimes. The second critical frequency is that of the CM *Ilg* noise oscillation frequency, typically 1 MHz for 100 ft (30m) cable lengths and 50 kHz for 1000 ft (300m) output cable lengths. CM surge impedance was measured from phase U conductor at the ASD to the return circuit ground system at the ASD, with the phase wires connected to the ground return circuit at the motor end.

Fig. 33 shows results for a configuration similar to the *Non-Recommended Random Lay* wiring practice of Fig. 6 that has a CM surge impedance consisting of a phase wire and a single isolated PE ground return wire. This wiring practice has acceptable impedance < 10 ohms only below 150 kHz. The unbundled PE wire has a self-inductance, which results in high impedance at higher noise frequencies, and is thus not useful for diverting and containing CM noise.

CM surge impedance Results for a *Tray Cable plus PE Wire* were not plotted, but followed data and discussion as for the *Random Lay* wiring practice.

Fig. 33 shows results for the *Conduit plus PE Wire* system of Fig. 23. CM surge impedance consists of a phase wire and a PE return wire, internal to the conduit, that is bonded at both ends of the conduit. The phase wire is now in close proximity to the ground return wire and outer coaxial tube. This results in a low effective loop area phase-to-ground and thus lower mutual inductance. Also, the coaxial steel tube, in parallel with the return PE wire, has a lower inductance than an isolated wire at higher frequencies. Thus, this system has a substantial reduction in impedance in the 100 kHz to 1 MHz range. However, skin effect resistance of the steel tube and wire inductance still forms unacceptable high impedance in the 10 MHz range. This wiring practice has acceptable impedance < 10 ohms only below 500 kHz. In addition, the non-isolated conduit system suffers from the fact that high frequency CM noise can unpredictably jump from the conduit surface to the ground grid at the conduit strap points, if the grid impedance is lower than the conduit high frequency impedance.

Fig. 33 also shows results for a *Tray Cable using Overall Foil Shield plus PE Wire*. CM surge impedance data is similar to the conduit system in the 100 kHz to 1 MHz range, while providing lower CM impedance than the conduit at a high 10 MHz frequency. This wiring practice has acceptable impedance < 10 ohms only below 800 kHz. The thin foil shield possesses higher resistance than desired.

Fig. 33 shows results for a *Tray Cable using Overall Braided Copper Shield, Foil Shield and Drain wire plus PE Wire*. This configuration has the lowest CM impedance over the entire frequency range and is best suited to divert high frequency CM noise out of the user ground grid.

At low noise frequencies, the shielded cable ground circuit impedance is essentially the dc resistance of the copper shield braid, aluminum foil and copper grounds in parallel. This is very low as compared to the ground grid impedance, so that CM noise current is diverted from the ground grid to the cable shield/ground. The shielded cable has an internal PE ground wire for low frequency noise, foil shield/drain wire for 2 MHz to 10 MHz high frequency noise and a low inductance/low resistance coaxial tinned copper braid covering both low and high frequency noise ranges. Acceptable impedance < 10 ohms is now extended to the 1.5 MHz range. Thus, this configuration is expected to be an effective noise reduction mitigation method, designed to capture most of the high frequency CM noise current and return it back to the drive out of the ground grid.

Surge impedance results for *Continuous Welded Aluminum Armor* are expected to be similar to the *Copper Braid* case discussed.

Fig. 34 shows CM current field test results for 300 ft (90m) of *Shielded Tray Cable* connected to an IGBT ASD having output voltage risetimes of 50 ns and wired per Fig. 24. A typical CM line-to-ground noise current of 6 Apk occurred during a voltage switch transition and was measured by placing all three phase leads through a current probe. Fig. 24 shows current in the braid and foil shields capture most of the high frequency CM noise current, and returns it back to the drive out of the ground grid. The PE ground wire absorbs some, but not all of the higher frequency noise during the voltage transition, As predicted from Fig. 33, the PE ground wire is ineffective during the CM noise high-frequency oscillation period of Fig. 34. The net CM noise current that is not returned by the shield/PE wire combination and which is conducted into the actual ground grid, may be measured by placing the entire bundled shielded cable through a current probe. Field experience has shown that for long cables, 95% of the total noise current generated returns in the shield/armor and 5% may be lost in the customer grid. Fig 34 graphically verifies shielded cable is a viable installation solution to ASD induced noise problems by its substantial reduction of both CM noise current magnitude and frequency in the ground grid.

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Capture & Re-Route Noise Back To Source

Shielded cable or conduit, discussed in the last section, is an integral part of capturing and returning CM noise out of the ground grid and back to ASD PE ground. The ASD does not have a metallic connection to ground. Thus, CM noise returning to the ASD PE ground must be re-routed away from the user ground grid and incoming 60 Hz power lines with either an EMI filter, high-frequency by-pass capacitors connected to the drive terminals or with an input isolation transformer.

A drive EMI filter (Fig. 35) may reduce transient I_{lg} magnitude to very low values in the primary ground grid, transformer *Xo* neutral circuit and 60 Hz power lines. The filter's high frequency by-pass capacitors (C_f) from line-to-ground re-route transient I_{lg} away from the ground grid, grounding resistor or input power lines, and back to the ASD inputs (R,S,T). Series filter inductors (L_f) present high impedance to the filter input and further reduce the possibility of I_{lg} flowing in the utility power lines or *Xo* neutral circuit.

CM capacitors added on each ASD from (+)V_{bus} -to-ground and (-)V_{bus} -to-ground in Fig. 29 act as high-frequency bypass capacitors which reroute transient I_{lg} current back to the ASD dc bus and away from the input ground grid and power lines. The difficulty lies in choosing a capacitor that is an effective solution for every possible system configuration.

Surge capacitors connected at input ac line-to-ground (R,S,T), similar to those in Fig. 35, may already be part of a plant's lightning protection scheme. These capacitors may inadvertently reduce CM Noise in the utility grid, since they function as high-frequency by-pass capacitors to transient I_{lg} current.

Use of a solidly grounded drive isolation transformer located as close as possible to the ASD input will totally eliminate the CM noise problem in the user's existing main transformer feed lines, HRG unit, or ground grid as shown in Fig. 36 [23]. Transient I_{lg} returning to the ASD PE ground is contained to flow only in the isolation transformer neutral circuit and not in the plant HRG neutral circuit. The isolation transformer also prevents high frequency I_{lg} current from conducting through the remainder of the plant electrical system ground grid and reduces the effect of CM noise on other system industrial equipment.

EFFECT OF EMI ON EQUIPMENT

This section demonstrates the advantageous effect of insuring solid PE panel grounds, using proper shield grounding techniques on both signal interfaces and output power leads, and using drive CM cores.

The frequency content of today's IGBT drives also presents unique challenges to the design and packaging/layout of internal drive sensors. This section will also provide a working understanding of the performance characteristics of a common current sensor in use by many drive manufacturers.

External interface & sensors and internal drive sensors listed below are examined in further detail.

- ***External Interface:** Analog Control Signals*
- ***External Sensor:** Tachometers*
- ***External Sensor:** Ground Fault Indicator*
- ***Internal Drive sensors:** Current Feedback*

External Interface: Analog Control Signals

Fig. 37 shows a drive *Analog Out*/*Common* interface signal (**SEND** = V_s = 10 Vdc) referenced to the drive PE terminal, which is connected to a 2 kΩ single-ended **RECEIVE** load with 200 ft (60m) of twisted-shielded pair cable. *Load Common* is bonded to a remote building structure "quiet" TE voltage potential. This test setup is used to demonstrate how a *Noisy Source Ground* and *Noisy Shield Ground* affect signal integrity.

Noisy Source Ground: A noisy source ground potential for drive logic common was created by using an isolated drive *PE Ground* wire that was 600 ft (190m) in length before bonding to building structure steel. This creates a high inductance ground to high-frequency CM transient current and thus a high CM *L*(di/dt)* voltage. The 200 ft (60m) signal cable length exceeds the *Safe Critical Interface Distance* of Fig. 13 for IGBT risetimes in the 50 ns to 200 ns range. Thus, CM voltage V_{1-2} is expected and will be impressed on the V_s = 10 Vdc single ended signal. Source ground *Potential #1* is noisy in Fig. 37, while receive ground is TE zero voltage *Potential #2*. Table II shows the pk-pk noise voltage on signal V_s for various shield connection terminations with this *Noisy Source Ground* condition setup.

Table II. Noise Voltage vs. Shield Connection Option

Shield Connection	Noisy Source Ground (Vpp)	Noisy Shield Ground (Vpp)	Drive CM Core (Vpp)
Drive	30	26	8
Open	16	14	6
Both	5	4	0.2
Load	8	4	0

Shield connection options, as demonstrated in Table II, are not effective if interface distance is long and drive logic PE source ground is noisy due to high inductance or high impedance PE ground. Bonding shield ends to both *Send/Receive* commons through the low impedance shield brings these potentials closer in instantaneous magnitude and phase. CM voltage on V_S is reduced since $V_{1-2} \sim 0$, even though both grounds are not at absolute zero potential. However, shield currents may flow and TE ground *Potential #2* is now polluted for other users.

Noisy Shield Ground: Test conditions above were repeated but now with only a 50 ft (15m) PE ground to the plant grid. Fig. 38 shows shield connection to a noisy drive PE ground impresses CM voltage on V_S as before. However, signal shield connection to the "quiet" load side TE ground vastly reduces CM noise as in Table II.

Equalizing Grounds with CM Core Solution**:** *Noisy Shield Ground* test conditions were repeated, but now with a CM core added on the drive output power leads as in Fig. 29. This reduces CM I_{lg} risetime to 2 µs. Fig. 13 indicates CM noise is not an issue for up to 600 ft (182m) of interface cable for the new reduced 2 µs risetime. Fig. 39 test results show CM noise is now significantly reduced for either open shields or drive end shield connections. CM cores allow instantaneous drive PE ground *Potential #1* & remote TE ground *Potential #2* to track each other so that $V_{1-2} \sim 0$. CM noise is thus eliminated with load side shield connections, without disadvantages of multi-point shield bonding.

External Sensor: Tachometers

Equalizing Grounds with Shielded Cable Solution**:** A field site similar to the *Non-Recommended* wiring practice of Fig. 6 experienced ASD tachometer interface noise glitches that occurred at the carrier frequency rate as shown in the bottom trace of Fig. 40. The problem was traced to high common mode voltage V_{1-3} developed between ground *Potential #3* at the motor frame and PE ground *Potential #1* at the drive, due to the CM I_{lg} risetime. Common mode V_{1-3} voltage induces a secondary CM noise on the interface leads as discussed in the *Noise Coupling Section.* The top trace of Fig. 40 shows the solution of using a shielded output power cable between the drive and motor. The low coaxial inductance and low resistance of the bonded shield insures that drive PE ground *Potential #1* & remote TE ground *Potential #2* instantaneously track each other during the CM I_{lg} transient. Thus, even though the ground potentials are non-zero, $V_{1-2} \sim 0$ and CM signal noise is thus eliminated.

External Sensor: Ground Fault Indicators

Other Multi-Drive Solutions: A GFI used with the HRG resistor of Fig. 25 is particularly sensitive to CM noise, since it is the summing junction for the CM I_{lg} transient currents from all the ASDs on the transformer feed. Rather than try to mitigate noise from each individual drive, the concept of a single 60 Hz filter at the HRG unit becomes more practical and effective. Also, Fig. 36 concept of a solidly grounded drive isolation transformer for just the drive lineup is effective in reducing noise in the MAIN plant HRG and plant ground grid [23].

Internal Sensors: ASD Current Transducers

ASD *Current Sensor Characterization:* Current sensor fidelity limits the ability of modern drives to detect peak current and can result in current feedback distortion. Strategies to overcome the adverse effects of reduced current sensor fidelity are often laden with compromises, none of which are satisfactory for all applications [27,28].

Phase Currents: Frequency Spectrum: In the modeling of EMI section, system components (power converter, cable, and motor) will be characterized with the impedance established for the electrical components and parasitics. The phase current–amplitude and harmonic content–is determined by the voltage and impedance spectrums. To demonstrate the complexity and difficulty this presents to drive design, examine the drive phase current for two typical operating conditions. Fig. 41 shows the three output phase voltages – u, v, and w – with respect to the positive bus for a 460 V 50 ns rise time IGBT drive with 300 ft (90m) of #12 AWG cable, and a 2 kHz carrier frequency. Fig. 42 is the same drive system, except the carrier frequency was increased to 8 kHz. A comparison of the phase currents is striking. The 2 kHz response of Fig. 41 clearly shows the low ripple frequency associated with the transient inductance of the load motor. In addition, an intermediate cable oscillation frequency (350 kHz) is present, but this component is well damped.

Fig. 42, however, demonstrates the adverse effects of higher carrier frequency. Now the low frequency ripple currents are barely discernible, while the intermediate cable frequency dominates. Raising the carrier frequency reduces the time between successive switching, resulting in higher reflected wave voltages, their associated currents and higher frequency parasitics. Furthermore, relaxing other parameters, for example increasing the cable length, will exacerbate the situation by decreasing the cable oscillation frequency and associated damping. Thus, accurate sampling of the current, whether for control or protection purposes, is a complex problem requiring the specification of the sensor and filter bandwidths.

Phase Currents: Detection A further understanding of the problem may be obtained by examining the phase current at different stages of its detection (Fig. 43) together with the impedance characteristics discussed in Modeling of EMI section. Fig. 44 displays an expanded view of the phase current (Fig. 43 I), current sensor output (Fig. 43 II), and filtered output signal (Fig. 43 III) for the same drive system of Fig. 41 and Fig. 42, however, with 10 ft (3m) of #12 AWG cable. The top trace is the u-phase drive output current measured with a current probe with a 25 MHz bandwidth. A discernable 7.5 MHz component is present in the response, which is consistent with the voltage spectrum of a drive having rise times in the 50-100 ns range. Examining the calculated impedance function for a motor and 10 ft (3m) of cable (Fig. 45) shows an impedance null around 6 MHz, very close to the drive pulse rise frequency. Clearly, the frequency content and amplitude of the phase current change as the system parameters, rise time and system impedance, vary.

Fig. 46 and Fig. 47 show the major elements of a Hall effect current sensor [28], the core with a secondary control winding (Is), the primary or motor phase conductor (Ip), and the sensor electronics [29]. The second trace in Fig. 44 is the Hall effect sensor output signal. This trace shows the sensor actually amplifies the high frequency components. Recent work has shown Hall effect devices can present a peculiar transfer function [27], [28]. For example, Fig. 48 shows the transfer function – Is/Ip – of a 25 amp Hall effect closed loop sensor. Notice the 15 dB gain around 7 MHz and the significant attenuation in the 200 kHz – 1 MHz region. Obviously, current fidelity is impaired. The significance of the impairment is determined by the intended function of the sensed signal.

Finally, the third trace shows despite filtering of the feedback signal, component limitations, board layout, etc. can defeat the best intentions of the designer. The signal at the filter output (Fig. 43 III) when presented to hardware overcurrent protection circuitry and the Analog to Digital Converter (ADC) shows the filtering to be inadequate. As pointed out in [28], considerable improvement can be made in limiting the current signal's frequency content by maintaining short traces, minimizing cross talk, and through proper isolation between power and control board to prevent ground bounce.

Phase Currents: Protection and Control Sensing of drive current has two primary purposes. The first purpose is overcurrent protection and the second is control. Overcurrent protection has a number of functional levels. One level of protection detects an absolute peak overcurrrent. Another level monitors the averaged amp seconds and takes action when limits are exceeded. Depending on the design, a drive's overcurrent circuit may be overly sensitive to the high frequency components of the current, resulting in nuisance trips and reduced reliability. Or, the opposite may result, to reduce occurrence of nuisance trips, the feedback filtering rejects important intermediate frequency components, therefore nullifying both the instantaneous overcurrent and the averaged amp second protection. In addition, the cable length may result in significant reflected wave current at a frequency near the null of the transducer's transfer function (Fig. 48). In this case the sensor attenuates the cable dominant component defeating the purpose of the overcurrent protection hardware[27], [28].

Second, a drive's control algorithms employ current feedback to initiate current limit control, provide dead time compensation, and in the case of high performance field orientation determination of slip and the applied voltage vector. However, the above discussion and previous reported work suggests the assumptions are overly simplified. Control design, therefore, must make trade-offs given the limitations presented by the current spectrum. Accurate dead time compensation requires instantaneous information about the polarity of the phase current. Given the sensor's bandwidth characteristics, accurate deadtime compensation must yield to acceptable dead time compensation. Often, the feedback current signal is sampled at a zero vector, implying the sampled value represents the fundamental current component [30], [31]. Zero state sampling may have to be replaced with an averaging technique.

Summarizing, given the bandwidth of drive currents, current sensors must be treated as a source of signal distortion. Proper application of current sensors requires:

- Verifying *di/dt* does not exceed the *di/dt* rating of the sensors.
- Response time of sensor is greater than the rise time of the current.
- Frequency content of phase current does not excite the undesirable region of the sensor.
- Sensor electronic components have specifications within expected frequency range.
- Ground, power supply integrity, and anti-aliasing filter effectiveness are not compromised by power/control board layout and inter-ground impedance.
- Employing sound layout practices or shielded sensors to reduce interference and improve signal fidelity for control purposes.

Sensor models for purposes of analysis and design require:

- A complexity dependent on the bandwidth of interest.
- System modeling techniques for accurate high frequency models.

Recommendations

- Employ shielded sensors to maximize fundamental component fidelity for zero vector sampling.
- Employ high sampling rate ADC and averaging principles in lieu of zero vector sampling can mitigate the undesirable characteristics of the sensor.
- Sampling rates must be based on the expected cable oscillation and rise time frequencies to prevent aliasing.

MODELING OF EMI

This section discusses EMI high frequency parasitic models for the Drive, Cable, Motor and System Differential Impedance and System Common Mode Impedance in the pursuit of determining I_{ll} and I_{lg} transient currents.

Drive Model

IGBT Parasitics: Today's IGBT combines the advantages of Metal Oxide Semiconductor Field Effect Transistor (MOSFET) with those of BJTs. An investigation into the high frequency behavior of IGBT ASDs requires modeling of the device and its environment. This requires models beyond the traditional lumped parameter approaches. High frequency modeling in this context must extend to the MHz range. Fig. 49 is a representative high frequency IGBT model; it retains the basic functionality and incorporates many parasitic elements [32]-[34]. Among the internal parasitics, the inter-region capacitances, gate to emitter (Miller), emitter to collector, and gate to collector, play significant roles in the life of the device and quality of the control [27], [35].

The consequence of high frequency parasitics becomes apparent when their effects are not accounted for in the design or when a drive is misapplied. Fig. 50 shows a 6-pack module rated 1200v and 8 amperes. The drive supplied a 1 hp motor by a 250 ft (75 m) of cable. In this case application guidelines- limiting cable lengths to < 100 ft.-were not followed. Arrows point to melted emitter regions of the individual IGBTs. An analysis concluded "excessive current" caused the damage, even though the "load" was well within the device rating of 8 amp. Clearly, the hardware overcurrent protection failed. Furthermore, the over temperature sensor did not sense the excessive heat calling into question its efficacy in this application.

With inadequate analysis at the design stage or misapplication in the field, the consequence of high frequency differential and common mode currents can result in increased downtime, customer dissatisfaction, and increased failure rates. Direct linking of cause and effect for the results shown in Fig. 50 requires a level of modeling, analysis, and design not often employed. Thus, the interaction of power devices with system parasitics brings an added dimension to drive design. To outline a system design methodology, each of the system components – motor, cable, and drive sensors – are examined in the following sections.

Cable Model

Cable Design and Construction: Power cables for ASDs come in a number of configurations. Fig. 31 shows the more common arrangements. Low frequency performance is essentially identical for all cables. Differences arise as the frequency increases. A simple examination of the physical construction will establish the cables presenting a high frequency impedance imbalance to the drive. For example, Fig. 31 presents a standard four-conductor tray cable. The unsymmetrical arrangement produces an asymmetrical coupling between conductors.

To minimize field problems and to ensure drive reliability, ASD manufactures may specify a special motor cable. For example, Fig. 31 has three phase conductors and three ground wires placed uniformly inside a Continuous Welded Aluminum Armor casing which is covered within a single PVC sheathing. The multiple ground conductors minimize the field imbalances between the phase conductors and ground. The armor assists in containing and draining off the capacitively charged, CM current or electrical noise.

Cable Modeling Fig. 4 depicts a typical cable. Per unit length cable elements include DM RLC parameters (R, L, C_{ll}) and CM capacitive elements to the ground conductor (C_{lg}) and to shield or conduit ($C_{lg\text{-}c}$). Proper modeling of the power cable is based on the bandwidth to be investigated. This is accomplished by modifying the elemental model to accommodate the desired frequencies. This can range from a lumped parameter series RLC or π equivalent to a distributed or transmission line representation [36]-[41]. For example, low frequency analysis may allow neglecting the capacitance and converting the distributed series RLs into a series lumped parameter model with values corresponding to the cable type and length. On the other hand, high frequency modeling (> 100 kHz) may require knowledge of the coupling impedances and/or traveling wave models.

The DM open ended cable impedance as a function of cable length can be discerned from Fig. 45. The motor presents a DM impedance with an impedance null at approximately 30 MHz. Adding 10 ft (3m) of cable in series with the motor shifts the first impedance null to 7 MHz. This shift occurs because the DM cable capacitance is in parallel with the motor DM impedance. Adding a 300 ft (90m) cable results in the capacitance dominating and shifting the first null to 400 kHz. Additionly, DM impedance nulls appear. The significance of these nulls is dependent on the DM voltage spectrum. Relative to BJT inverters, today's IGBT inverters have substantially larger voltage at these frequencies as discussed earlier. Thus, high frequency DM currents are present, which challenges the design of the current sensor and protection circuitry, and adversely affects the control [27], [28], [39-41]. Employing relatively simple models for the motor, cable, and inverter allows the design engineer to examine the dominant system components and their interaction with today's IGBT power converters.

The CM cable impedance is comparable to the DM cable impedance, except it starts as a high impedance, decreases to a low impedance null with increasing frequency, and exhibits a repetition peak and null as expected.

Motor Model

The five element motor model is the standard for motor control and analysis. Limitations of this fixed – lumped parameter model are evident over the entire frequency spectrum [39]-[48]. It is the authors' experience, confirming the conclusions of other investigators, a reasonable upper limit for modeling the machine's differential impedance as an inductive system is in the range of 10 kHz – 100 kHz [48], [49]. Above this range the machine appears capacitive into the 1-3 MHz range. Beyond approximately 3 MHz the machine resembles a transmission line.

When modeling ac machines to account for high frequency effects an engineer must determine the complexity necessary to represent the phenomena to be investigated. If the inner turn voltage distribution is desired, then a Finite Element Analysis (FEA) may be needed. In this case, motor differential (C_{mll}) and common mode (C_{mg}) capacitances of Fig. 4 would be modeled. An FEA analysis may be conducted to provide equivalent circuit parameters for a motor model, as in Fig. 51 [50]. However, an investigation of motor overvoltages resulting from IGBT ASDs may only need a simple tank circuit as in Fig. 52 [40]. In this case, simple system identification measurements combined with an appropriate parameter optimization algorithm may be adequate. Here the objective is not accuracy of minute details of the terminal voltage, but an estimate of the expected peak terminal voltage for selecting the mitigation method [13], [39].

Fig. 53 and Fig. 54 shows an example of applying the tank circuit to an investigation of motor overvoltages. Fig 53 shows the DM impedance for 1 hp induction machines. The impedance plots – motor A and motor B - bracket the tested sample. A polynomial equation resulting from a least squares fit of the averaged data is also included. Finally, the tank circuit parameters are determined using the polynomial expression and an optimization routine [45]. This motor model is combined with a cable model and a simulation developed to examine the particular application [39-41,47,51,52].

Fig. 54 shows experimental and simulation results for a simple line charging condition and 500 ft (150m) of #12 AWG cable. A distributed cable model was employed with a 50 ns IGBT rise time device model. The motor voltage is dominated by the cable oscillation frequency, which the simulation accurately reproduces. Also, the simulation's peak terminal voltage is within 5% of the experimental results.

Motor CM impedance has also been researched [44], [48]. Similar to the open ended cable CM, motor CM impedance is low frequency dominated by capacitance and exhibits a sequence of node and anti-nodes with increasing frequency.

System Model

System Impedance – Differential: Characterizing the system/load impedance aids in drive design and its proper application. Understanding the load impedance as a function of frequency and cable length, brings an added dimension to the design process by bounding the current spectrum. Knowing the current spectrum allows the design engineer to make informed decisions as to proper current sensing technology. The line-to-line current transient I_{ll} can be modeled from the differential impedance study and decisions on acceptable current sensor response can be made.

Fig. 45 displays the calculated system differential impedance vs. frequency for three different systems, a 10 hp (7.5kW) induction motor, the motor with 10 ft (3m) of #12 AWG cable, and the motor with 300 ft (90m) of #12 AWG cable. These impedance characteristics approximate those corresponding to a non-zero state of the drive. Each case presents a significant variation in impedance, with the nodes and anti-nodes increasing in number and moving into the lower frequency spectrum with increasing cable length. System component impedance functions combined with the voltage spectrum of IGBT drives result in complex current spectrums. Establishing the exact current signature is impossible, but knowing the trends aids in the design and application of IGBT ASDs.

System Impedance – Common Mode: Characterization of the common mode system / load impedance was done in [13] for a 250 hp ASD application with 163 one hp motors and over eight miles (13 km) of wire in conduit that was switched synchronously. The result was an I_{lg} current transient of over 400 Apk. CM modeling techniques for the components in the system and solutions to reduce I_{lg} are given in reference [13].

EMI STANDARDS & TEST METHODS

EMI standards that define allowable conducted and radiated emission levels for ASDs are discussed in this section. Functional description of the test equipment and test methods required is also described. Lastly, conducted and radiated emission test results are demonstrated for an ASD used with shielded cable and various EMI filter solutions. The following topics are covered in further detail.

- ***How Do EMI Filters Work?***
- ***Conducted & Radiated Emission Levels***
- ***Frequency Characteristics of Noise Source***
- ***Line Impedance Stabilization Network***
- ***Typical EMI Filter Schematic***
- ***Measurement of Conducted Emissions***
- ***Measurement of Radiated Emissions***

How Do EMI Filters Work ?

Proper grounding and cabinet layout, proper shield termination of control wire, use of shielded input/output power cables and CM cores on drive power and drive interface leads solve the majority of drive EMI problems. However, an additional EMI input filter may be required to reduce EMI conducted and radiated emissions low enough for European CE *Class A* and *Class B* conformity standards, FCC *Class A* or *Class B* standards, or for drives installed in residential areas where potential AM radio and TV interference problems exist.

Line-to-ground current I_{lg} was shown to be transiently sourced from the drive output during IGBT risetime and fall time voltage transitions, with I_{lg} returning via the ground grid to the ASD supply transformer *Xo* connection and back to the drive, via one or all of the three phase input lines.

CM cores on the drive output reduced the peak I_{lg} current and slowed the effective *di/dt* risetime from phase-to-ground. Shielded drive input cables to transformer supply *Xo* and shielded output motor leads collected most of I_{lg} and kept it out of the ground grid, so that CM noise voltages across the ground grid are minimized.

The EMI filter of Fig. 35 works on the same series path described. However, instead of a high impedance CM core to limit ground current at the drive output leads, the EMI filter contains a large CM core inductance and individual phase inductors that are high impedance "blockers", to limit the high frequency series ground return current to extremely low values in the ac MAIN supply. EMI filters also contain CM line-to-ground ac rated capacitors, which function as low impedance bypass capacitors that re-route most of the high frequency ground noise current I_{lg}, returning on the output shielded cable, back to drive ac input terminals and out of the ground grid. Examination of Fig. 35 shows EMI filters are only effective if used with shielded output cable, that is bonded to the drive frame and motor frame. This insures I_{lg} is contained in the shield and not in the ground grid between *Potential* #2 and #3, where a large loop antenna area could be formed. Fig. 35 also shows EMI filters are ineffective, if the filter frame is not bonded and in close proximity to the drive frame, since this allows I_{lg} to generate a noise voltage and radiated emissions between *Potential* #2 and #1. Likewise, input shielded cable is required to limit radiated emissions between ac input R,S,T terminals and the EMI filter output, which is returning noisy I_{lg} current. However, standard three wire tray cable can be used to the EMI filter input, since very little CM noise current exists there.

Line Impedance Stabilization Network (LISN) equipment at the EMI filter input in Fig. 35 detects noise voltage (V_n) developed in the plant ac MAIN supply. LISNs measure CM noise voltage, since CM is greater than normal mode noise and is the predominant field problem.

Conducted & Radiated Emission Levels

Maximum allowable drive noise voltage conducted into power lines, without interference to external line equipment, is typically stated in *dBV* or *dBμV*, due to large noise attenuation ratio's defined in Table III. A 100 μV noise level above 1 μV is thus expressed as 40 *dBμV* with V_{in}=1 μV, V_{out} =100 μV.

$$V_{n\,(dB)} = 20\ \mathrm{Log}_{10}\,(V_{out} / V_{in})$$

Table III. EMI Performance vs. Noise Level

Attenuation (dBV)	**Attenuation (Voltage Ratio)**	**EMI Protection**
0 to 10	1:1 - 3:1	Poor
10 to 30	3:1 - 30:1	Minimum
30 to 60	30:1 - 1000:1	Average
> 60	1000:1	Good

LISNs measure noise voltage and spectrum analyzers convert it to *dBμV* units over the sanctioned conducted emission frequency band of 150 kHz to 30 MHz. Limits from 10 kHz to 150 kHz are proposed but not required at this writing. Quasi-peak (QP) detectors streamline EMI measurement time but have higher QP *dBμV* limits than Average *dBuV* of Table IV. Fig. 55 shows allowable conducted emission limits from a Quasi-peak detector in *dBuV vs. Frequency*.

Radiated electric field emissions are expressed in *dB mV/m*, rather than V/m, when comparing EMI results. Thus, 1 mV/m using V_{out} = 1000 µV and V_{in} = 1 µV results in 60 *dB µV/m.* Radiated emission interference problems are noticeable on AM radio, TV and radio-controlled devices more so than for industrial instrumentation. Radiated troubles may begin at field strengths of 0.1 V/m to 3 V/m [5].

European Union basic EMC standards applied to drives are listed in EN55011, while specifications that declare emission limits are found in generic EMC standards applied to drives listed in EN50081-1 and EN50081-2 [53]. *Class B* limits for residential, commercial and light commercial sites follow EN50081-1, while *Class A* limits for heavy industry sites follow EN50081-2. *Class B* limits are mostly needed to eliminate AM radio and TV interference problems.

Table VI. Allowable CE Emission Levels

Conducted Emission Limits [dBµV] over 150 kHz - 30 MHz			
Class	150 kHz – 500 kHz	0.5 – 5 MHz	5 – 30 MHz
A	AV (66), QP (79)	AV (60), QP (73)	AV (60), QP(73)
B	AV (56-46), QP (66-56)	AV (46), QP (56)	AV(50), QP(60)

Radiated Emission Limits [dBµV /m] over 30 MHz - 1GHz		
Class	30 MHz - 230 MHz	230 MHz - 1 GHz
A @ 30 Meters	30	37
B @ 10 Meters	30	37

CLASS A = EN 50081-2 , CISPR 11, GROUP 1
CLASS B = EN 50081-1 , CISPR 22, GROUP 2

Frequency Characteristics of Noise Source

PWM output voltage, internal SMPS, and drive semiconductor transients are the main EMI noise sources in the conducted emission test frequency range of 150 kHz to 30 MHz.

Line-to-line ASD output voltage waveforms of Figs. 2 and 3 induce an associated high frequency line-to-line cable charge current transient, which is sourced and returned to the ASD, totally within the output phase wires in Fig. 18. The use of shielded output cable alone solves any radiated emission problem due to this current.

The neutral-to-ground CM ASD output voltage waveform of Fig. 9 induces an associated high frequency line-to-ground noise current transient through stray system cable and motor capacitance. The current transient is sensed by the LISN in Fig. 35 and subsequently converted to *dBuV* readings. This section shows that measured LISN *"Voltage vs. Frequency*" spectrum is proportional to ASD *"CM Voltage vs. Frequency*" spectrum of Fig 11.

The SMPS has similar voltage spectrum waveshape as the PWM output voltage and also induces CM and normal mode noise voltage that can exit out both ASD input and ASD output power leads to ground.

Other noise sources are semiconductor recovery voltage spikes, creating noise in the 20 - 30 MHz ranges that exit both input and output power leads to ground.

Line Impedance Stabilization Network

LISNs in Fig. 35 stabilize line impedance at 50 Ω for noise voltage measurements greater than 1 MHz. Variations in measured noise voltage due to different user line impedances or EMI filter interactions is thus eliminated. Fig. 56 shows a single phase schematic of a CISPR 16 three phase LISN with Drive Under Test (DUT) and ac MAIN phase-to-ground connections. Components change with current rating and frequency range. L_1 simulates typical line inductance of 50 µH. L_2, C_3, R_5, C_2, R_3 form an ac MAIN filter preventing external noise from affecting DUT noise voltage measurements in the 10 kHz to 150 kHz range. In the 150 kHz to 30 MHz range, L_2, C_3, R_5 are not used and R_3 = 0. LISNs measure conducted drive noise via the high frequency bypass capacitor C_1, which routes CM high frequency noise voltage to the $R_1 + R_2$ = R = 50 Ω measuring device. In the 2nd range of interest here, LISN impedance is a parallel L_1 inductor and resistor R = 50 Ω for frequencies > 1 MHz.

Typical EMI Filter Schematic

EMI filters are comprised of single stage L-C filters, each with the characteristic second order - 40 dB/decade attenuation from resonant frequency ($f_r = 1 / (2\pi(LC)^{0.5})$). Thus, if -40 dB attenuation at undesirable noise frequency f_n is desired, then filter L and C components are selected for $f_r = f_n / 10$. EMI filter designs must minimize capacitor $I_{leakage}$ to ground for safety reasons and insure filter resonance with drive noise sources does not occur under any ASD operating condition

In the multistage EMI filter of Fig. 57, load side (Y_{1load}) capacitors are high frequency bypass capacitors to CM I_{lg} noise generated during drive output switching. Line-to-ground impedance ($Zc = 1 / (2 \pi f_n C_y)$) is lower at (Y_{1load}), than a CM current path from ASD PE to transformer *Xo*, to the three phase ac MAIN line and through the high impedance filter inductor "blockers" ($Z_L = 2\ \pi\ f_n$ L). The Y_{2load} capacitor in series with the X_{2load} line-to-line capacitor, also functions as a CM line-to-ground bypass filter for I_{lg}. Thus, the first stage L_1' line-to-ground noise voltage is very low and is ~ $I_{lg} * Z_c$. Differential inductor (L_{PHASE}) and CM inductor (L_{CM}), along with Y_{1line}, X_{2line}, and Y_{2line} form an additional line-to-ground filter stage that attenuates $V_{L1'\text{-ground}}$ noise voltage by another 40 dB/decade stage to the required *dBμV* level.

Line-to-line high frequency noise appearing at the ASD ac line R,S,T terminals is primarily reduced in amplitude by the X_{2load} bypass capacitors. CM inductors L_{CM} insert minimal inductance line-to-line, so that phase inductors L_{PHASE} and X_{2line} capacitors attenuate line-to-line noise by another 40 dB/decade stage to the required *dBμV* level.

Measurement of Conducted Emissions

No Filter: *Curve A* of Fig. 55 shows a 480V ASD with *fc* = 4 kHz exceeds *Class A & B* margins. The wide band of noise frequency is due to the PWM pulse width constantly changing over a given fundamental frequency cycle. The expected -20dB/dec decay rate of the spectrum envelope is evident between 400 kHz and 4 MHz as predicted in Fig. 11. The spectrum breakpoint frequency ($0.32/t_{rise}$) that correlates with the IGBT risetime and fall tine of 50 – 100 ns is also evident at 3 MHz -6 MHz. The measured attenuation slope change past this breakpoint agrees with the theoretical –40 dB/decade as predicted in Fig. 11.

Standard Filter: *Curve B* of Fig. 55 shows the ASD still exceeds *Class A & B* margins, even with the standard 2-stage EMI filter of Fig. 57. The 5 MHz noise frequency correlated to the IGBT voltage risetime and induced I_{lg} risetime, is now much more prevalent. A 12 MHz peak is due to semiconductor risetime of the SMPS.

Standard Filter & Shielded Cables: *Curve C* of Fig. 55 shows 20 to 30 *dBμV* improvements by using shielded cable on the ASD input and output power leads. The IGBT risetime peak at 5 MHz is reduced 30 *dBμV*, as well as 20 *dBμV* attenuation of the SMPS risetime peak at 12 MHz. This indicates that the low impedance of the co-axial shielded armor cable insures most of the CM I_{lg} current goes directly to the EMI filter CM caps, and back to the drive input as expected. This leaves little high frequency noise current coupled into the ground grid and ac MAINS supply before the LISN. Continuous welded aluminum armor Metal Clad cable and braided copper shield tray cable have reduced EMI emissions over both conducted and radiated frequency range. The co-axial nature reduces conducted emissions, while the seamless characteristic or high coverage flexible braid of these cables have attenuated radiated electric fields due to noise by eddy current shielding.

Special Filter & Shielded Cables: *Curve D* of Fig. 55 shows *Class B* requirements are met when using a special designed EMI filter matched to the ASD, along with shielded armor cable on the drive input and output power leads. Solid wire bonding practices to the metal of both drive and EMI filter and use of a metal cover for the drive are also required.

Measurement of Radiated Emissions

An EMI filter conforming to the conducted emission limits in the 150 kHz to 30 MHz band is an essential component required to also meet radiated emission test requirements in the specified 30 MHz to 1 GHz frequency band, as in Fig. 58. However, the ultra fast clock transitions of logic boards, shielded logic cables and printed circuit board layout are also a dominant influence at these ultra high frequencies. EMI technology has progressed to the point, where the use of metal covers to control ASD radiated emissions, has now been replaced with plastic covers using selective application of metalized coatings.

Conclusion

Today's automation controllers bring together control architectures and motor controllers that only a few years ago were unheard of. However, their proper design and subsequent installation requires attention to areas previously of minor concern. High dv/dt associated with today's IGBTs forces design engineers to consider the interaction of all functional elements-device, package/layout, control, communications, and system components – before production.

Both the design and applications engineer are better prepared to address problems when supported by an understanding of the consequences of common and differential mode interference, including its cause, effect, and mitigation. To assist in this preparation, the article presents the method and conditions by which an Adjustable Speed Drive (ASD) produces high frequency differential and zero sequence current, which may interfere with drive sensors and sensitive electronics found in industry applications.

Design, layout, and interface of drive sensors require a system's approach, which accounts for the interaction of device, cable, and load. Ultimately, compromises are made, resulting in limitations (e.g. cable length) imposed by the application.

It is difficult to predict when an ElectroMagnetic Interference EMI issue will occur. Vendor variations in the noise thresholds of electronic equipment must also be known and considered, along with system application variations in line-to-ground capacitance with hp, cable length, cable type, grounding philosophy, power device pulse risetime variation, carrier frequency, output frequency, line reactor usage and use of single vs. multi-drive systems. However, from observations made, it appears that lower hp drives (< 10 hp) with short output cables may not create enough ASD induced zero sequence current to cause EMI issues.

It is always desirable to know when to apply corrective measures to avoid EMI problems up front before the equipment is installed, so that the system can be properly designed from the beginning rather than finding the problem in the ASD start up phase. Several corrective measures can be implemented in the pre-installation phase, including proper grounding, proper panel layout of drives and controls, proper cable selection and shielding of input and output power cables, proper shielding of control and interface cables, and sufficient separation distance of ASD power leads from signal leads. These measures are found to fix (or prevent) the majority of drive related EMI problems. Many of these are found in ASD vendor application and installation guidelines.

Post-installation EMI issues sometimes occur after an installed base of ASDs have been working correctly with other system automation equipment. Additional sensitive electronic equipment of unknown noise threshold or additional quantity of ASDs may have been added to change the system conditions. In this case, simple corrective measure to further attenuate the noise such as Common Mode cores, line reactors or adding high frequency bypass capacitors to the drive terminals is possible. Past experience has shown the use of drive EMI filters has been limited to residential areas where TV and AM radio interference are of concern.

If it is desired to avoid ASD generated zero sequence currents and voltages from entering other portions of the plants electrical system, shielded input and output power cables with an isolation transformer, connected delta-wye grounded, can be used to provide the most predictable control over the noise path taken.

However, while this article has brought attention and awareness to EMI issues, there have been hundreds of thousands of drive installations with no EMI issues when following the basic guidelines presented.

A case in point is one industrial site with over 5,000 drives in the plant and interfacing with the full sophistication of automation equipment from laptop computers to Personal Computers, Programmable Logic Controllers, analog controllers and mainframe computers.

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Appendix of Terms

	Isolation transformer output terminals
ADC	Analog to Digital Converter
AM	AM radio broadcast band (535 kHz to 1.705 MHz)
ASD	Adjustable Speed Drive
AWG	American Wire Gauge
BJT	Bipolar Junction Transistor
c	Speed of light $c = 3*10^8$ m/s
CE	
C_f	EMI filter high frequency bypass capacitor
CISPR	
C_{lc} - C_{lg-c}	Capacitance - line to shield or conduit
C_{lg} - C_{l-g}	Capacitance - line to ground
C_{lg-m}	Capacitance - line to ground motor
C_{ll}	Cable Capacitance line-to-line
C_{ll-m}	Differential Mode Capacitance - motor line to line
CM	Common Mode
CMMR	Common Mode noise Rejection Ratio
C_{s-HI} C_{s-LO}	Capacitance HI and Low signals
CT	Current probe
dB	Decibel
di/dt	change in current per unit time
DM	Differential Mode
DUT	Device Under Test
dv/dt	change in voltage per unit time
EMI	ElectroMagnetic Interference
f_c	Carrier frequency
FCC	Federal Communications Commission
FEA	Finite Element Analysis
FM	FM radio broadcast band (88 to 108 MHz)
f_n	noise current frequency
f_o	ASD output frequency
f_r	risetime frequency
GFI	Ground Fault Indicator
GHz	Gigahertz
GND	Ground
HRG	High Resistance Ground
$I_{0-1-2-3-4-5-6}$	Current between referenced nodes
IGBT	Insulated Gate Bipolar Transistor
I_{lg}	ASD output line-to-ground current
I_{ll}	ASD output line-to-line current
I_{motor}	ASD output phase current
I_p	Hall effect sensor primary current
I_s	Hall effect sensor secondary winding current
I_{signal}	Signal ground

kHz	Kilohertz
L_{01} L_{02} L_{03}	Cable Inductance line-to-line
l_c	Critical distance
L_f	EMI filter series inductor
LISN	Line Impedance Stabilization Network
MC	Metal Clad cable
MHz	Megahertz
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
NEC	National Electric Code
ns	nanosecond = 10^{-9} second
PC	Personal Computer
PE	Power Equipment ground
PLC	Programmable Logic Controller
PVC	Poly Vinyl Chloride
PWM	Pulse Width Modulation
QP	Quasi Peak detector
R_{01} R_{02} R_{03}	Cable Resistance line-to-line
RF	Radio Frequency bandwidth (see AM and FM)
RFI	Radio Frequency Interference
RLC	Resistive, Inductive, Capacitive
rms	root mean square
RST	ASD ac line power terminals
SCR	Silicon Controller Rectifier
SMPS	Switch Mode Power Supply
TE	True Earth ground
THD	Total Harmonic Distortion
TV	Television broadcast bands (54 – 72 MHz, 76 – 88 MHz, 174 – 216 MHz, and 512 – 806 MHz)
UVW	ASD output power terminals
V/Hz	Volts per Hertz
V_0, V_1, V_2, V_3, V_4, V_5, V_6	Voltage potential at node 0-6
$V_{0-1-2-3-4-5-6}$	Voltage between referenced nodes
V_{dc_bus} V_{bus} V_{dc}	ASD dc bus voltage
V_n	Noise voltage
V_{ng}	motor winding virtual neutral point
V_s	Sending end signal
V_{u-v} V_{u-w} V_{v-w}	ASD output line-to-line voltage
Xo	transformer winding or motor winding neutral point
λ	Wavelength
μs	microsecond = 10^{-6} second
τ	Pulse width (tau)
t_{rise}	Power device pulse risetime