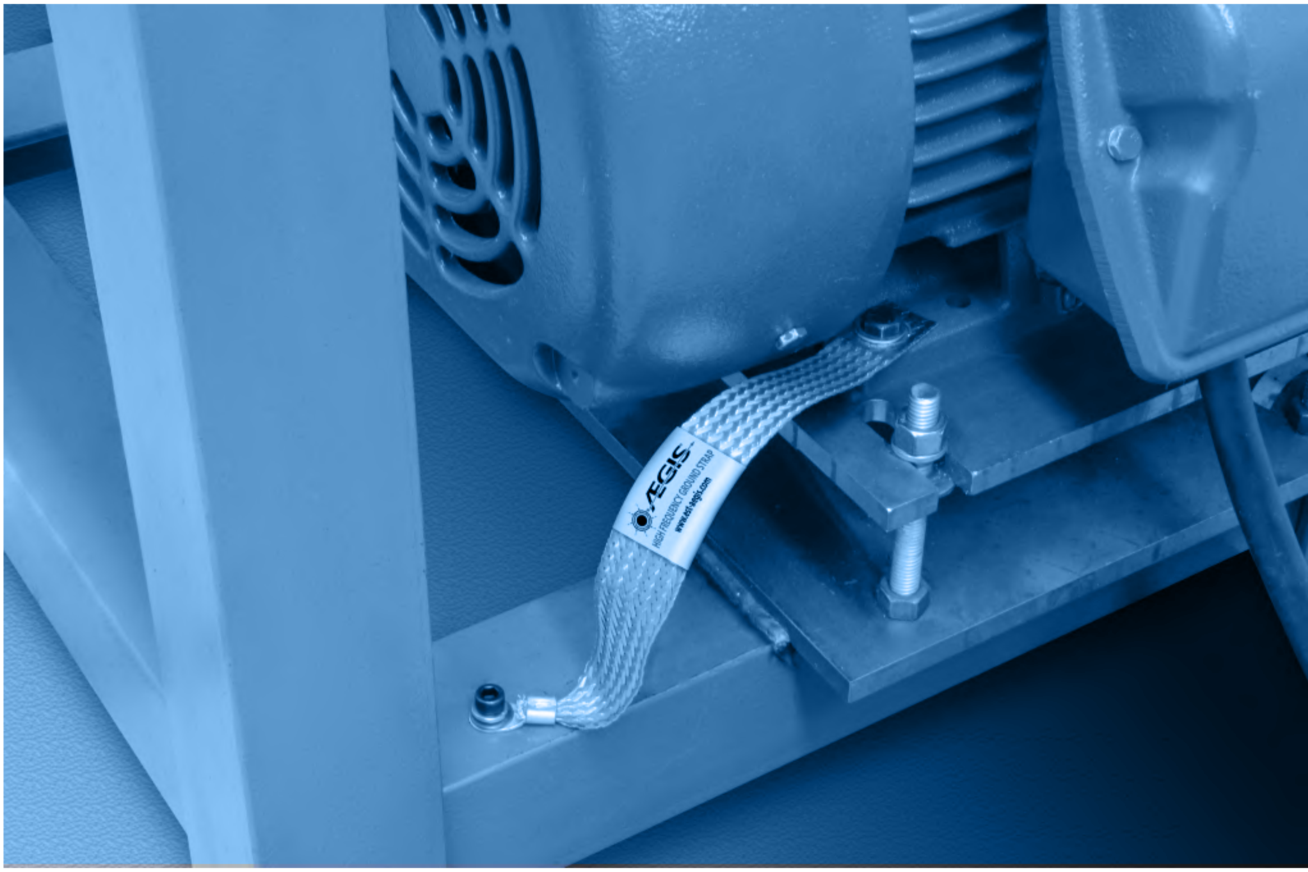
High-Frequency Bonding for Inverter-Driven Motors and Systems



Overview

Today's pulse-width modulated inverters generate high–frequency voltages on the shafts of the motors they control — voltages that can discharge through motor bearings, destroying them within months. While well-designed shaft grounding rings can safely conduct these discharges from shaft to motor frame, inadequate grounding will prevent the flow of high-frequency currents to earth ground, resulting in damage to coupled equipment. To equalize transient potentials and provide a very–low–impedance path to earth ground, high-frequency ground straps should be used to bond all system components to one another and to earth ground.

ÆGIS®

Introduction

For three-phase motor systems run on line voltage, input power is balanced in frequency, phase, and amplitude, and system grounding (for safety) according to electrical codes is sufficient. For VFD- or inverter-driven systems, however, high-frequency currents that result from pulse-width-modulated VFD power pulses can create capacitively coupled currents from the stator windings to the motor frame. In addition to a low-impedance path within the power lead cable to enable the return of common mode currents to the inverter, the motor ground should be electrically bonded to the inverter ground by means of an alternate low-impedance path. And to equalize transient potentials between the motor frame and coupled equipment and prevent voltage excursions (due to non-zero impedances within the system) from discharging through motor bearings, high-frequency ground straps should be used to bond all grounded equipment within the system.

The Causes of High-Frequency Currents in Motor Systems

Electric induction motors are designed to run on 3-phase sine-wave (50 or 60 Hz) power. When operated on normal line voltage, input power is balanced in frequency, phase, and amplitude. As a result, common mode voltage — the sum of the 3 phases — always equals 0 volts.

But when a motor is operated by an inverter — also known as a variable frequency drive (VFD) or adjustable speed drive (ASD) — power to the motor consists of a series of positive and negative pulses instead of a smooth sine wave. Due to the rapid switching between all 3 phases, common mode voltage takes the form of a "square wave" or "6-step wave", and the common mode voltage is never balanced.

In addition, induction motor design results in capacitive coupling between the stator windings and frame as well as between the stator windings and rotor of VFD-controlled motors [Figure 1]. This produces a potential difference (voltage) between the motor frame and the rotor.

The capacitively induced voltages will discharge through any available path to ground, but will split among the various paths in inverse proportion to the impedance of each path. So without a low-impedance path such as a shaft grounding ring with low-impedance microfibers, these currents will discharge through the motor bearings,

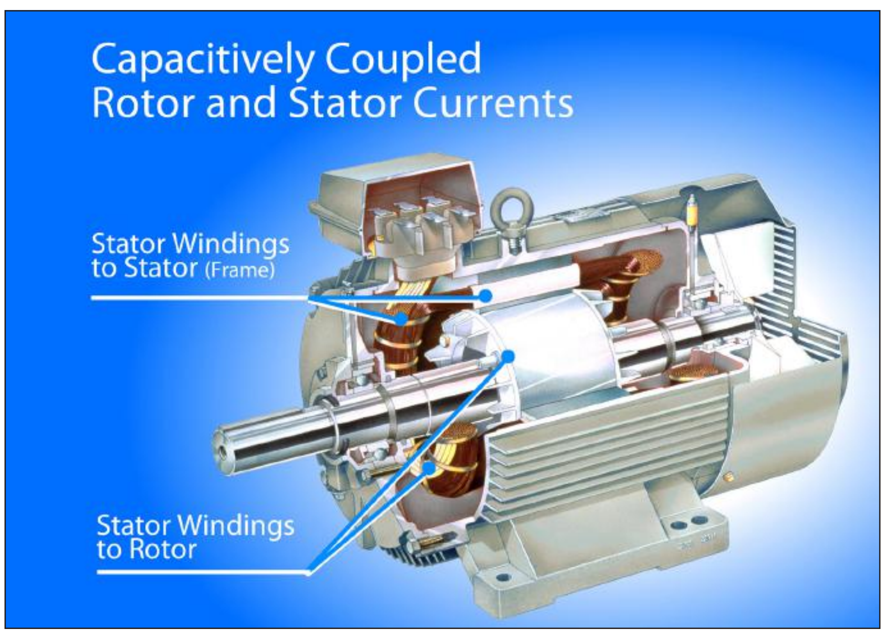


Figure 1

The unbalanced power input from a VFD produces capacitive coupling between a motor's stator windings and frame, and between the stator windings and rotor. Without a low-impedance path to ground, the high-frequency currents produced by these couplings can damage motor bearings and interfere with proper system operation.

causing electrical discharge machining - small fusion craters (pitting) in the surface of the bearings and race. Over time, this can result in frosting — widespread pitting that produces a dull, marred surface finish — and eventual bearing failure. In a phenomenon known as fluting, accumulated pitting produces washboard-like ridges in the bearing race, accelerating bearing wear and bearing failure — often in as little as 3 months.

While a low-impedance shaft grounding ring will protect motor bearings by facilitating shaft-to-frame discharge, it will not ensure the necessary unimpeded return of high-frequency currents from the motor to the VFD. To provide the lowest possible impedance path from the motor frame and connected equipment back to VFD, most major motor and drive manufacturers recommend high-frequency ground straps.

VFD-Driven System Components Require Bonding As Well As Grounding

Like most electrical equipment, the motors and drives that comprise a VFD-driven system must be grounded to a facility ground to comply with electrical codes. This is typically achieved through the main electrical ground from the 60 Hz supply. But while this type of ground is sufficient for safety purposes, it is inadequate for high-frequency currents, which require a very-low-impedance path.

In typical ground systems — even those that meet electrical codes — there can be multiple ground paths from the motor to the drive, and these paths are often not tied together.

To prevent ground loops caused by transient unequal potentials between sections of a ground system, all ground connections must be bonded using high-frequency ground straps. These straps provide very low-impedance paths to connect the motor frame to the frames of driven/coupled equipment, especially when:

1) The motor and coupled equipment are not mounted on a common baseplate;
2) The motor and coupled equipment are connected by a non-conductive coupling; or
3) The ground path is subject to intermittent impedance changes (due to flexible conduit, for example) that might redirect normal voltages through motor bearings.

Causes of Impedance to High-Frequency Currents

Impedance is the total opposition to alternating current by an electric circuit, including resistive and reactive components, and like resistance is measured in ohms.

There are several factors that can cause impedance to high-frequency currents, including:

- The length of wire used for electrical connections within a circuit. In general, the longer the wire, the greater the impedance.
- Paint, corrosion, dissimilar metals, and multiple connection points can create impedances between surfaces.
- Unshielded wire that can induce electrical noise (EMI and RFI) across other unshielded wires running within the same conduit.

Another significant source of impedance to high-frequency currents is the shape and surface area of the wire on which they flow. While DC current will flow through the entire cross-section of a wire and low-frequency AC current will flow through all but a very small center portion of a wire, high-frequency AC current will flow through only the very outermost perimeter of a cross-section. This phenomenon, known as the skin effect, is a major cause of impedance to high-frequency currents in VFD-driven motor systems.

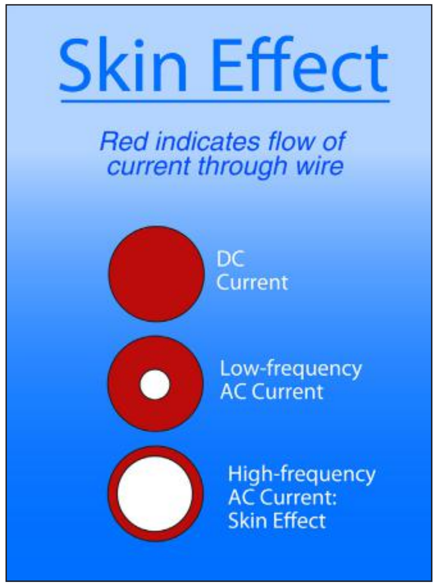


Figure 2

The skin effect is a major cause of impedance to high-frequency currents. As shown here, while DC current will flow through the entire cross-section of a wire and low-frequency AC current will flow through all but the center section of a wire, high-frequency current flows only along the outer edge or "skin" of a wire.

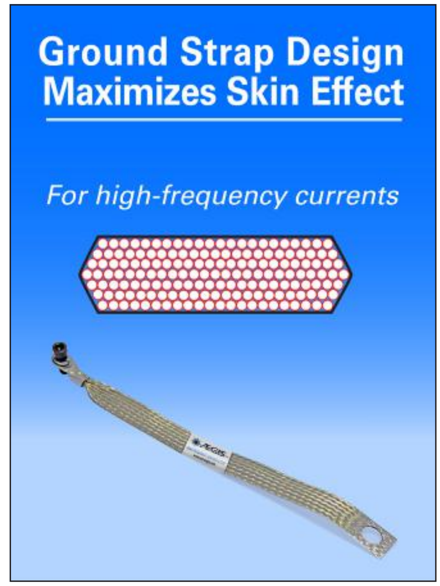


Figure 3

Ground straps are designed to exploit the skin effect. Their flat, wide, braided design maximizes surface area, thereby minimizing impedance to high-frequency currents.

Ground Straps — Designed to Provide a Very-Low-Impedance Path for High-Frequency Currents

The skin effect applies to a single strand of wire [Figure 2]. So maximizing the flow of high-frequency current through a cable would require insulating each individual strand of wire within the cable. Since this would be cost-prohibitive, the next best solution would be to maximize the surface area of a conductor, thereby maximizing the portion of the conductor available to transfer high-frequency currents. The resulting design is a wide, flat, braided metal conductor that looks like a strap — a high-frequency ground strap [Figure 3].

Straps should be tin-plated to enhance conductivity and inhibit oxidation and corrosion. To maximize utility and ease of use, straps should also be designed with fittings for connection to either NEMA or IEC motor frames.

Recommended for High-Frequency Currents by Motor and Drive Manufacturers Alike

To facilitate the flow of high-frequency currents and optimize the performance of inverter-driven motor systems, major motor and drive manufacturers recommend bonding all motors, drives, and driven or connected equipment within the system using high-frequency ground straps [Figure 4].

In its Technical Guide No. 5: *Bearing Currents in Modern AC Drive Systems*, ABB recommends that system designers "Add high frequency bonding connections between the installations and known earth reference points to equalize the potential of affected items, using braided straps of copper…"

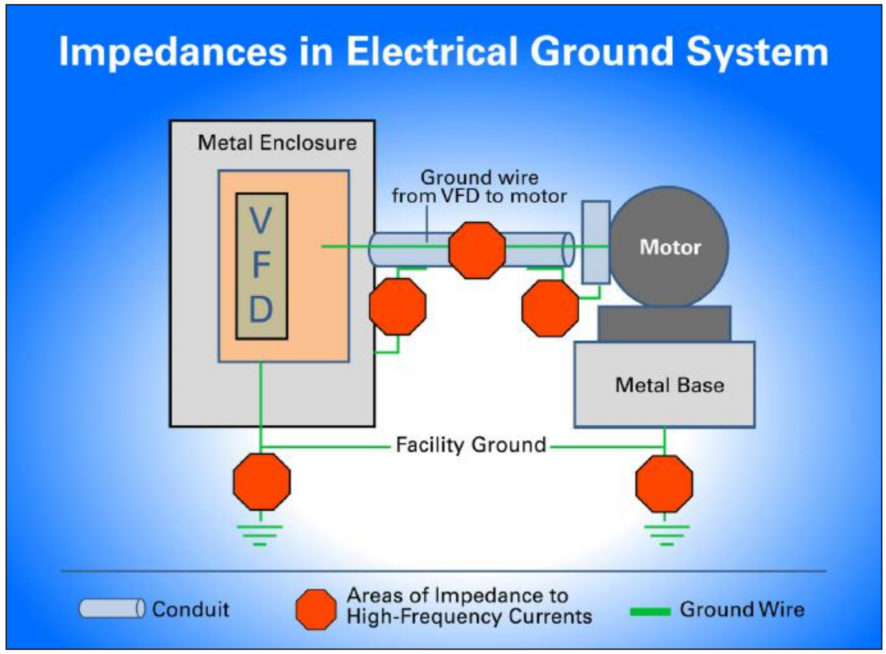
These connections "must be made at the points where discontinuity between the earth level of the inverter and that of the motor is suspected. Additionally, it may be necessary to equalize the potential between the frames of the motor and the driven machinery to short the current path through the motor and the driven machine bearings."

In its *Industrial Automation Wiring and Grounding Guidelines*, Allen Bradley suggests: "In addition to making good connections through each bolt or stud, use... 1-inch copper braid... to connect each chassis, enclosure and central ground bus mounted on the back-panel."

In a Technical White Paper entitled, "*Increased Reports of Bearing Damage in AC Motors Operating from Modern PWM VFD's*", Nidec Motor Corporation notes: "One approach that simplifies the solution is to utilize the following components: Proper grounding connection

Figure 4

Motor-driven systems must be grounded for safety. But many of the connections within these systems (marked with red symbols) offer high impedance to high-frequency currents. The small-gauge ground wire from the motor terminal box back to the VFD; inadequate grounding of the conduit between the motor terminal box and the VFD enclosure; poor bonding between motors and driven equipment; and paint on or corrosion of facility grounds can all impede the flow of high-frequency currents to ground.



points, proper grounding cables and bonding straps for high frequency conditions and proper termination devices for high frequencies…"

In its *Engineering Guide for HVAC & Refrigeration Applications*, Danfoss observes the following points in the Guide's "Practical Aspects of Earthing" section: "A large conductor surface area for draining high-frequency currents can be obtained by using fine stranded wire, such as… special earthing straps or cables."

"Braided earthing straps are often used nowadays in practice…"

"Note: System earthing has a substantial effect on smooth, trouble-free facility operation. Ground loops must be avoided. Good potential equalization is essential."

And in the white paper "*Inverter-Driven Induction Motors Shaft and Bearing Solutions*", Baldor recommends: "Proper grounding of the motor frame is also important… ground straps should also be connected between the motor frame and the driven load equipment frame to allow a low impedance, alternate path for shaft currents."

"High frequency ground strap impedance is lowest for straps with fine conductors and the largest width-to-length ratio."

"In all cases, ground straps should be connected directly metal-to-metal (not through a painted surface) to provide the lowest impedance path for high-frequency currents."

Best Practices for Grounding of High-Frequency Currents

NOTE: High-frequency ground straps must be used in addition to shaft grounding, such as AEGIS® Shaft Grounding Rings. The low-impedance path from shaft to frame, provided by the AEGIS® Ring, protects motor bearings by steering shaft voltage away from them to the motor frame. A high-frequency ground strap then conducts them from motor frame to ground.

The proper use of high-frequency ground straps will ensure:

1) An alternate low-impedance path for capacitively induced high-frequency currents back to the VFD

Figure 5:

High-frequency ground straps should be used to create an alternate return path for high-frequency currents from the motor back to the drive. They should also be used to bond all grounded equipment to create multiple low-impedance paths to ground for high-frequency currents, thereby preventing ground loops.

2) The equalization of transient potentials between the motor frame and coupled equipment to prevent voltage excursions (due to non-zero impedances) within the system.

To provide an alternate low-impedance path for capacitively-induced high-frequency currents back to the VFD or inverter, the following best practices should be employed:

1) Connect the motor foot to a grounded metal base with a high-frequency ground strap
2) Connect the metal (motor) base to the VFD panel ground
3) Connect the VFD ground to the VFD panel ground.

To equalize transient potentials between the motor frame and coupled equipment within the system, the following best practices are recommended [Figure 5]:

1) Connect the motor foot to the facility ground with a high-frequency ground strap
2) Bond driven equipment to the motor or to the common facility ground with high-frequency ground straps
3) Ground the motor foot to the VFD ground bus using a high-frequency ground strap
4) Bond both the motor frame and the VFD ground to metal conduit with high-frequency ground straps.

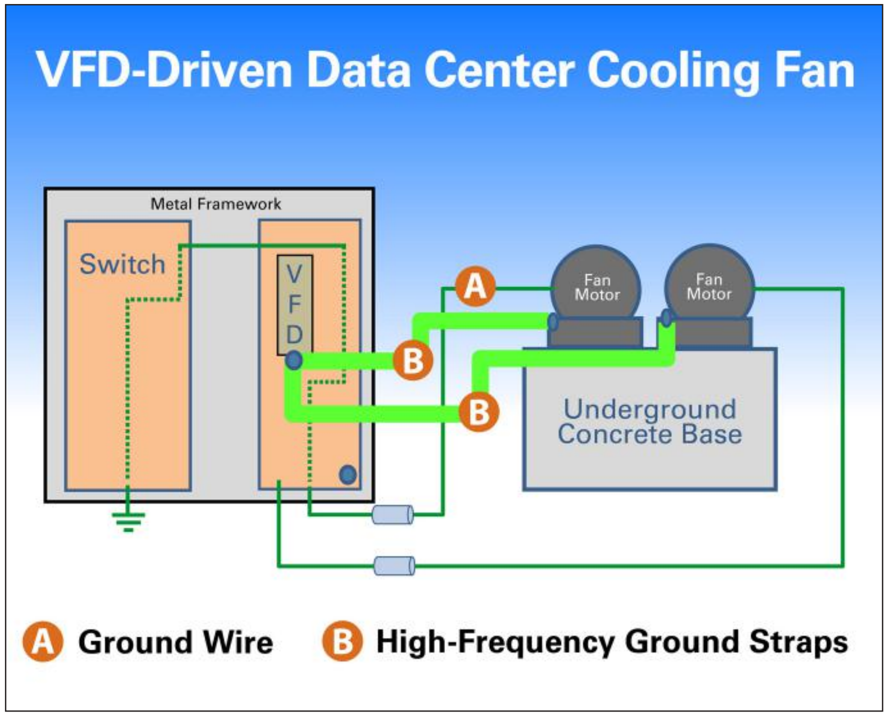


Figure 6:

When VFD-driven fan motors in a data center began experiencing problems, maintenance personnel suspected that the 10-gauge ground wire (A) between the motor bases and the VFD cabinet was insufficient to ground high-frequency currents. To provide a low-impedance path to ground for these currents, they installed high-frequency ground straps (B) between the foot and grounded metal base of each motor, and between the metal bases and both the VFD ground and the VFD panel ground.

Case Study: Ensuring a Low-Impedance Path From Data Center Cooling Motors Back to the VFD

When a data center began experiencing problems with its VFD-controlled cooling system, the problem turned out to be an inadequate return path for high-frequency currents back to the VFD.

PROBLEM:

The only ground connecting the cooling fan motors to the VFD cabinet was 10-gauge wire running through an ungrounded conduit to motor junction box. While sufficient to meet electrical code, this wire had high-impedance to high-frequency currents created by the common mode voltage induced on the rotor and motor frame. Since there was no separate ground connection to the motor frame or mounting plate, there was no alternate low-impedance path to ground for these high-frequency currents.

SOLUTION:

Installing AEGIS® Shaft Grounding Rings on the fan motors provided a low-impedance discharge path for capacitively induced rotor-stator voltages around the bearings and safely to the motor frame.

Installing AEGIS® HF Ground Straps from the motor frame mounting screw directly to the VFD ground connection in the VFD cabinet provided a very-low-impedance return path for high-frequency rotor and stator currents from the motor frame to the VFD [Figure 6].

AEGIS® Guide Specification

Construction Specification Institute - Section 23 05 13: 2.1 Motors

A. General Requirements – Shaft Grounding

1) *All motors operated on variable frequency drives shall be equipped with a maintenance free, conductive micro fiber shaft grounding ring with a minimum of two rows of circumferential micro fibers to discharge damaging shaft voltages away from the bearings to ground. [Figure 7A]*

2) *Application Note: Motors up to 100 HP shall be provided with one shaft grounding ring installed on either the drive end or non-drive end. Motors over 100 HP shall be provided with an insulated bearing on the non-drive end and a shaft grounding ring on the drive end of the motor. Grounding rings shall be provided and installed by the motor manufacturer or contractor and shall be installed in accordance with the shaft grounding ring manufacturer's recommendations.*

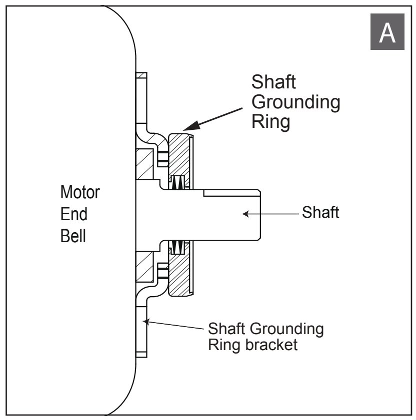


Figure 7A:

To protect a motor against VFD-induced bearing damage that can shorten its life, install a circumferential microfiber grounding ring around its motor shaft.

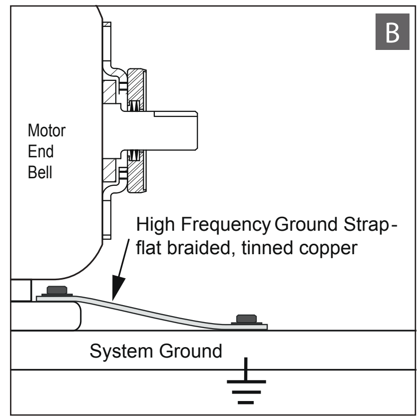


Figure 7B:

To equalize transient potentials within a VFD-driven motor system and prevent ground loops, install high-frequency ground straps between motor frames and driven equipment as well as between motor frames and an earth ground.

B. General Requirements - High-Frequency Bonding

1) *All motors operated on variable frequency drives shall be bonded from the motor foot to system ground with a high-frequency ground strap made of flat braided, tinned copper with terminations to accommodate motor foot and system ground connection. [Figure 7B]*

2) *Application Note: High-frequency grounding straps must be used to ensure the proper grounding of all inverter-driven induction motor frames.*

   a. References: *ABB Technical Guide No. 5*
   Allen Bradley Publication 1770-4.1 Application Data,
   Industrial Automation Wiring and Grounding Guidelines

Recommended parts: *AEGIS® SGR Bearing Protection Ring*
AEGIS® HF Ground Strap

Recommended source: *Electro Static Technology – ITW*
Manufacturer of AEGIS® products
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Conclusion

Designed specifically for minimal impedance to high-frequency currents, AEGIS® HF Ground Straps eliminate transient potentials between components in VFD-driven motor systems. And by bonding system components together, they eliminate ground loops and create an ultra-low impedance path for VFD-induced high-frequency currents from motor frame back to the VFD and to earth ground, preventing damage to motors and coupled equipment.

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