Installation Considerations for IGBT AC Drives

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Abstract: In the last four years, Adjustable Speed ac Drive (ASD) manufacturers have migrated from Bipolar Junction Transistor (BJT) semiconductors to Insulated Gate Bipolar Transistors (IGBTs) as the preferred output switching device. The advantage of IGBTs over BJTs is that device rise and fall time switching capability is 5 - 10 times faster, resulting in lower device switching loss and a more efficient drive. However, for a similar motor cable length as the BJT drive, the faster output voltage risetime of the IGBT drive may increase the dielectric voltage stress on the motor and cable due to a phenomenon called reflected wave. Faster output *dv/dt* transitions of IGBT drives also increases the possibility for phenomenon such as increased Common Mode (CM) electrical noise, Electromagnetic Interference (EMI) problems and increased capacitive cable charging current problems. Also, recent experience suggests any Pulse Width Modulated (PWM) drive with a steep fronted output voltage wave form may increase motor shaft voltage and lead to a bearing current phenomenon known as fluting. This paper provides a basic understanding of these issues, as well as solutions, to insure a successful drive system installation.

I. INTRODUCTION

A. Why the Migration to IGBT devices ?

The low switching loss feature of the IGBT is advantageous to both drive and motor. Reduced semiconductor switching loss results in smaller heat sinks and ultimately lower drive package cost. The IGBT being a voltage rather than current controlled gate device has a lower base drive circuit cost that also results in lower drive package cost. The low switching loss, along with fast transition times, may now allow higher carrier or switching frequencies (f_c) in the 6 to 12 kHz region compared to a 1 to 2 kHz limitation for BJTs. As shown in Fig. 1, higher f_c frequencies of IGBT drives produce less peak current ripple, thus producing less current harmonic motor heating and allowing rated motor torque with lower peak current than BJT drives. IGBT drives with high f_c values have substantially reduced motor ripple current and better torque performance in the low speed region < 10 Hz, where motor counter EMF sinewave voltage is minimal and ripple current is predominately a function of motor leakage reactance and switch interval time. The higher f_c frequency now obtainable also reduces motor lamination noise in the audible range. These system advantages have created a greater demand for IGBTs, thereby shifting semiconductor manufacturer cost reduction efforts toward the IGBT and making IGBTs the preferred switch for next generation drives.

B. Installation Issues

***(1) Old VFD Issue - Motor Harmonic Heating*:** A PWM drive output does not produce a sinusoidal output voltage wave form but generates a train a continuous train of pulses as in Fig. 4. Each pulse voltage magnitude is the dc bus voltage (~ 1.4 x Input system rms voltage) and pulse *dv/dt* transition rise / fall time, illustrated in Fig. 10, was on the order of 0.5 to 2 µs for BJT drives. The main installation concern of these drives was determining the motor derating required to handle the additional motor heating due to current and voltage harmonics of the non sinusoidal wave forms [1,2]. This issue of VFD rating for motors in Fig. 2 has historically been addressed by specifying Inverter Duty Rated Motors to NEMA MG 1 part 30 and NEMA MG 1 part 31 [3,4]. Figure 3 shows that a motor, at rated frequency and load, under inverter operation may have a 10°C higher temperature rise than the same motor on sinewave power [5]. Constant Torque (CT) type loads further increase motor temperature rise in Fig. 3 as drive output frequency (motor speed) is reduced. This is due to reduced motor cooling since the internal motor fan speed is also reduced. At some frequency an external fan is required for CT loads. Variable Torque (VT) rated loads usually have maximum temperature rise at rated load and frequency. Some drive manufacturers are supplying a "Power Match Matrix" approach for CT and VT type loads so that the correct drive and motor are matched to the application and the customer is not burdened with motor heating issues [6].

Besides improper VFD rating, inadequate cooling is another application issue resulting in premature motor life. As seen in Table I, maintaining a cool, dry environment that is free of contaminants is essential to any drive - motor application.

Table I. Survey of Motor Failures* [5]

Cause of Failure		%
Contamination		43
Moisture	17	
Oil & Grease	20	
Chips & Dust	5	
Chemical	1	
Overload (Overheating)		25
Bearing failures		12
Single phasing		10
Normal insulation deterioration from old age		5
Miscellaneous		3
Unknown		2

* based on 4,000 failures over several years

(2) New VFD Issue-Motor Voltage Stress & EMI However, IGBT drives introduce additional drive system issues relative to motor selection, load cabling and installation due to voltage transition capability that is now in the 0.05 to 0.4 µs range. The faster drive output risetimes now have a greater influence on motor and cable transient voltages and emphasize a need to understand the reflected wave phenomenon [7-9] and its solutions [10]. Faster output *dv/dt*, defined as pulse dc bus voltage magnitude divided by pulse transition time, interacts with stray system capacitance to generate higher magnitudes of electrical ground noise current than with BJT drives and may affect installations with sensitive electronic equipment. This phenomenon is termed Common Mode noise and is further discussed along with simple solutions. Electrical noise discussion is extended to include EMI noise mitigation methods to insure AM radio interference from drive operation is totally eliminated. The faster output *dv/dt* also increases parasitic cable capacitance charging current which increases apparent rms output current and affects the maximum motor cable distance allowed for IGBT drives < 3 hp. Lastly, the steep fronted output switching wave form from all manufacturers of PWM drives, both BJT or IGBT, create a neutral shift of the motor neutral with respect to frame ground potential. Capacitive coupling from the motor stator winding neutral to the rotor increases the rotor shaft voltage as compared to that under utility sinewave source excitation. Increased shaft voltage may lead to increased bearing currents which may pit the bearing raceway. The specific application and condition where this becomes

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an issue is discussed along with possible solutions.

II. REFLECTED WAVE PHENOMENON

A. Background of Reflected Wave Problem

Fig. 4 shows a PWM drive output waveform with peak pulse voltage equal to dc bus magnitude (V_{bus}). Fig. 4 also shows peak pulse voltage at the motor terminals is not necessarily V_{bus} but has momentary transient over-voltages at every pulse transition. This over-voltage phenomenon, known as "Reflected Wave", "Transmission Line Effect" or "Standing Wave" may produce potentially destructive voltage stress on the motor insulation. The per unit overvoltage magnitude (motor $V_{ll(pk)}$ / drive V_{bus}) is dependent upon drive-cable-motor circuit dynamics defined by drive output voltage magnitude and risetime, cable surge impedance characteristics, motor surge impedance to the pulse voltage, cable length and spacing of the train of pulses by the PWM modulator [11].

Transmission line theory basics for pulses sent down an initially uncharged cable is reviewed in [12]. From theory, whenever cable surge impedance does not match load (motor) surge impedance, a reflected wave may occur at the load terminals. Reflected wave magnitude is dependent on the extent of impedance mismatch occurring, with a maximum value equal to incoming pulse voltage [11,12]. Incoming pulse and reflected wave magnitudes add so that, in theory, up to twice bus voltage (2 pu) may exist on line to line motor terminals for an uncharged cable condition. Reference [12] also shows cable to motor surge impedance mismatch is greatest for motors < 50 hp, so that potential for twice bus overvoltage peaks (1264 Vpk / 650Vdc = 1.95 pu) is greatest in this range. A single 2 pu pulses of Fig. 4 is expanded in Fig. 5.

Drive pulse risetime is controlled by semiconductor device switching time and determines a critical cable distance l_c where 2 pu peak motor over-voltage is fully developed. Critical distances for various semiconductor risetimes are shown in Fig. 6 using results from "Standing Wave" analysis techniques [11]. Reflected wave phenomenon has always been possible on AC motors with older BJT and GTO device technology. However, 2 pu voltage occurred outside the realm of normal application distances < 200 ft. Fig. 6 shows that, for a given motor cable length, as device technology has changed, the transient motor overvoltage *magnitude has steadily increased along with faster risetimes*. Thus, reflected wave is now an application issue to consider. Fig. 6 calculations and Fig. 7 test data show that cable lengths < l_c. develop correspondingly less than 2 *pu* overvoltage. Cable lengths > l_c. will have at least 2 *pu* voltage and possibly up to 3 pu values depending on a complex interaction between PWM modulation techniques, spacing of PWM pulses, carrier frequency selected, cable natural frequency of oscillation and cable high frequency damping losses [13].

Basically, motor voltages may be > 2 pu depending on zero voltage dwell time spacing of the PWM line to line voltage pulses. High carrier frequencies space pulses closer together and may not let the unterminated transient voltage in Fig. 5 to fully decay before the next pulse. This usually occurs on long cable lengths where trapped charge on the cable can create terminal voltage greater than the theoretical transmission line estimate of 2 pu. A > 2 pu phenomenon might also occur in pulse dropping regions of a drive operating between 45 Hz and 60 Hz output. These conditions are difficult to predict without simulation because of the dynamic interaction between modulation and cable. Typical test results for unterminated > 2 pu motor voltage vs. Cable Length are shown in Fig. 7 starting at 100 ft for a 4 kHz carrier frequency selected. The highest peak motor overvoltage at each cable length was recorded in Fig. 7.

B. Effect of Transients on the Motor

The magnitude and risetime of the reflected wave has a major influence on the dielectric withstand capability of the motor. Drive output risetime may be measured or obtained from drive vendors. Reflected wave voltage magnitude at a certain cable length may be estimated from Fig. 6 for distances < l_c. The value is best obtained from drive vendors for cable lengths > l_c., where > 2 pu may occur, since it is modulation dependent and may go as high as 3 pu. Fig. 8 shows various motor vendor insulation dielectric capability to withstand surge voltages with a given risetime [11]. Also shown is an IEEE working group report on estimating maximum magnitude and risetime surge capability for a usable life of 100 non repetitive surges [14]. The high surge capability of the 480V IEEE curve at risetimes > 6 μs is limited by total dielectric breakdown of the magnet wire. Motor vendor curves for ASD operation in Fig. 8 have lower maximum values due to concern over partial discharges and corona within the motor [11,15]. This is due to repetitive reflected wave voltage stress on every pulse edge that may exceed the Corona Inception Voltage (CIV) level of the motor [16] and which occurs at the high carrier frequency selected e.g., 2,000 to 12,000 times a second. The downward derate slope of the motor vendor curves for fast surge voltage risetimes is due to a nonlinear distribution of the peak reflected wave voltage within the stator winding. High voltage stress within the winding turns may also contribute to corona induced dielectric failure. Reference [16] discusses motor failure mechanisms in more detail.

A 480 V BJT drive with dc bus of 650 Vdc, output risetime of 2 μs, and motor cable length of 100 ft will have a 1.2 pu overvoltage (780 Vpk) at the motor from Fig. 6. For the same 100 ft. cable length, a 480V IGBT drive, with output risetime at 0.1 μs will have ~ 2 pu or 1,300 Vpk at the motor. A plot of BJT operating point of 780 Vpk at 2 μs in Fig. 8 shows operation is well within motor maximum dielectric withstand capability and should expect no reflected wave issues. The IGBT operating point of 1,300 Vpk at 0.1 μs on Fig. 8 shows operation is outside motor maximum dielectric withstand capability of most vendors and may have reflected wave issues in the application. Of interest to IGBT drives is the region of Fig. 8 in the 0.1 μs range. Motor vendor *Z* has a 1,000 Vpk capability at 0.1 μs while vendors *X* and *Y* have ~ 1,200 Vpk capability at 0.1 μs. The classification of these two motor groups has been verified with corona testing [16]. Some drive manufacturers have taken the 480 V pu overvoltage vs. cable distance information of Fig. 7 and for each hp frame size, state maximum allowable safe distances that insure motor voltage is < 1,000 Vpk or < 1,200 Vpk [17]. This information allows easy determination if external protection devices are required for the cable length anticipated in the application. Customers may be relieved of coordinating peak applied voltage with motor dielectric withstand by choosing a vendor that supplies both drive and motor where drive - motor compatibility issues and options, have been investigated and tested .

Customers should only specify "Inverter Rated" motors. These motors are designed to handle the extra harmonic heating. They may or may not have extra insulation such as phase paper between windings to handle the extra dielectric stress. Inverter Rated motor designs to NEMA MG 1 part 30 standard have a 1,000 Vpk capability at 2 μs risetime. Thus, these motors are adequate for most BJT drives but not IGBT drives. Inverter rated motors designed to NEMA MG1 Part 31 para. 31.40.4.2 "Voltage Spikes" must be capable of 1,600 Vpk at 0.1 μs risetime in Fig. 8 and must be used with IGBT drives to insure dielectric survival at long cable distances. However, NEMA test standards are lacking on how to test a motor to see if it is indeed capable of repetitive 1,600 Vpk surges at 0. 1 μs risetime and also lacking on how long 1,600 Vpk inverter rated motors are expected to last in service.

C. Solutions to Reflected Wave Problem

(1) Select 240 V System Voltage: A 240 V IGBT drive has a 300 Vdc bus. Reflected wave motor voltages of 2 pu (600 Vpk) and 3 pu (900 Vpk) with a 100 ns output voltage risetime drive are within Fig. 8 dielectric withstand for standard 1,000 Vpk *Inverter Duty* motors. Field experience has also shown reflected wave is not an issue on 240 V systems.

(2)Specify NEMA MG1 Part 31 Inverter Duty Motors: 480 V systems have a 2 pu reflected wave voltage of 1,300 Vpk so that NEMA MG 1 Part 31 design of 1,600 Vpk insulation or higher is required. This motor eliminates the need for external motor protection on 480V systems as shown in Fig. 7.

(3) Limit Motor Cable Length: IGBT drives have output risetimes from 50 ns to 400 ns. Maximum cable distances that limit motor terminal voltages to 480 V motor vendor capabilities of NEMA MG1 Part 30 of 1,000 Vpk (1.55 pu) or typical 1,200 Vpk (1.85 pu) can be determined from Fig. 6 depending on drive output risetime. For example, a 400 ns IGBT drive with a 1,200 Vpk motor can have a 150 ft cable length before external protection is required. The intersection of the motor capability line and the drive pu overvoltage vs cable length curve in Fig. 7 gives a maximum allowable cable distance. Fig. 7 shows a typical 480 V drive output voltage vs. cable length intersecting a 1,000 Vpk and 1,200 Vpk motor capability line. Some drive manufacturers have given maximum cable distances for each drive hp using 1,000 or 1,200 Vpk motors, since output risetimes and cable - motor surge impedance mismatch changes at each drive hp size [17].

(4) Pre and Post Installation Solutions: If the maximum allowable motor cable distance is exceeded for existing 1,000 and 1,200 Vpk motors or 1,600 Vpk motors are not obtainable, then external motor protection may be required. Solutions such as a line reactor or R-L-C filters mounted at the inverter output or a line termination network mounted near the motor are possible.

(a) Line Reactor at Drive Output: The fast inverter output risetime interacts with the inductance of the reactor and cable - motor capacitance, so that motor terminal voltage is sloped off to a slower risetime and voltage magnitude is also reduced. Fig. 5 shows motor voltage risetime is ~ 10 μs with a 1,000 Vpk magnitude on the PWM pulse edge vs. the 1,264 Vpk at 100 ns unterminated drive pulse with no external protection. The 1,000 Vpk at 10 μs risetime pulse should be within the safe dielectric envelope of Fig. 8 for most motors. A typical peak voltage vs. cable length for this solution is shown in Fig. 7. Maximum cable lengths for coordination with 1,000 Vpk motors are extended from 30 ft with no protection to 275 ft with a reactor at the drive. The reactor extends maximum cable length to 600 ft. when used with 1,200 Volt motors as shown in Fig. 7. Reactor designs should be recommended by the drive manufacturer, since low loss reactors may actually resonant the voltage to 2 pu. Commercially available *dv/dt* filters consisting of reactors, capacitors and damping resistors are also a possibility to limit motor magnitude and risetime to < 1,000 Volt peak with a risetime of 2 μs when long cable lengths are required.

(b) Line Termination Network (LTN) near Motor: The LTN is a NEMA 4X device mounted near the motor [10-12]. The LTN theory of operation is based on transmission line analysis. The LTN passive network elements closely match the cable surge impedance so that voltage reflection is eliminated [18]. A single LTN is possible for the entire hp range from 2 to 500 hp since bundled cable surge impedance only marginally changes from #18 awg to 500 MCM and motor surge impedance is always much greater than cable impedance [12]. Motor terminal voltage is not sloped off but has the same risetime to the Vbus level as the drive output risetime. However, peak motor terminal voltage is usually less than 1.2 pu as shown in Fig. 7. Terminator waveform plots in Fig. 5 and 9 show the reflected wave peak voltage minimized for a single PWM pulse sent from the drive. The LTN will limit peak voltage at 600 ft of cable to 780 Vpk on a 480 V system and 960 Vpk on a 575 V system. Both values are safe values within the motor 1,000 Vpk at 0.1 us capability shown in Fig. 8.

III. COMMON MODE NOISE PHENOMENON

There is a possibility for electrical noise from drive operation to cause EMI interference with adjacent sensitive electronic equipment when a large quantity of drives are assembled in a concentrated area. This section discusses the basic noise problem common to all AC drives and what solutions are available to mitigate its effect.

A. What is Common Mode (CM) Noise ?

Electro Magnetic 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 equipment malfunction or non operation [19]. Common Mode Noise is a type of electrical noise induced on signals with respect to a reference ground [20]. CM Noise problems imply a source of noise, a means of coupling noise by conduction or radiation and circuits / sensitive equipment susceptible to the magnitude, frequency and repetition rate of the noise impressed [21]. Each aspect of the noise problem is covered in detail, starting with effects of CM noise on susceptible circuits.

B. Susceptible Circuits:

CM noise can affect an installation in a number of areas. Control interface examples are encoder feedback, 0-10V I/O and 4-20 ma current loop sense. PLC communication links including RS-232, RS 484, Remote I/O, Data Highway Plus, Scan bus and Device Net. Susceptible equipment examples are ultrasonic sensors, weighing and temperature sensors, bar code/vision systems, capacitive proximity or photoelectric sensors, and computers.

C. Noise Source: VFD Common Mode Output Current

All drive manufacturer's have abrupt voltage transitions on the drive output as in Fig. 10 that are an inherent source of radiated and conducted noise. The majority of drive related noise interference with PLC's, controllers and instrumentation is conducted noise currents whose magnitude is determined by the amount of stray capacitive coupling phase to ground during the fast switching voltage transitions on the drive output. Voltage transition times are essentially controlled by rise and fall times of the semiconductor technology used. IGBT drive output voltage has abrupt 0.05 to 0.1 μs transitions to and from the DC bus level, which minimizes power loss, while BJT drives are less efficient having 1 to 2 μs transition times. IGBT's have maximized drive efficiency, reduced motor current harmonics with higher carrier frequencies and reduced drive heatsink size. This is a result of low switching losses associated with fast rise times.

However, IGBT output *dv/dt* is now 10 to 40 times greater than with BJTs. Both cable and motor line to ground capacitance $C_{l\text{-}g}$ interact during this high *dv/dt* transition to generate transient phase to ground currents referred to as common mode (CM), zero sequence or ground currents. These CM phase currents (I_{ao}, I_{bo}, I_{co}) do not go to the motor and return on another phase. IGBT peak I_{ao} current may reach 20 Amp peak and is approximated from Ohm's law for capacitor circuits as $I_{ao} = (C_{l-g})\ (dv/dt)$. There is a positive and negative I_{ao} during each switching cycle. Measurements have shown peak I_{ao} is similar in magnitude for low hp as well as high hp IGBT drives.

Faster drive risetimes and higher bus voltages cause higher *dv/dt* resulting in larger CM noise current magnitudes that have a greater chance of affecting sensitive equipment. Drive voltage transition risetime determines an equivalent noise coupling frequency defined as $f_n = 0.318 / t_{rise}$. A CM ground current with a 50 ns risetime corresponds to f_n = 6 MHz noise spectrum. The higher the equivalent noise coupling frequency, the easier it is to couple into susceptible circuits. Drive carrier frequency (f_c) in Fig. 10 determines the repetition rate of noise currents coupled to ground. There is a positive and negative I_{ao} during each carrier cycle. Higher f_c will create more electrical noise. Increasing the number of drives also generates additional CM current in an installation.

D. Noise Coupling: Conducted CM Current in Ground

The system CM current path taken with poor wiring practice using unshielded phase output wires randomly laid in a cable tray and a ground wire occurring at the motor is shown in Fig. 11. A transient CM current I_{ao} is sourced out of the drive during an output voltage transition, e.g., phase "A" IGBT switching on to the + DC bus. Part of this current flows thru the cable capacitance to the grounded cable tray at *Potential #2* and I_{ao} also flows thru motor stator winding capacitance to ground and into the Power Equipment (PE) ground grid at *Potential #3* via the grounded wire at the motor. These CM currents flow thru the ground grid, bypassing drive PE, until they find the feeder transformer secondary grounded neutral, where a path back to the drive source can occur on phase A, B or C. Once inside the drive, the CM current path selects the bridge rectifier diode that is conducting back to the + DC bus source. Building structure steel provides a True Earth (TE) ground for the solidly grounded transformer neutral.

The ground grid is high impedance to high frequency ground noise current I_{ao} so that an instantaneous voltage difference across ground grid *Potential #1* through *Potential #4* are created. Noise voltage across the ground grid is referred to as Common Mode (CM) noise voltage. Common Mode voltage is impressed on the susceptible interface equipment between the drive logic ground *Potential #1* (which is noisy compared to structure steel) and a remote interface ground *Potential # 4*, which is referenced to a low noise zero voltage TE potential. Common Mode voltage is also impressed between the encoder case at *Potential #3* and drive PE logic ground at *Potential #1*. Successful encoder operation depends on how much CM noise voltage is capacitively coupled from the noisy encoder case into encoder circuitry thru stray capacitance. The slide also shows that additional equipment users referencing to ground grid potentials *V1, V2* and *V3* may also experience CM voltage problems. The ability of external interface equipment to properly function in the presence of high frequency noise depends on it's common mode noise rejection ratio threshold tested at the noise frequency f_n.

Poor Wiring practice in Fig. 11 also exemplifies a radiated emissions problem due to a loop antenna formed between drive output wires to return ground and drive input wires to return ground grid. Thus, a better wiring practice is desired prior to drive installation.

E. Noise Abatement Solutions:

There are three basic steps to drive noise mitigation: grounding, attenuating the noise source and shielding the noise current away from sensitive equipment.

(1) Grounding: The selection of a low impedance single point grounding node, drive - equipment panel grounds and selection of a ground system philosophy are important to CM noise mitigation. Noise mitigation involves a discussion of safety PE equipment ground and signal TE grounds.

(a) TE Ground: Building structure steel is usually the best connection for zero voltage True Earth (TE) potential since girders are connected together in a low impedance grid pattern that have multiple column paths into ground. Ground resistance measurements of 1 to 2 ohms between columns is typical. Ground resistance is affected by soil resistivity which is also a function of moisture content. There has been instances where TE was low impedance until the summer months when the ground water table dries up. Multiple ground rods may not be a low impedance to drive induced high frequency EMI noise current. Ground rods driven into a plant floor have exhibited 1,000 - 5,000 ohms between it and building structure steel due to stones and dry rocky soil under the concrete floor. However, ground rods in low resistivity soil may be adequate.

(b) PE Ground: A Power Equipment (PE) terminal usually serves as safety equipment ground for AC & DC drives. Ungrounded drive metal accumulates electrical charge thru leakage current resulting in voltages greater than the recognized safe touch potential of 50 V. Thus, all drive metallic parts (internal & chassis) are bonded together and a wire is brought to drive PE terminal. Drive PE is wired to a cabinet PE copper bus bar that is scraped and bonded to the cabinet metal. The panel mounting the multiple drives and other panel mounted equipment should also be bonded to copper PE bus. Insure armor, conduit and cable trays for drive input and output wires are bonded to the drive cabinet and copper PE bus, since as shown later, the PE ground also conducts drive high frequency noise currents. An appropriate sized single ground conductor leaving the cabinet (based on upstream fuse / breaker rating per NEC code) is then bonded to True Earth (TE) zero voltage ground. This insures safe touch voltage potentials exist under ground fault conditions.

(c) System Grounding Practice: Ungrounded, High Resistance or Solid Ground. The philosophy of the ground system for drive input power is usually specified by the user and based on user concerns (beyond the scope of this paper) other than electrical noise.

A solid grounded wye secondary system is a low impedance to the transient CM noise current and completes the return path back to the drive input leads from the ground grid. Highest CM current magnitude occurs with this system but very little CM noise goes out into the PE grid beyond the transformer neutral connection in Fig. 11, so that CM noise is contained. An advantage of grounded secondary systems is that primary side line to ground high voltage transients are attenuated by typically 20 dB on the secondary side, thus reducing the amount of transient energy the drive's Metal Oxide Varistors (MOV) transient protectors must handle.

A high resistance ground system would add typically 150-200 Ω to the Fig. 11 T1 secondary neutral circuit that is grounded. This resistor is in the series path of the CM noise current return and significantly reduces peak CM current magnitude to small levels such that potential differences in the plant ground grid caused by CM noise is minimal. Surge testing has shown acceptable primary to secondary line to ground transient voltage reduction.

An ungrounded secondary system breaks the CM return current path back to the drive input so very little CM current in the ground grid exists. Thus, CM noise is reduced. However, a disadvantage is that surge test results show primary to secondary line to ground high voltage transients are passed directly to the secondary side without attenuation. Also, safety concerns must be addressed with this system.

(2) Attenuate the Noise Source: The best way to eliminate system noise is to attenuate it at the source (the drive) before it gets out into the system grid and takes multiple high frequency sneak paths which are hard to track down in an installation. Past experience has shown Common Mode chokes on the drive output and CM cores on the interface equipment are highly effective in ensuring fully operational tripless systems in medium to high risk installations. A Common Mode Choke (CMC) is an inductor with output Phase A, B and C conductors all wound in the same direction thru a common magnetic core. The CMC provides a high inductance and high impedance to any line to ground based capacitive noise current generated during the drive's fast switching output voltage edges. Thus, the magnitude and rise times of these noise currents are substantially reduced below noise thresholds of affected equipment. The CMC is an optimal noise reduction technique since it does not affect the line to line power circuit while "choking" or high impedance blocking the ground based noise currents. As such, it takes up less physical space than an output line reactor. CMC's should be considered in installations with susceptible electronics. They may be used on retrofit situations, older systems with 3 wires in a conduit or preferably with the recommended shielded wiring practice to obtain maximum noise reduction benefit.

Drive PWM voltage transitions of 50-100 ns do not change when a CMC is added to the output. However, CM high frequency line to ground current magnitude is substantially reduced from 20 Amp peak to less than 5 Apk, as well as the rate of rise (*di/dt*) which is limited by the CMC inductance. Peak ground current now occurs at 5 μs instead of 100 ns and at a *di/dt* rate of 1 A/us versus 200 A/us without a CMC as in Fig. 12 The reduced ground current magnitude and low *di/dt* rate maintain ground potential difference fluctuations close to zero voltage or true earth ground. As a result, common mode voltages are reduced and error free operation of PLC, interface electronics and sensitive equipment is possible.

(3) Shield Noise Away From Equipment: The third step is to predictably control the path of the attenuated high frequency CM noise away from any sensitive equipment referenced to ground by using 4 conductors in a conduit or better yet 4 conductor shielded / armor cable with insulated PVC jacket.

(a) Shielding Noise with 3 wire plus ground Conductor in Conduit: The system CM current path taken with 3 phase output wires plus ground wire enclosed in a conduit is shown in Fig. 13. The conduit is bonded to drive cabinet and motor junction box and the green ground PE wire is connected to ground stud in the motor junction box and drive cabinet PE bus. A transient CM current I_{ao} is sourced from the drive as before. Part of I_{ao} flows thru cable capacitance to the grounded conduit wall and part thru motor stator winding capacitance to frame ground. Both green wire and conduit absorb most motor capacitive current and return it back to the drive out of the ground grid, thereby reducing "ground noise" for the length of the run as shown. A conduit may have accidental contact with grid ground structure due to straps, support, etc. The AC resistance characteristics of earth are generally variable and unpredictable. Thus, it is difficult to predict how noise current divides between wire, conduit or back to the ground grid inducing CM voltages. Drive PE cabinet wire, if grounded to building structure steel, sends CM currents back into the ground grid, thru the feeder transformer secondary grounded neutral, back to the drive input conductors and returning to the inverter noise source thru a drive input rectifier diode.

Radiated electric fields from output wires are greatly attenuated by the conduit wall. However, CM voltage problems may still exist on susceptible interface equipment between the drive logic ground *Potential #1* (which is noisy compared to structure steel) and interface TE zero voltage ground *Potential #4*. Thus, a 4 wire conduit back to the transformer source is recommended with conduit & green wire bonded to the secondary *Xo* neutral terminal and another wire from *Xo* to the ground grid structure. This gives the CM noise a predictable metallic return path out of the ground grid. If possible, it is desirable to bring the drive isolation transformer closer to the drive cabinet to reduce noise current paths into ground. Use of a CM core in high risk applications will eliminate any concern over noise leakage to ground thru accidental conduit contact.

(b) Shielded Power Cable Controls Conducted Noise Current Path: The drive generates perfectly balanced phase voltages so that fundamental frequency phase currents are also a balanced set, eg. $I_a + I_b + I_c = 0$. During the switching transition of phase voltages, high frequency line to ground capacitive CM noise currents (I_{ao}, I_{bo} and I_{co}) are generated from cable phase conductor to the cable green ground wire, phase to cable shield and motor winding to ground. These CM currents (I_{ao}, I_{bo}, I_{co}) sourced from the drive are also called zero sequence currents. These currents have 3 return path options back to the drive; the 60 Hz green Safety wire, the cable shield / armor or the customer ground grid. The predominant return path is the shield / armor since it has the lowest impedance to the high frequency noise. The shield / armor is isolated from accidental contact with grounds by a PVC outer coating so that the majority of noise current flows in the controlled path of the cable and very little high frequency noise goes into the customer PE ground grid. Ground potential differences will be minimized between true building structure earth ground and customers grounding at PE grid in *User #2* and *User #N*.

Noise current returning on the shield or safety ground wire is routed to drive PE terminal, down to the cabinet PE ground bus, out the cabinet PE ground wire, to the customer ground grid at *User #1* and then to the grounded neutral of the drive source transformer. The noise completes a return path back to the DC bus source via drive input phase A, B or C depending on which drive input bridge diode is conducting. If the drive input transformer is far away, then the ground grid pollution at *User #1* may exist and the use of drive input shielded power cables back to the main supply may also be desirable.

Radiated emissions in this cable are minimal since the armor completely covers the noisy power wires. Also, the armor prevents EMI coupling to other signal cables that might be routed in the same cable tray. Thus, the use of CMC to attenuate the noise combined with drive input and output shielded / armor cables to control the noise path are effective noise reduction mitigation methods.

(c) Diverting Noise from Susceptible Equipment with Proper Cabinet Layout: Grouping the input and output conduit / armor to one side of the cabinet as shown in Fig. 15 and separating the Programmable Logic Controller (PLC) and susceptible equipment to the opposite side will eliminate many effects of CM noise currents on PLC operation. CM noise current returning on the output conduit or armor will flow into the cabinet bond and most likely exit out the adjacent input conduit / armor bond near the cabinet top, well away from sensitive equipment. CM current on the return ground wire from the motor will flow to the copper PE bus and back up the input PE ground wire, also away from sensitive equipment. If cabinet PE ground wire to the closest building structure steel is deemed

necessary, then if this wire is taken from the right side under the conduits and drives, the CM noise is still shunted away from the PLC backplane.

IV. USE of EMI / RFI FILTERS

The use of proper grounding, proper cabinet layout, proper shield termination of control wire, shielded power cables on input and output, and using CM cores on drive power leads and drive interface leads will solve the majority of any EMI noise problem that might arise. However, there are installations where the above solutions may not reduce EMI emissions low enough with respect to surrounding ultra - susceptible equipment requirements.

IGBT drive installations in heavily residential areas are examples of where consideration to an EMI filter might be given to solve possible AM radio and TV interference problems. Other examples are hospitals that use CAT scanners or NMR machines off the same power source. Drive based equipment that must meet European CE conformity standards must also use an EMI / RFI filter connected to the drive input.

A. How Does the EMI Filter Work ?

It was previously shown how common mode line to ground noise current I_{ao} is transiently sourced from the drive output during the drive semiconductor risetime. It also was shown that I_{ao} returns via the ground grid to the supply transformer *Xo* connection and back to the drive via the 3 phase input lines. It was also shown that a CM core on the *drive output* significantly reduced I_{ao} peak and slowed the effective risetime to ground. Further, shielded cables on both drive input leads to the transformer supply *Xo* and output power leads to the motor were shown to collect most of I_{ao} and keep it out of the ground grid where CM voltages may be developed.

The EMI filter of Fig. 16 that is used with output shielded cables works on the same series noise path described. However, instead of placing a high impedance CM core to limit ground current at the *drive output* leads, the EMI filter on the *drive input* contains a high impedance CM core inductance, as well as individual phase inductors, to limit the series ground return current to extremely low values. In addition, the EMI filter contains high frequency common mode *line to ground* bypass capacitors that short circuit any high frequency ground noise current returning on the output shielded cable, right back to the drive R,S,T terminals. In a simplified explanation, the EMI filter low impedance bypass capacitors return most of the noise current to the drive input, out of the ground grid, and the EMI filter CM and phase inductors are high impedance blockers to insure that little high frequency noise current is allowed to flow in the plant power lines or ground grid that is ahead of the EMI filter.

The LISN connected to the EMI filter input is the equipment that detects just how much noise voltage is developed in the plant power lines. The LISN measures Common Mode noise voltage on the line. The reason being past EMI experience has shown this type of noise is greater than normal mode noise and appears to be the predominant problem in the field. Fig. 17 shows that a typical PWM drive operating without shielded cables exceeds the conducted emission Class A and B limits regulated by European Norm EN 50008-1 & 2 between 150 kHz and 30 MHz (similar to FCC Class A and B limits). This implies that drive operation will interfere with TV, radio and other communication in this frequency band.

B. EMI Filter and Shielded Cable Solution

Fig. 18 shows that with a specially designed input EMI filter matched to the drive, shielded armor cable on both drive input and output cables and a metal cover on the drive, that class B limits are met. Reference [22] has more information on emission limit interpretation, filters available and detail filter design which is beyond the scope of this paper.

V. CABLE CHARGING CURRENT PHENOMENON

A drive to motor 3 wire plus ground cable consists of C_{o1} line to line stray distributed capacitance and C_{og} distributed line to ground cable capacitance. There also exists a motor line to ground capacitance, defined by the stator winding capacitance to the motor PE frame ground, which may be added to C_{og} . During each *dv/dt* transition on the drive output line to line pulse, a capacitive coupled cable charging current is sourced from the drive, flows through C_{o1} and returns through another phase. Charging current is approximated by $I_{line} = C_{o1}\ (dv\ /\ dt)$. The drive switching transition in a given phase output also sources another cable charging current path from line to ground through C_{og} and approximated by $I_{line} = C_{og}\ (dv\ /\ dt)$. Fig. 19 shows the additional drive capacitive coupled current paths taken during a *dv/dt* transition. These additional currents may still exist whether the motor is connected or not. Fig. 20 shows the capacitive coupled current spikes could exceed the normal drive rated current for a given motor load.

This phenomenon exists for all drives. However, drives < 2 hp are more susceptible to over-current trip due the additional charging currents. This phenomenon is exhibited to a greater degree on 460 V drives than on 230 V drives due to the higher output transition voltage. This phenomenon is made worse by having long leads on small hp drives or multiple cable loads from a single small drive. The rms current value of this charging current is made higher and may approach the drive rms overload limit by increasing the carrier frequency (the number of device switchings per second). Shielded motor cable has higher capacitance line to line and line to ground than wires in a conduit and may increase the charging current magnitude. Capacitively coupled currents can also exist between the output wires of different drives that are routed in the same conduit. It is recommended that no more than 3 drive output wires be routed in the same conduit to prevent additional drive to drive capacitive currents resulting from tightly bundled output wires in a conduit.

General methods to mitigate this effect are by reducing carrier frequency to 2 kHz, reducing cable lengths to manufacturer recommended values, and using 230 V drives when possible. Over-sizing the drive hp for a smaller motor hp load is also effective to insure cable charging limits are not met. Some drive manufacturers have recommended maximum allowable cable distances for various drive and motor hp combinations in the < 2 hp applications to mitigate the cable charge effect at the installation planning stage. Another mitigation technique is to add a 3 phase inductor on the drive output to reduce the cable charge current magnitude.

VI. BEARING CURRENT PHENOMENON

A. Bearing Current Problem Background

Motor bearing problems were recently reported on ac machines driven by ASD's in air mover fan applications. A few applications had bearing failures after a few months of operation. Examination of the bearings indicated fluting induced by Electrical Discharge Machining (EDM) [23]. The initial stage of fluting is characterized by microscopic pits in the raceway caused by high bearing current density concentrated in a localized spot as shown in Fig. 21. The high localized temperature softens the raceway metal and as the ball rolls over the pit, the pits become transverse grooves in the later stages of fluting as in Fig. 22. Continuous application of bearing current increases mechanical wear and causes bearing failure.

B. Motor Bearing Currents Operated on Utility Power

All rotating machines develop bearing currents (I_b), whether dc or ac, large or small horsepower. The historical sinewave operation cause of I_b on sinewave operated ac motors dates back to 1924 [24] and has been understood to be high values of electro-magnet induced rotor shaft voltages caused by magnetic dissymetries inherent in the motor construction. The shaft voltage induced along the axial length of the machine has a resulting circulating bearing current whose magnitude is limited only by bearing impedance. This electro-magnetic induced circulating current path in Fig. 23 is from one end of the shaft, through the impedance of the bearing to frame ground, back through the opposite bearing impedance and returning back to the shaft. Bearing impedance is low (like a resistor) at low speeds and attains values in the meg-ohm range (like a capacitor) as motor speed increases above 10 % of rated. Technical literature indicates that as speed increases, the balls ride on a lubricating oil film forming a boundary between race and ball, with the exception of instantaneous asperity point contacts. The oil film acts as a capacitor that gets charged by rotor shaft voltage. When the shaft voltage applied to the oil film capacitor reaches the dielectric breakdown strength voltage the film can withstand or when a ball bearing asperity point contacts the raceway in a small contact area, then a destructive instantaneous high discharge current (EDM) of the film capacitor takes place to pit the bearing. The amount of mechanical damage depends on the magnitude of bearing current density defined as bearing current divided by bearing contact area. A large bearing contact area can dissipate the heat even in the presence of high EDM current magnitudes. NEMA MG1 recommends shaft voltages of < 1 Vrms as a measurable indicator that reduces resulting bearing current magnitudes to safe levels that prevent fluting [4]. Bearing current problems on utility sinewave power has only been a concern for larger hp ac motors, since only then is end to end shaft voltage magnitude large enough to charge the oil film capacitor to breakdown voltages. The historic solution to this *electro-magnetic induced shaft voltage* phenomenon is to break the series circuit oil film charging path by using insulated bearings on the non drive end side.

C. Motor Bearing Currents Operated on ASD Power

Bearing current damage is also possible when operated on non sinusoidal PWM voltage source inverters with steep fronted waveforms. This phenomenon was recently investigated in more detail [25 - 29]. In contrast to traditional *electro-magnetic effects* found in sinewave driven machines, *all* types of PWM inverters excite an *electro-static capacitive coupling effect* between the stator and rotor, creating high shaft or rotor voltages (V_{rg}) to ground. The stator neutral on sinewave operation has a voltage close to zero voltage potential, while stator neutral voltage to frame ground on inverters may reach hundreds of volts due to PWM modulation as in Fig. 24. Maximum stator neutral to ground voltage is a zero sequence source of approximately (V_{bus} / 2), but may have transient edges of higher values with long cable length due to transmission line reflected wave effects. The step modulation zero sequence source is shown schematically in Fig. 25 The main coupling mechanism for V_{rg} is the stator to rotor capacitance (C_{sr}) which is a low impedance at the PWM frequencies and allows charging and discharging of the rotor through the bearing oil film capacitor (C_b). Stator winding slot capacitance to frame (C_{sf}) and rotor to frame capacitance (C_{rf}) are also included for a complete model by are not as dominant as the C_{sr} path to charge C_b. Steel ball bearing resistance is denoted as R_b while Z_l is a non linear impedance that either represents bearing film dielectric breakdown or a random mechanical intermittent shorting of C_b through microscopic point contacts of the ball. Fig. 26 shows the capacitor coupling path from the stator end windings and stator slot openings through the C_{sr} air gap to the rotor shaft, down through the inner bearing race, ball bearing, oil film C_b and out to the bearing outer race to frame ground. Two key elements are what voltage conditions will break down the insulating grease film, and how the resulting bearing current densities affect bearing life.

Fig. 24 shows when the ball bearing asperity point contacts puncture through the C_b oil film, the V_{rg} voltage is zero. When the microscopic point contacts are open the C_b voltage is allowed to charge in a capacitor divider action between C_b and C_{sr}, synchronous with the V_{sng} modulation as in Fig. 24. A destructive 3 to 4 amp peak EDM current discharge, occurring in < 100 ns and pitting the bearing race, is shown when V_{sng} voltage of 100 Vpk charges the V_{rg} voltage to the 10 V breakdown voltage of the bearing oil lubricant film. The result is an EDM current impulse through a small localized bearing contact area. Fig. 27 shows a time expanded version of Fig. 24 with theV_{sng} voltage capacitively coupled to the rotor shaft voltage, which charges the bearing oil film to breakdown, that is then followed by an instantaneous EDM discharge. Bearing current density with EDM peak currents occurring is high enough to cause damage and reduce bearing life. Bearing current density (in Amp peak / sq. mm) is defined as the EDM bearing current discharge divided by the localized bearing contact surface area between ball and race. Fig. 28 shows that as the bearing current density increases, the mechanical life may quickly decrease after a certain (Amp peak / sq. mm) threshold value is reached.

There are also smaller currents of < 250 ma peak magnitude that occur with every *dv/dt* switch of the inverter in Fig. 24. It is believed that the current density at the point contact area is within the safe zone of Fig. 28 and is not high enough to cause damage with these currents.

D. Conditions and Measurement of the Problem

The vast majority of ASD applications probably do not have bearing current problems. ASD bearing current may only be a problem for minimal shaft mechanical load conditions, since as shaft load is increased, the bearing contact area increases and may decrease bearing current density to safe levels. Also, many applications contain other bearings on the shaft which may divert I_b current to other multiple bearings. This may decrease bearing current density in each bearing to safe levels. These type of loads have not been a problem to date.

Shaft voltage to ground may be measured with an oscilloscope connected between frame and a multistrand wire brushed up against the rotor shaft. Peak voltage measurements > 2 volts may only indicate the possibility for bearing current. The only positive way is to identify and separate bearing currents is with a test motor setup as in Fig. 26. This will identify EDM type currents. To determine a safe bearing current density requires calculating bearing contact area, which can be done, but also is difficult to establish [28]. Thus, there is not a good bearing current problem indicator available on site in the field, except to run the existing application and analyze problems as they occur.

E. Solutions to the Problem

If a bearing current problem is perceived, then the following various actions are possible. At the present writing, solutions (1) and (5) seem to be the most promising.

(1) Use Shaft Grounding attachment on Rotor. This system maintains rotor shaft voltage at frame potential by using metallic brushes on the shaft that are connected to the frame to bleed off excess charge. How well the grounding is maintained over years of life is yet to be determined. However, in the short term the method is effective. Cost and maintenance is a major disadvantage of this system.

(2) Use Conductive grease. This prevents oil film charge up to breakdown levels where EDM currents may occur and is only a short term solution. The disadvantage is that now the bearing mechanical wear life is substantially reduced due to abrasive particles in the grease.

(3) Use ceramic ball bearings. No pitting is possible with ceramic coated balls. The cost and delivery time makes this approach prohibitive because of small demand for this product.

(4) Use of insulated bearings. The traditional *electro-magnetic* bearing current problem used only a thin insulating coating of the bearing to break the end to end circulating current path. There has been reports of limited success in applying this type of insulated bearing to solve the *electro-static coupling* problem on ASD's.

(5) Use an ESIM. Recently, an Electrostatic Shielded Induction Motor (ESIM) has shown promise to eliminate ASD shaft voltage buildup [23,29]. The ESIM re-routes stator winding coupling capacitance current to a grounded internal non rotating shield mounted in the motor air gap as in Fig. 29. Rotor shaft voltage is thus maintained at zero voltage potential independent of the V_{sng} modulation voltage from Fig. 25 schematic. Since the ac motor transfers power by electromagnetic induction across the air gap, the motor power rating is unaffected by the single point grounded shield depicted in Fig. 30. Fig. 31 shows that ASD V_{sng} modulation voltage couples 30 Vpk onto the rotor shaft of a standard ac motor, while only a 2.2 volt peak voltage is seen with an ESIM motor. Examination for bearing current with an ESIM revealed no EDM currents occurred and *dv/dt* current were reduced to 17 ma, so that bearing current density is essentially zero. Thus, bearing life is dictated now limited only by mechanical attributes.

Other factors such as drive voltage, drive carrier frequency and drive output frequency, cable length and type, and output filter devices that might effect the bearing current problem are discussed. The use of 230 V vs. 460 V drives reduces V_{rg} peak voltage, but the reduction may not be enough to prevent film breakdown. Thus, EDM currents have a smaller magnitude but may still be outside the safe bearing current density zone. Lower drive carrier frequencies will reduce the amount of *dv/dt* and EDM current possible in a given time frame but does not change the destructive EDM magnitude. The effect of carrier frequency on extending bearing life is not well correlated at this time. Drive output frequency settings for < 10 % base speed are not a problem, since bearings can handle large currents when at or near non-rotation. Long motor cable lengths increase V_{sng} voltage to higher levels by transmission line effects and increase the possibility for V_{rg} oil film breakdown problems. In contrast to some literature in the field, armor cable does not mitigate bearing current problems. R-L-C drive output filters to reduce reflected wave line to line motor voltage, also tend to reduce the less destructive *dv/dt* bearing currents. However, the inductances in these filters also increase V_{sng} voltage to higher levels by transmission line effects and increase the possibility for V_{rg} oil film breakdown and EDM problems.

It appears the most promising solution to the motor bearing current problem when used with AC variable speed drives is to use the electro-magnetic induction principles of Tesla, combined with the electro-static shielding principles of Faraday in a single machine, designated the Electrostatic Shielded Induction Motor.

VII. CONCLUSION

This paper has showed the significant advantages of going to IGBTs as the preferred semiconductor of choice in new VFD designs relative to reduced drive size, reduced cost and increased drive performance. The next generation of new IGBT drives have the same old motor heating and derating issues as the BJT predecessor. However, the faster switching IGBT has also introduced additional drive system issues in terms of increased motor dielectric stress and increased EMI system noise.

A review of the reflected wave phenomenon was presented so that system users may understand the limitations of the new technology prior to installation. Knowing motor cable length, drive risetime and motor dielectric capability guarantees a successful installation by co-ordinating applied stress with motor dielectric withstand capability. Some drive manufacturers have performed this coordination by giving maximum safe cable distances before external protection devices must be used and extended safe cable distances with external motor voltage protection added. Various solutions to the voltage stress problem were also given. The motor industry is rapidly improving its dielectric capability with new magnet wire and varnish so that the external solutions may only be temporarily needed over the next few years.

Even though the motors may ultimately be dielectrically compatible with fast switching IGBT drives with no external protection, the system EMI noise may still be an issue. Proper grounding, shielding and panel layout techniques prior to installation are shown to solve most EMI problems encountered. The Common Mode Choke was shown to be an external noise solution that virtually eliminates any concern for system EMI problems.

The motor bearing problem is a more recent problem that has surfaced on a few motor applications with light shaft loads. An understanding of the dynamics and conditions of the problem was presented. Bearing failure to date has been perceived as creating audible noise in a quiet room environment. Many VFD applications are running in industry with no perceived problem. An ESIM motor was described that should be a reliable solution to the bearing current problem when operated on VFD drives.

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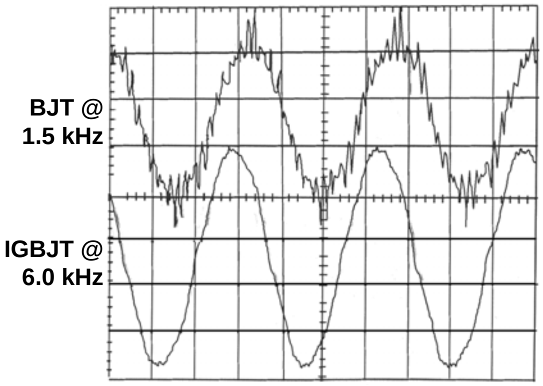


Fig.1 Phase Current of BJT drive @ fc =1.5 kHz and Phase Current of IGBT drive @ fc = 6 kHz

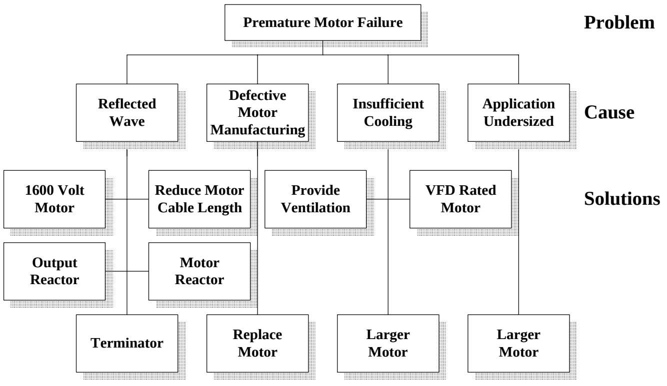


Fig. 2 Causes of Premature Motor Failure

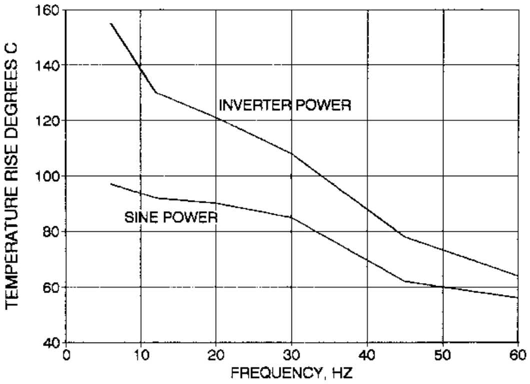


Fig. 3 Motor Temperature Rise on Sinewave & Inverter Power [5]

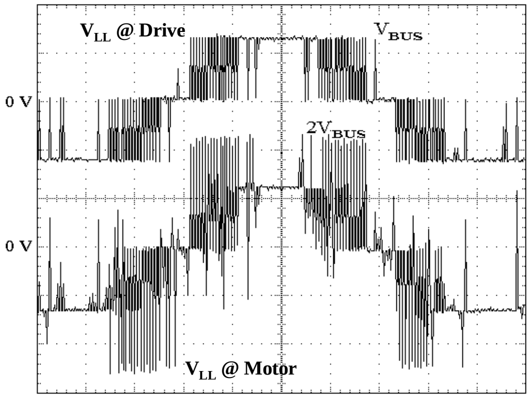


Fig. 4 PWM Voltage at Drive and Motor Terminals

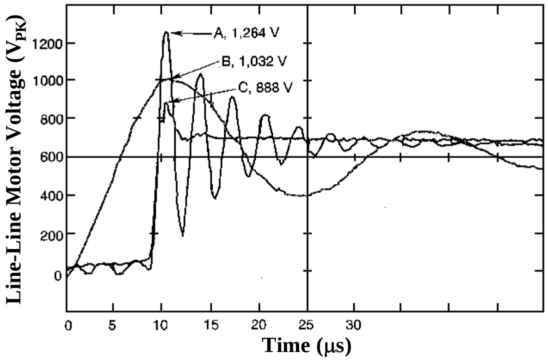


Fig. 5 Motor Reflected Wave Pulse Amplitude [5us/div:200v/div]
(A) Unterminated (B) Reactor at Drive (C) Terminator

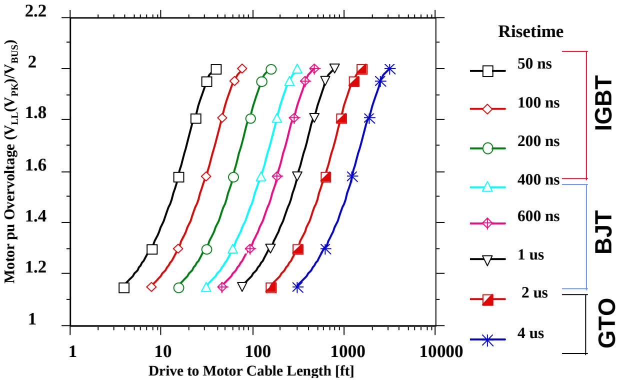


Fig. 6 Motor pu Over-Voltage vs. Cable Length vs. Risetime

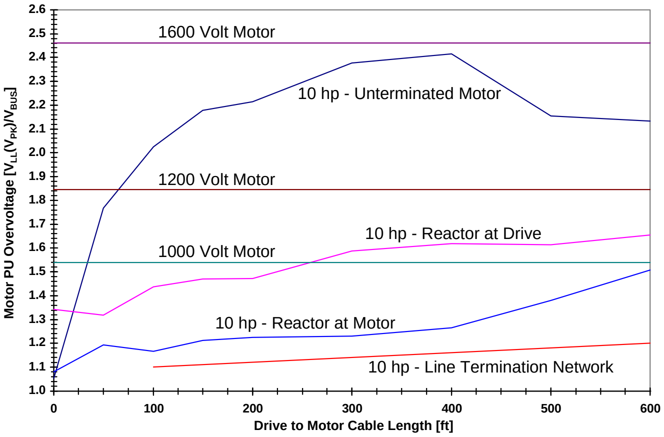


Fig. 7 Motor pu Over-Voltage vs. Cable Length vs. Solution

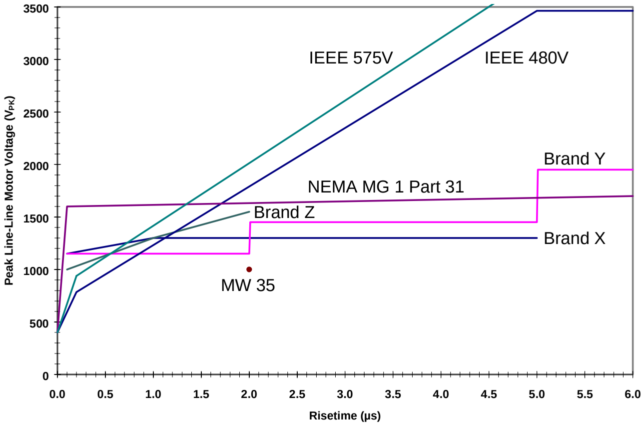


Fig. 8 Motor Dielectric Withstand Envelope vs. Surge Risetime

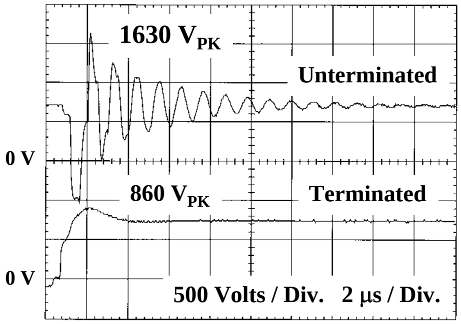


Fig. 9 Motor Voltage With and Without Termination Network

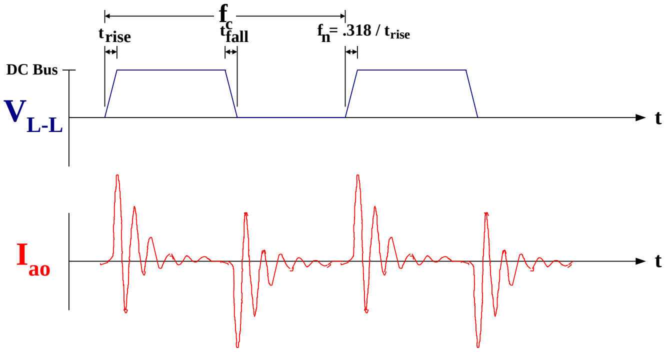


Fig. 10 Noise Source: Drive Induced Common Mode Current

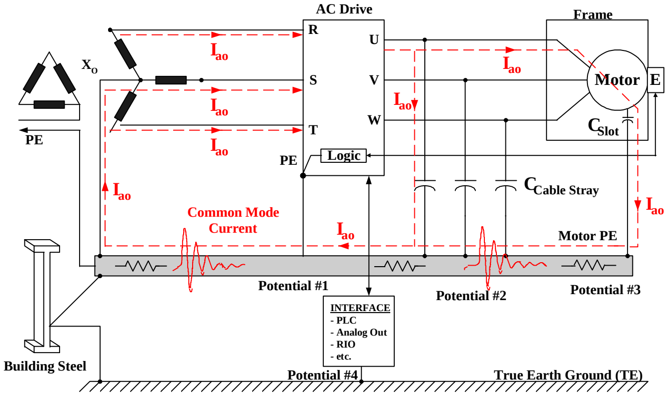


Fig. 11 Poor Wiring Practice: Random Unshielded Cable w/o Gnd

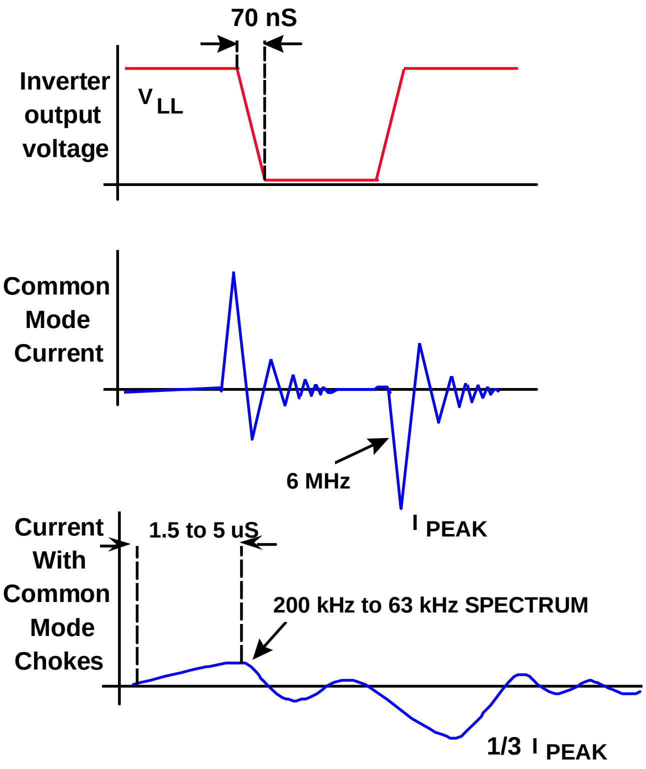


Fig. 12 Attenuation of Drive Noise with Common Mode Chokes

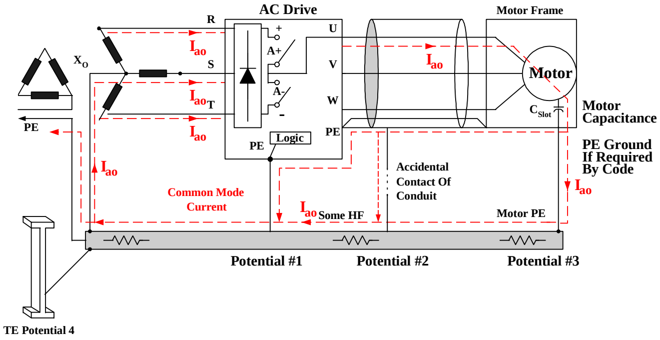


Fig. 13 Better Wiring Practice: 3 Conductor & Ground in Conduit

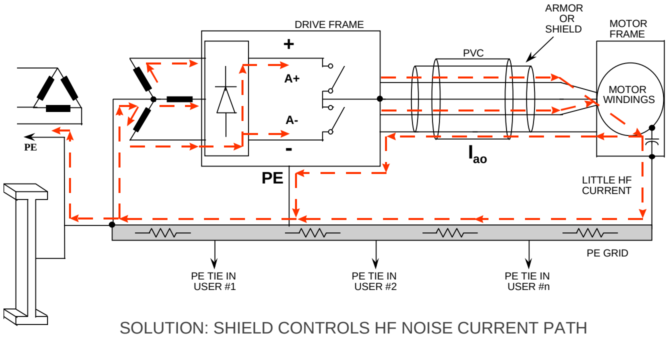


Fig. 14 Shielded Power Cable Controls Conducted Noise Path

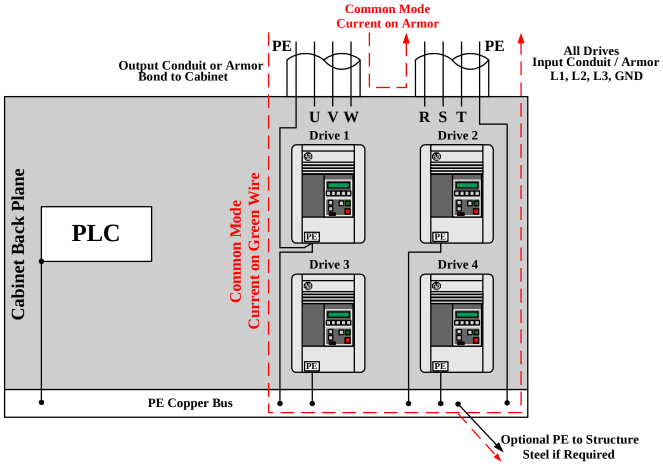


Fig. 15 Proper Cabinet Ground - Drives & Susceptible Equipment

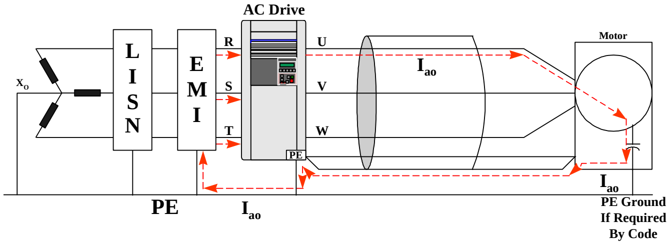


Fig. 16 Noise Current Paths Controlled with an Input EMI Filter

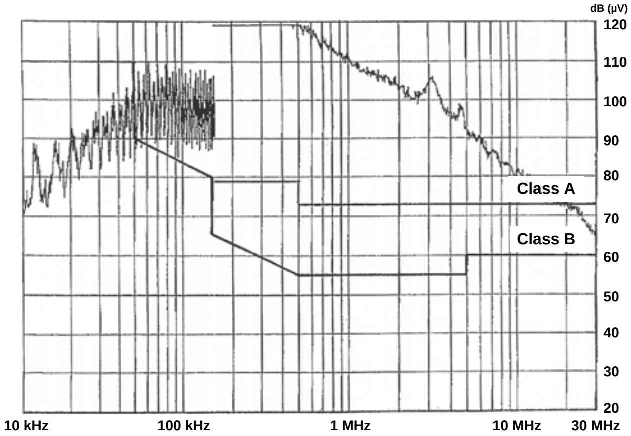


Fig. 17 Measurement of Conducted Drive Noise without Filter

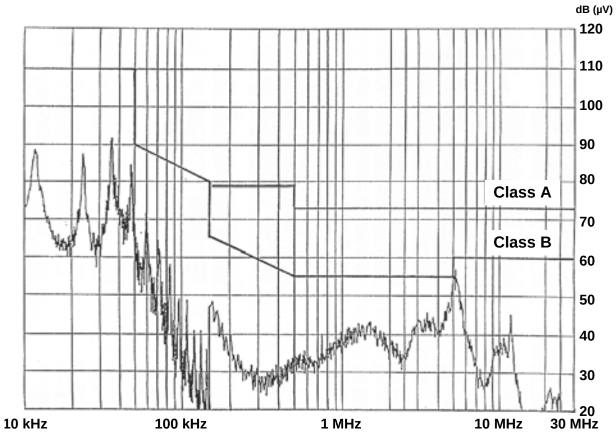
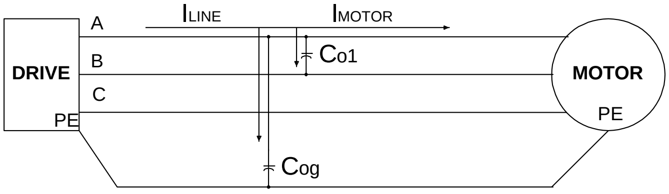


Fig. 18 Class B Conducted Emissions with Filter/Shielded Cables



Capacitively coupled currents could exceed the drive rating.

Co1 = Line to line capacitance path

Cog = Capacitance path line to ground

Fig. 19 Cable Charging Current Paths

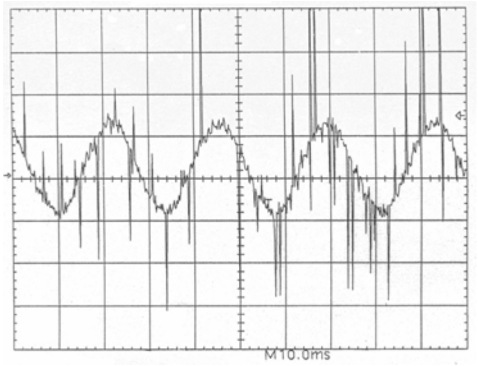


Fig. 20 Cable Charging Current Exceeding Rated Phase Current

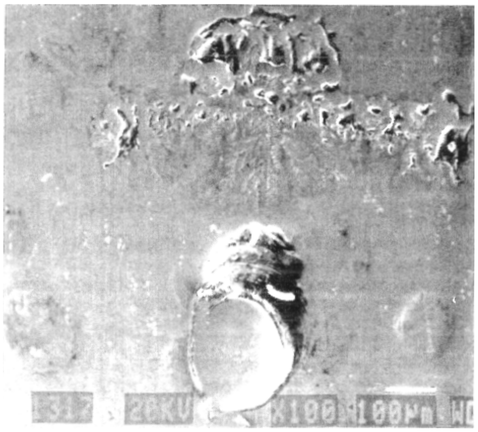


Fig. 21 Initial Stage of Fluting - Microscopic Pits Induced By EDM Currents

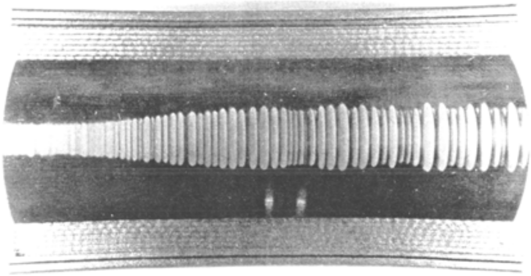


Fig. 22 Later Stage of Fluting - Grooves on Bearing Race

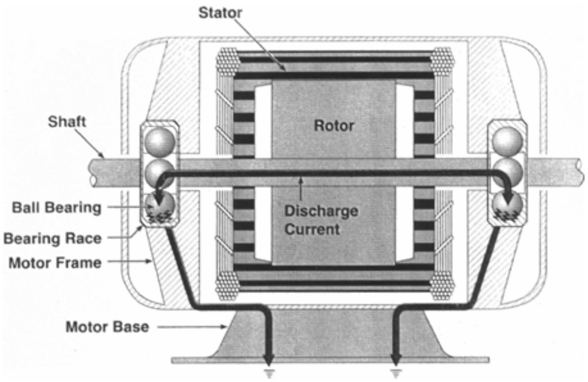


Fig. 23 Historical Electromagnetic Induced Shaft Voltage & Bearing Current Path

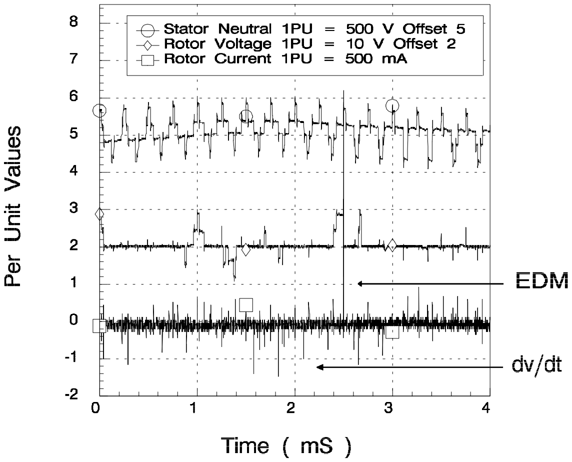


Fig. 24 ASD Operation with Electro-static Induced Bearing Current At 60 Hz Showing Stator Neutral To Ground Source Voltage, Rotor To Ground Shaft Voltage and Resulting Bearing Current

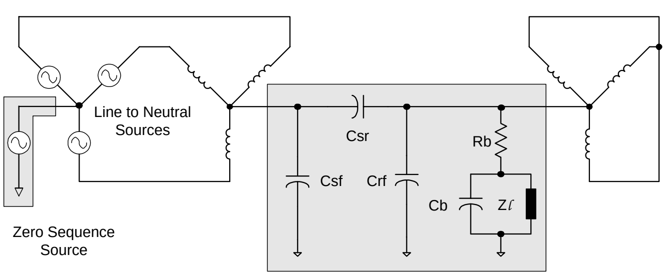


Fig. 25 ASD Modulation Source and Capacitive Coupling Mechanism for Bearing Currents and Shaft Voltages

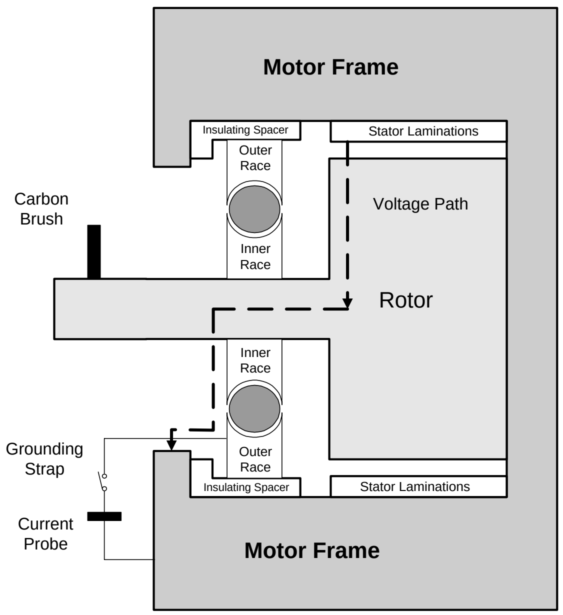


Fig. 26 Physical Description of Capacitive Coupling Path From Stator to Bearing Race

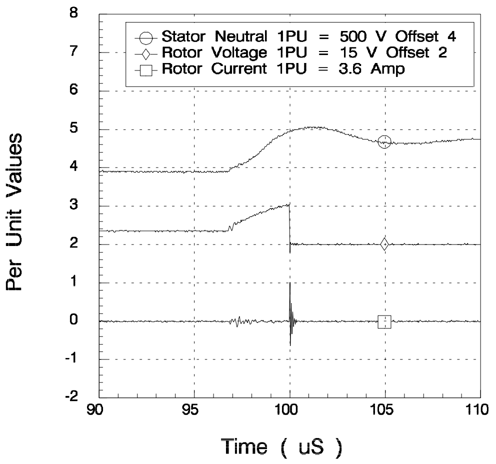


Fig. 27 Expanded EDM impulse due to V_{sng} Coupling

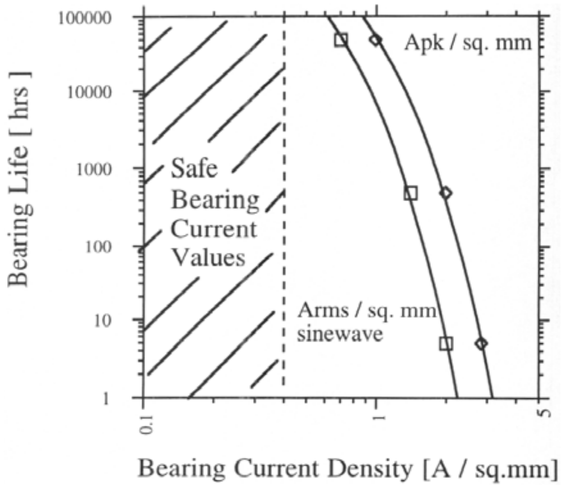


Fig. 28 Estimated Safe Bearing Current Density Levels

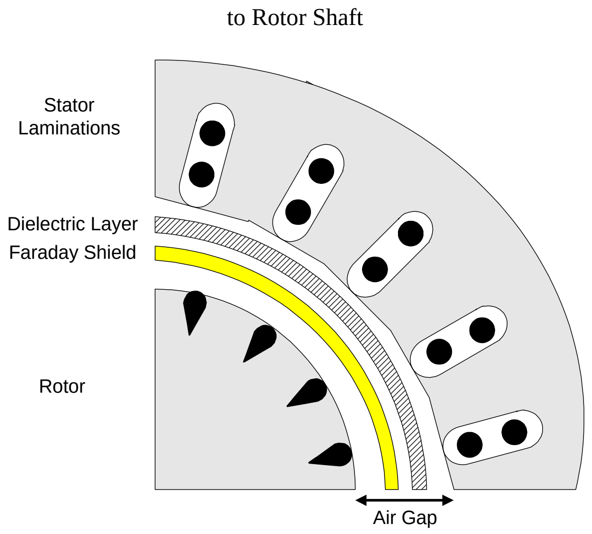


Fig. 29 ESIM Construction Using Copper Tape or Spray

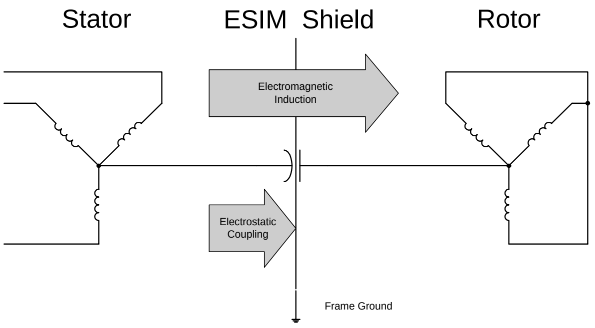


Fig. 30 ESIM Theory of Operation

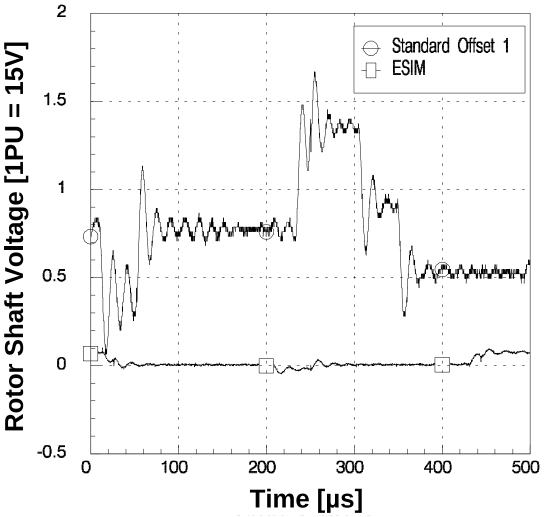


Fig. 31 Rotor Shaft Voltage of Standard Induction Motor & ESIM Operating on an IGBT ASD