Applying Squirrel Cage Induction Motors on Low Voltage Pulse Width Modulated Adjustable Speed Drive Systems

Revision 1

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When applying an Adjustable Speed Drive (ASD) the entire system must be taken into consideration. This very much includes the electric motor, with several key factors to consider:

- Voltage Surges
- Speed Range
- Shaft Voltages
- Resonances, Sound, and Vibration
- Duty Cycle
- Service Factor
- Accessory Mounting
- Retrofitting with Existing Motors

This paper deals with applications of “off the shelf” three phase Squirrel Cage Induction Motors (SCIM) applied to ASD systems comprising the currently most common “off the shelf” drive topology -- Voltage Pulse Width Modulated (VPWM) inverters. The output switching devices are assumed to be Insulated Gate Bipolar Transistors (IGBT).

Voltage Surges

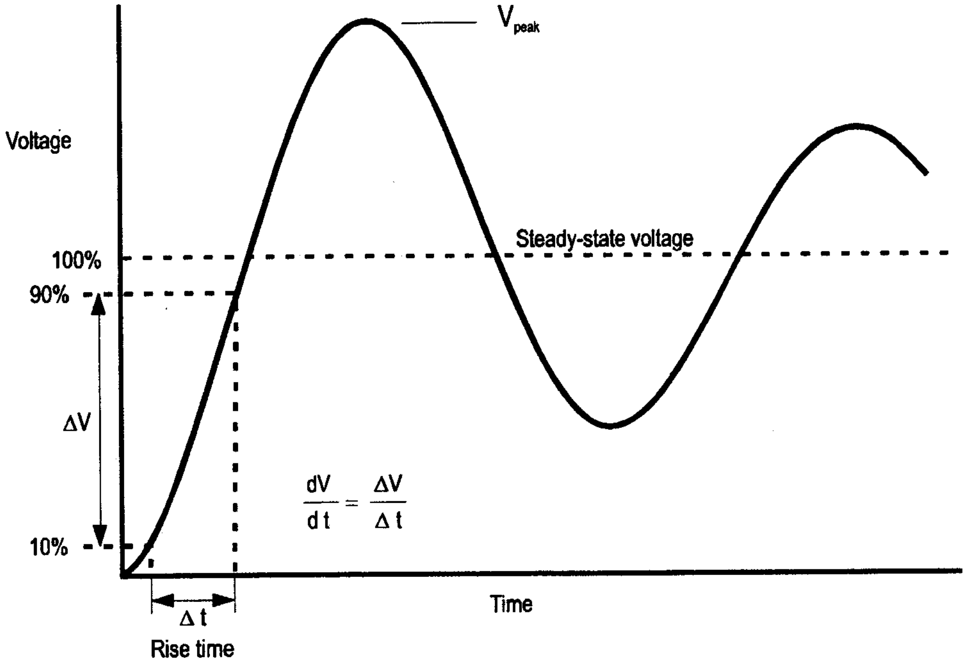
It is strongly recommended that the user purchase motors for ASD applications that meet NEMA MG-1 part 31.4.4.2 Voltage Spike standards.

It is often assumed that when someone asks for an “inverter motor” that they are asking for a motor with an insulation system that meets either NEMA MG-1 Part 30.2.2.8 Voltage Stress or NEMA MG-1 part 31.1.4.4.2 Voltage Spikes. These sections of NEMA exist to address the concern of potential motor damage caused by High Voltage spikes, the Transmission Line effect. Designers of power distribution and digital communications systems have long known the Transmission Line effect. In ASD applications, it is caused by a miss-match of impedances between the cable (low surge impedance) and the motor (which has high surge impedance).

All ASDs output square wave voltage pulses. The steady-state voltage value of this wave is the same as the DC bus voltage. These pulses are issued at the carrier frequency rate, which can be from hundreds of cycles per seconds (Hz) to 20,000 Hz or more.

Most ASDs have the capability to adjust the carrier frequency. Typical industrial drives ship with the carrier frequency preset in the 2,000 Hz (or 2 kHz) to 5 kHz range. Drives more commonly used in HVAC applications may have the carrier frequency preset into the 10 kHz range. The width (or on time) of the pulses is constantly varying and it is the root mean square (RMS) value of these pulses that is the effective output voltage of the ASD. This is the PW portion of a VPWM ASD. The output voltage is constantly changing because the motor desires a constant “Volts per HZ” relationship so that the core does not get over excited at lower frequencies. (see “Over Speed” below).

The problem is that none of these pulses are really square. Every time the transistors turn on, the leading edge of the waveform imposes a voltage overshoot (or peak voltage), with an associated rise time, on to the motor terminals. The leading edge of the square waveform looks like this:



Simply stated, the motor acts as a capacitor to the system, storing energy during the overshoot and supplying energy back into the system during undershoot. This causes a ringing effect, or standing wave effect, which can go on at very high frequencies for several cycles. Longer cable leads have higher impedance and thus will cause more overshoot, the overshoot and the ringing being driven by the energy stored in the leads. The industry accepted value of the peak voltage created by this effect is 2 times the peak voltage, but recent papers lead to the possibility of 3 times the peak voltage in rarer circumstances. NEMA has assumed the 2 times value. Part 31.4.4.2 calls for motors with base ratings of 600 Volt or less to have an insulation system that can withstand a peak voltage of 3.1 times the rated voltage at a rise time of 0.1 microseconds (μs) or more. The 3.1 times is derived from the formula $V_{peak} \leq 1.1 \times 2 \times \sqrt{2} \times V_{rated}$. In this formula the 1.1 is a 10% safety factor, the 2 is the Transmission Line factor, and √2 x the rated voltage is the DC bus level.

The reason for the recommendation to purchase part 31 Voltage Spike standard motors in the first paragraph of this section is due to the large difference between part 30 and part 31 Voltage Stress withstand ability. Part 31 is described above and in summary is 3.1 x rated voltage, 0.1 microsecond rise time. Part 30 allows for motors with a much weaker Voltage Stress withstand rating. For part 30 motors, the ASD system must deliver a peak voltage of ≤ 1 kV with a rise time of ≥ 2 microseconds when the motors base voltage rating is ≤ 600 volts. This does not mean that these motors cannot be applied on ASD systems. What it does mean is that the vast majority of these applications will require the use of a long lead filter (see below in this section for an explanation of how a long lead filter protects the motor).

The above explains how voltage spikes are created; the following explains what happens from there. The rise time of these voltages spikes is very quick in IGBT type ASDs.

(Previous transistor technologies had longer rise times and thus had less impact on the motor windings, but had limitations in other areas.)

Traditional thought is that a voltage imposed on a group of windings will create an equal voltage drop per winding. For example if you had a coil of wire consisting of 10 winding loops, and applied 100 volts to it, each winding would have 10 volts applied to it. Contrary to this thought, the fast rise time of a PWM wave form causes the spike voltage to concentrate in the first winding of the motor. 90% or more of the voltage spike will commonly be induced into the first winding.

When two conductors lying side by side have a voltage potential difference between them, the voltage is distributed through the insulation system that separates the conductors. Although rare, if the voltage spike is high enough and/or the insulation is weak enough (pin holes per inch is an insulation inconsistency in the wire coating process that should be minimized) an immediate failure can occur. The more likely situation is that an air gap is present between the insulation and the conductor. If the voltage difference is high enough it causes the air to break down into charged particles, called corona (or partial discharge). Ozone is created through this process (it can be measured and sometimes even smelled by the human nose, and the partial discharge may be heard as a buzzing sound). The ozone chemically attacks the insulation destroying it and creating a greater air gap. The corona also accelerates the charged particles causing them to mechanically damage the insulation. The corona inception voltage (civ) is the voltage level where corona breakdown starts. With thousands of voltage spikes occurring per second, the damage from this effect can causes the insulation to break down very rapidly and the windings to short out in what is called a “Turn to Turn” failure. Turn to turn failures can occur for other reasons, but the rewind shop should be able to determine if the failure is a first winding failure or not. If the failure is a first winding failure on an ASD application then simply repairing the motor will not solve the problem, it will occur again unless remedial action is taken.

Remedial action can take two forms, and sometimes it is desirable or even necessary to use both in a belt and suspenders type approach. It should be noted that the problem is very prominent in 575 Volt applications, less so in 460 Volt systems especially if shorter cable lengths are used, and virtually non-existent in 230 volt applications. This is because the voltage spikes are a factor of the system voltage so the lower the system voltage the lower the spike, while at the same time the insulation system supplied in a 575 volt motor is usually the same system supplied in a 460 or 230 volt motor.

One remedial approach is to order motors that have wire with insulation values as per NEMA MG-1 Part 31.4.4.2. Wire that meets this insulation level is often called inverter duty wire or simply inverter wire. Practically speaking this approach means that all of the motors in a plant need to have inverter wire in them, as at some stage motors will fail and the ones on ASDs will need to be replaced with motors containing inverter wire. This approach has the best chance for long term success in new, green field, industrial plants, since existing plants have existing motors in their fleet that may not have inverter grade wire in them. The end user should consider updating their rewind specification so that any motors that are rewound meet this insulation level as well.

Some motor manufacturers have switched to inverter wire in all of their Severe Duty and/or NEMA Premium motors. Others will provide inverter wire if it is requested, often at no additional charge, but sometimes with a longer delivery time.

The wire manufacturers publish the test values of their products which are typically in the 2.2 kV, 0.04 μs rise time range. This is an “out of the box” condition of the wire and some consideration should be given to how it is handled by the motor manufacturer. Handling of the wire such as running it through the winding machinery, and inserting it into the slots of the winding can cause additional nicks or cracks in the insulation to occur. Some motor manufacturers will offer the wire company’s test values, and some have gone the extra step of testing the inverter wire wound motors at the NEMA values. It is up to the end user to be informed on what the manufacturers are offering, and what levels they will warranty their product to.

The other approach is to provide a long lead filter on applications where the cable lengths exceed the manufacturer’s recommendations. RLC filters installed at the drive terminals work in a wider variety of instances. “Terminator” type LC filters installed at the motor terminals are often sufficient, but care should be taken to ensure they are installed in a clean location as they can get very hot. In some cases reactors on their own will limit the voltage spikes below the civ, but often they don’t. Reactors may appear to be working as the motor doesn’t fail as fast, but they are only limiting the energy that is causing the corona, and thus damage is still occurring, but at a slower rate. Reactors are not that much less expensive than a long lead filter and are not recommended as a satisfactory solution.

Another approach that is similar to the second one above has been proposed. It is to measure the civ of a particular motor, then to measure the voltage spike at the motors terminals, thus determining which individual ASD systems require remedial action. This approach has not been utilized often and may not be a commercially practical solution as an installation standard, but may be very practical in trouble shooting problem applications.

Voltage Spikes can be caused by issues other than the Transmission Line effect and have been measured at times at levels much above the 2 times DC bus levels. These situations are much less common and may best be handled on a case by case basis. The long lead filter approach is often the solution for these instances and may add some importance to adopting this approach as the plant’s industrial standard.

Speed Ranges and Duty Cycles

It is important to understand the load characteristics when considering the operating speed range of an application. Load characteristics breakdown into two main categories, Variable Torque (VT) or Constant Torque (CT), with a third but less common application being Constant Horsepower (CHp).

Again, this paper deals with the application of “off the shelf” motors on ASDs, but keep in mind special ASD motors with turn down ratios of 100:1 or even 1000:1 do exist and may be appropriate in heavy duty turn down speed range applications.

Variable Torque

Variable Torque loads are often prime applications for an ASD as the energy savings that may be obtained can lead to very fast paybacks. VT loads are usually centrifugal loads such as fans, blowers, centrifugal pumps and compressors. The flow, pressure, and horsepower requirements of these loads follow laws of Affinity. With these Affinity Laws:

Speed is directly proportional to Flow

Speed^2 is proportional to Pressure (or Head)

Speed^3 is proportional to Hp.

Putting this into a useable table, and considering that electrical folks could care less about pressure it looks like this:

Numeric Description of the Affinity Laws

Speed	Flow	Required Power
100%	100%	100%
90%	90%	73%
80%	80%	51%
70%	70%	34%
60%	60%	22%
50%	50%	13%
40%	40%	6%
30%	30%	3%

From this table you can see that if speed/flow is reduced to 80%, the required Hp is reduced by the cube of the speed reduction to approximately 50% (51.2% to be exact). Other than speed control the other ways to reduce the flow involve the motor running at full speed and base Hp and pushing against a restriction of some kind, a vane in the case of a fan, or a control valve in the case of a pump. By use of an ASD the Hp requirements decrease significantly with the reduction of flow, thus saving energy costs, and also the cost of an expensive control device, the vane or control valve.

This same phenomenon is why a motor on an ASD can have a very wide speed range in a VT application. When the speed of the motor is reduced the cooling fan flow is reduced directly proportional to the speed reduction. At the same time the Hp required is reduced by the cube of the speed reduction. This means that the heat produced inside the motor is reduced faster than the reduced ability of the fan to process cooling air. At some stage other factors come into play, example -- the ability of the bearings to lubricate themselves, and therefore limit the speed reduction. A typical motor will have a minimum speed of 3 - 6 Hz, which is often shown as a ratio of the base speed of 60 Hz (such as 20:1 for the 3 Hz example or 10:1 for the 6 Hz example) but there may be no real limit to the turn down capability of a particular motor on a VT application.

Constant Torque

By the very nature of the term, Constant Torque loads are loads that require a constant torque over their speed range. Examples of CT loads are; conveyors, lifting equipment, reciprocating compressors, and positive displacement (PD) pumps. Since Hp is proportional to torque x RPM, in constant torque applications Hp varies directly with speed. The cooling fan flow rate is also varying directly with the speed. Since the Hp requirements are not dropping off as fast as they do in VT applications, the speed range of a CT application is significantly less than a VT application. Typical minimum speeds will be from 10to 30 Hz, or ratios of 6:1 to 2:1.

The speed range of a CT or even a VT application can often be extended by replacing the motor coupled fan with a fan being driven by an auxiliary motor, or with an external blower, thus providing more cooling air at a fixed speed. On smaller Hp loads it may be practical to consider a Totally Enclosed Non Ventilated (TENV) motor. This is a motor that has sufficient inherent heat sink ability such that fan driven cooling air is not required to keep it cool.

There is another load type that has characteristics that requires more attention to speed range, Constant Hp loads. Examples of these are winders, cutters and lathes. Since the term defines a load that has a constant Hp over the speed range, but the fan flow is diminishing directly as the speed reduction, the speed range without some auxiliary fan driver or over sizing of the motor is very limited.

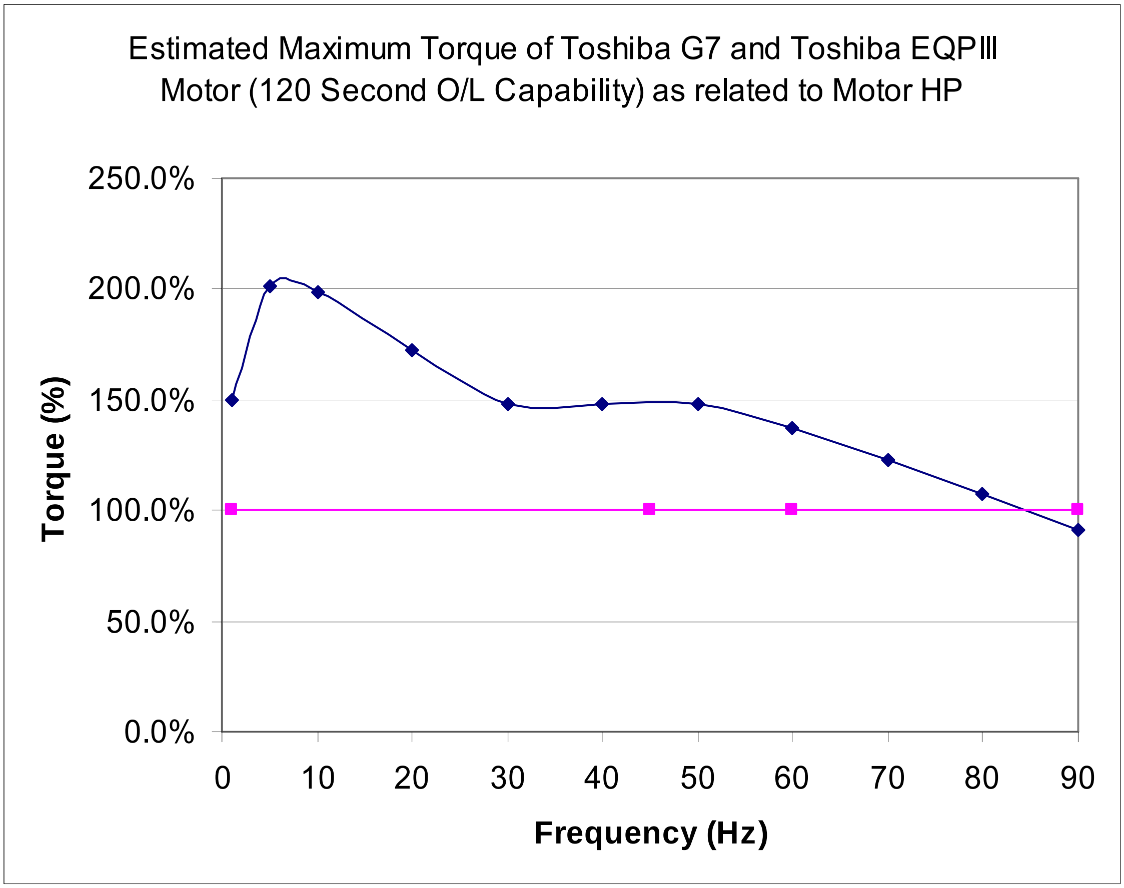
Over Speeding

Up to now we have only considered turning down the speed, or under speeding the motors. Things get much more complicated when over speeding of the motors is required. Usually motor over speeding is considered to increase the throughput of an Industrial facility. Once the nameplate value of the equipment is reached often the only way to increase production, short of buying higher nameplated, expensive, equipment is to make it all run faster.

SCI Motors like to have a constant “Volts per Hz ratio” applied to them. That is, in general terms, for ½ the speed they like to see ½ the voltage, for ⅓ the speed they want to see ⅓ the voltage. When we get to 60 Hz (full speed) they want to see full voltage. Above 60 Hz the system has no more voltage to provide, so the **motor’s** characteristics become Constant Hp. The **load’s** characteristic stays the same as they were, typically VT or CT. As discussed a VT load’s requirement is that the Hp varies as the Speed^3. The application will quickly become Hp limited, to the extent that it is often difficult to over speed a VT load to even 105% speed. CT applications have the Hp requirements increasing directly with the speed increase and since motors are often oversized slightly anyways, they can often be speed up to 110%, to 125%, or even 150% of base speed. In many cases, whether a VT or CT load, an over sized motor may be required to supply enough Hp or torque for the over speed condition. While over speeding up to 90 Hz is often possible, with perhaps oversized motors, over speeding above 90 Hz becomes even more difficult.

The motor manufacturer must be contacted prior to over speeding any motor.
Over speeding of motors also introduces higher centrifugal forces to the rotor of the motor. All motor manufacturers have restrictions on over speeding their motors. Some motor manufacturers will not permit any over speeding of 2 pole (3600 RPM synchronous speed) motors.

All over speed applications deserve to have specific application engineering time spent on them if a trouble free application is to be obtained. Some ASD/Motor manufacturers can plot the combined torque of the motor/drive combination against the load characteristics to determine if the motor/drive combination has enough torque for the speed range required. See a sample below. In this example the motor should not be run much over 80 Hz.



Sample application with a 40 HP drive and motor on a CT load

Duty Cycle

When considering the application speed range it is a good practice to consider the duty cycle. If a motor is to operate at a very low speed, but for only a couple of minutes out of an hour, cooling of the motor at that speed is much less a factor than if it is to operate continuously at that low speed. Engineering needs to know the duty cycle so that they can make appropriate decisions based on it, without possibly requiring expensive remedial actions that may be unnecessary.

Shaft Voltages

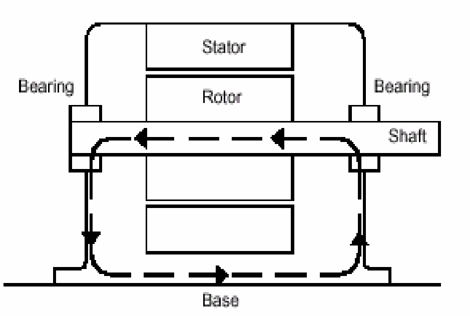
The following is excerpted from an IEEE report titled “Practical Guide to Understanding Bearing Damage related to PWM Drives” written by IEEE members and Toshiba International employees Don Macdonald, and Will Gray.

The phenomenon of motor shaft voltages producing circulating shaft currents has been recognized since the 1920s. When a motor is operated by sinusoidal power, shaft voltages are caused by alternating flux linkages with the shaft. The linkages are associated with flux unbalance caused by:

- rotor static or dynamic eccentricity
- rotor and stator slotting
- axial cooling holes in the stator and/or rotor laminations
- shaft keyways
- rotor core support arms
- joints between segmental laminations
- directional properties of magnetic materials
- supply unbalance
- transient conditions.1

Shaft voltages exceeding 300mV require one bearing of the motor to be insulated to prevent circulating current damage to the bearings. (see Fig 1) Typically this phenomenon only occurs on 500 frames and larger machines. Normally the Opposite Drive End (ODE) bearing is chosen. If the Drive End (DE) is insulated, the driven load can provide an electrical path that completes the loop to allow current to flow.

Fig.1 Inductive circulating currents



PWM drives can cause increased circulating currents to flow due to a high-frequency flux produced by common-mode currents which link the stator, rotor and bearing loop. This is an inductive rather than capacitive effect. Motors become more asymmetrical at high frequencies because the high-frequency capacitive coupled currents depend heavily on the location of the first few turns within the slot. Since placement of the turns in random-wound motors is not well controlled by any manufacturer, even a motor which is symmetrical at low frequencies becomes asymmetrical at high frequencies.

In addition to the preceding, PWM drives utilizing IGBTs can cause Electric Discharge Machining (EDM) currents. PWM inverters excite capacitive coupling between the stator windings, the rotor and the stator frame. This common mode current does not circulate but rather travels to ground (see Fig 2). The path to ground can be through both motor bearings and/or load or auxiliary equipment bearings (see Fig 3).

Fig.2 Capacitive coupled current flow

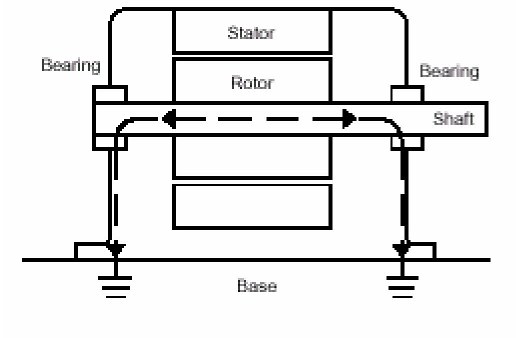
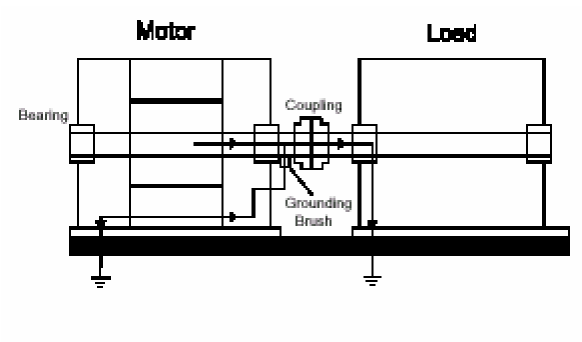


Fig. 3 Paths for common-mode currents to ground



The existence of EDM currents with PWM voltage source inverter drives depends on the presence of all of the following conditions:

1. Excitation, which is provided by the source voltage to ground
2. A capacitive coupling mechanism, between stator and rotor
3. Sufficient rotor voltage build-up which is dependent on the existence of bearing capacitance

Conclusions

When a bearing fails, especially on a motor being powered by a PWM ASD, the bearing and lubricant should be examined to determine the cause of failure. If the damage is due to EDM, corrective measures should be considered.

There are several possible practical solutions to mitigate bearing currents which include:

1. Selecting a carrier frequency which is between 1500 and 3000Hz if practical. This significantly reduces the energy transferred to the rotor.
2. Adding a common mode filter to mitigate common mode noise. The ratio of common-mode noise caused by a PWM drive compared to a sine wave is in the order of 10:1 or more. The addition of a filter which combines both common-mode and differential-mode filtering can reduce this ratio by as much as 70%. A common-mode filter connects the wye point of the filter to a “neutral” point on the DC bus. This filter arrangement provides a low-impedance path from the output of the ASD back to a neutral point on the DC bus instead of through the motor. (Note that further research has shown that the wye point of the filter can be connected to the negative DC bus with similar results).
3. Insulating both motor bearings to prevent current flow plus isolating all mechanical load and/or auxiliary equipment bearings (such as tachometers).
4. Adding a shaft grounding brush or brushes to shunt common mode currents (ideally with the ODE bearing being insulated).
5. Making sure that the motor frame is suitably grounded for high frequency currents. This prevents stator frame currents from flowing through the connected mechanical load or auxiliary equipment bearings via the motor bearings (or grounding brush).
6. Changing the cable to the recommended type to minimize the common mode current. Testing has shown that cables which have a continuous shield or continuous armor provide the lowest common-mode current plus relatively low frame voltage. The recommended cable for PWM ASD application has six symmetrical conductors, 3∅ and 3 ground conductors) with a continuous corrugated-aluminum armor-type sheath
7. As a temporary measure, using conductive grease. Why temporary? When a high-resistivity grease is used and the bearings are “floating” on the oil film, the equivalent-circuit characteristic changes from a resistor to a capacitor. If the rotor voltage exceeds the threshold voltage of the oil film between the balls or rollers and the races of the bearing, the oil film’s dielectric strength is exceeded. At this point, destructive EDM currents and arcing occur.

Resonances, Sound, and Vibration

NEMA MG-1 part 31.4.5 comments on some issues surrounding resonances, sound, and vibration. It recommends that motors applied on inverter systems be designed to limit the amount of resonances, sound, and vibration. Since this paper is addressing the application of “off the shelf” motors there is no further motor design issues that can be addressed.

From a vibration standpoint care should be taken to ensure that a massive base structure is designed, and that the base is flat and level. As well care should be taken to insure that the motor is properly shimmed and not installed with a soft foot. Both of these will help in limiting vibration levels that occur.

All motors have a critical resonant vibration point. 4 pole, 6 pole and greater pole motors are commonly designed so that the first critical resonance is above 60 Hz. 2 pole motors are usually designed so that the first critical is below 60 Hz. The connected mechanical equipment also has a critical resonance speed. On across the line applications since the motors operate at 60 Hz there are usually no resonant vibration issues on LV motors. However when applied on ASDs the frequencies outputted can possibly be at multiples of these critical speeds and excessive vibration can occur. The common fix is to “jump” these vibration frequencies by programming the drive so that it does not run at the speed that causes an excess vibration.

Drives operated at low carrier frequencies will hum due mostly to vibration in the laminations of the stator and rotor. In some cases this hum can be very annoying. In HVAC applications the hum can be magnified if the motor is mounted inside the air plenum. As a remedy the carrier frequency can be increased so that the vibration is beyond the audible noise spectrum. The carrier frequency to accomplish this can be quite high, 10 kHz or more. It should be recognized that two potentially adverse situations may occur at higher carrier frequencies;

1. Damaging voltage spikes will be occurring much more often, possibly causing a first winding failure and/or increased bearing currents,
2. At higher carrier frequencies the IGBTs may overheat if high loads are applied. The ASD may be designed to automatically de-rate it’s output, and/or the drive manufacturer may have engineering guidelines requiring de-rating the ASD if applied at high carrier frequencies. In some cases a larger drive may be required for trouble free operation.

Service Factor

The PWM output introduces extra heating effect in the motor due to the non-sinusoidal waveform. The motor will operate from 5 to 15% hotter when operated on an ASD. NEMA MG-1 Part 31.3.7 states that “A motor covered by this Part 31 shall have a service factor of 1.0”. It is common practice that an “off the shelf” motor with a nameplated service factor (SF) of 1.15 will lose the SF and become a motor with a SF of 1.0 when applied on an ASD.

Accessory Mounting

Accessories in ASD applications are typically speed/shaft positioning sensing devices (such as encoders, tachometers, or resolvers) and/or external cooling fans or blowers.

Wherever practical a special motor should be specified when mounting of accessories is required. It is possible for a local rewind shop to have a stub shaft mounted on the fan end of an “off the shelf” motor, but it is a much more elegant solution if the motor shaft was originally machined for it and the fan cover is built to house it. The same applies to mounting of non-coupled muffin fans or blowers.

Retrofitting with Existing Motors

With LV ASDs retrofitting to existing motors is relatively easy, but some questions need to be answered:

1. Does the motor have NEMA MG-1 Part 31 inverter wire? Often there will be no markings on the motor to help with the answer. The motor manufacturer may not have records to be able to answer this question, and even if they can state that it originally had inverter wire there is always the rewind factor, was the motor rewound? Often that answer is, “Who knows”. If it was, were inverter wire and inverter wiring standards used in the rewind? It is often best to assume that the motor does not have inverter wire in it. ***This does not mean that it cannot be used on an ASD!*** Many thousands (perhaps hundreds of thousands) of IGBT VPWM drives were/are successfully installed on motors before inverter wire was developed. A little more engineering thought may be required, and It may mean that there is more chance that a long lead filter is required.

2. What is the condition of the windings? If the insulation in the windings has degraded over time, applying an ASD could accelerate the failure of the motor due to the voltage spikes. Testing the motor by meggering it will give some indication of the winding condition. A polarization index (PI) test now, if you are performing them on a regular basis and/or have a base line PI test taken when the motor was new to compare it to, will indicate if the insulation has degraded from new. It is not fair to blame the ASD for failing a motor with poor insulation. I recall an Industrial Electrical Superintendent in a pulp mill telling me that his best guess is that 10% of his motors will fail on restart after a maintenance turn around. That is without any changes to the system. This is likely mostly due to deteriorating motor insulation, and the presence of more moisture when the motors are off (no heat in the motor to drive the moisture out if the motor is not running). If the insulation in your existing motor fleet is similar, ASDs will find the problem motors real quick.

Other than that applying an existing motor on an ASD is no different than applying an “off the shelf” motor.

Be cautioned, applying existing MV Motors onto MV ASDs is a very different situation due to the diverse ASD topologies currently being offered. You may very well need to purchase a new motor in a MV ASD application.

Conclusion

While there are special motors that meet more than merely the insulation requirements of NEMA MG-1 Part 31.4.4.2 Voltage Spikes, applying “off the shelf” motors with “off the shelf” ASDs is very simple to do these days. That being said, more than one customer has sworn that they will “never use those X$#% ASDs again!!!” when they themselves have failed to engineer the system up front. Use an engineering firm to design the system, make use of your drive supplier’s application expertise, or use your own in house expertise. It is well worth the effort to spend a bit of time engineering the application to assure success.