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Introduction

Most experienced motor technicians are well prepared to deal with traditional three phase motor failures caused by water, dust, grease, failed bearings, misaligned motor shafts, or even just old age. However, modern electronically controlled motors, more commonly referred to as adjustable speed drives. present a unique set of problems. This application note will focus on electrical measurements that can be used to diagnose bad components and other conditions that may lead to premature motor failure in adjustable speed drives (ASDs).



Troubleshooting Philosophy

There are many different ways to go about troubleshooting an electrical circuit, and a good troubleshooter will always find the problem - eventually. The procedure set forth in this application note will begin looking at the motor and work back towards the electrical source. Additionally, it will emphasize checking the simple and easy things first. A lot of time and money can be wasted replacing perfectly good parts when the only thing wrong is a loose connection.

Make accurate measurements. Of course nobody makes inaccurate measurements on purpose, but this is easier to do than you think when working in a high energy, noisy environment like ASDs. Don't use grounded test instruments if it can be avoided. They can introduce noise into a measurement where none existed before. Avoid touching instruments and probes if possible while taking the reading, as electrical noise can get coupled through your hands which may also affect the reading. Use current clamps which are well shielded and terminated with BNC connectors. Current clamps that put out 10 mV/amp or 100 mV/amp will have better signal to noise ratio than 1 mV/amp clamps when making current measurements less than 20 amps.

Finally, document electrical measurements at key test points in the circuit *when the system is functioning properly*. If a good drawing doesn't exist – make one. A simple one-line, or even block diagram will do. Write down voltage and temperature measurements at key test points. This will save lots of time and head-scratching later.

Making Safe Measurements

Before any electrical measurements are made, be sure you understand *completely* how to make them safely. No test instrument is completely safe if used improperly, but you should also be aware that many test instruments on the market are not appropriate for testing adjustable speed drives. The following information is explained in more detail in the Fluke application note, ABCs of *Multimeter Safety* and the video with the same name.1 The main points are summarized below. If you install or maintain modern adjustable speed drives (ASDs), then please don't skip this section as there could be hazardous voltages that exist in your measurement application that you are not aware of.

Safety ratings for electrical test equipment

The International Electrotechnical Commission (IEC) is the primary independent organization that defines safety standards for test equipment manufacturers. There is much confusion about what these standards mean and how they should be used to determine the right instrument for the right application. The following section will help clarify this selection process.

The IEC 1010 standard for test equipment safety states two basic parameters; a voltage rating and an overvoltage category rating. The voltage rating is the maximum continuous working voltage that can be measured. This is fairly straightforward and simple, although I'm sure many of you have noticed that your DMM or scope will often give a reading higher than its maximum voltage rating. Your test instrument should **never** be operated above its voltage rating. Most test instruments are designed to have a 10% overvoltage safety margin, but if for some reason you see a

¹ ABCs of Multimeter Safety Application Note, Literature code BO317UEN Rev. A. The ABCs of Digital Multimeter Safety Video, P/N 609104.

voltage displayed above the rating, or see the overload (OL) being displayed, disconnect the measurement device immediately.

Probably the most confusing issue is when the voltage rating is coupled with a category rating. The category ratings below in Figure 1 show the measurement environment expected for a given category. The main criteria for the different categories is the transient voltage that the test instrument can withstand, and maybe even more importantly, how much energy (volt/amps) is available to feed any short circuit that may occur as a result of the transient. Transients may originate from sources outside the building, i.e., lighting strikes, utility switching and power line fault clearing activity, or they may originate from inside the building for example, as a result of load switching. The measurement is considered to be safer the further the test instrument is away from the transient source,

as the transient voltage gets dampened considerably as it makes its way into the building, and through the internal distribution system.

The measurement environment for an adjustable speed drive is not always straight-forward and may vary from installation to installation. For example, a 100 HP drive instal-led 25 feet from the switchgear would be considered a CAT III measurement environment, but if that same drive was installed 70 feet from the switchgear and had an isolation transformer or line reactors preceding it, it could be argued that it is more like a CAT II environment. If you are working in both environments, be safe and use only CAT III rated test instruments.

What may not be readily obvious from the looking at Table 2 is the difference between a 1000V CAT II rated meter and a 600V CAT III rated meter. At first glance, you might think the 1000V CAT II meter is the better choice because it has a higher working voltage than the 600V CAT III



Figure 1. IEC-1010 category ratings diagram for various measurement locations

meter and it can handle the same level of high voltage transient, which is true. However, the 600V CAT III meter can safely handle six times the power as the 1000V CAT II meter, should a transient cause a fault within the meter.

The bottom line recommendation for test instruments used on ASDs is they should be 600V or 1000V CAT III rated. Some manufacturers have dual rated 600V CAT III/1000V CAT II test instruments and probes which are the next best thing to a 1000V CAT III test instrument. CAT II instruments should be avoided altogether unless you are certain to be making measurements only on fractional horsepower drives that are plugged into a wall receptacle. As the design guidelines for CAT IV have yet to be defined and adopted, there are no official CAT IV test instruments available.

Also, avoid meters that claim to be "designed to meet" IEC-1010 specifications or that do not carry the test certification of an independent testing lab such as UL, CSA, VDE, TUV or MSHA, as they do not always meet the specifications for which they claim to be designed. Always look for independent certification of test instruments for ASD measurements. See Table 7 at the end of this application note for recommended Fluke instruments.

Once you've selected a test instrument with an adequate safety rating, then it's up to you to follow the measurement safety practices as outlined below, as even a meter designed with safety in mind can be unsafe if misapplied.

- Work on de-energized circuits whenever possible using proper lockout/tag-out procedures.
- Use protective gear when working on live circuits (insulated tools, safety glasses, insulated mat,

flame resistant clothing and remove jewelry).

- Do not measure voltages above the working voltage rating of the test instrument or in high energy measurement environments for which it's not rated.
- Use the three-point test method:
 - Test a known live circuit.
 Test the target circuit.
 Test the live circuit again to be sure the meter is still functioning properly.
- Hook on the ground lead first, then connect the hot lead. Then reverse the procedure by taking off the hot lead first, then the ground second.
- Hang or rest the meter if possible to avoid holding it in your hands.

• Use the old electrician's trick of keeping one hand in the pocket to lessen the chance of a closed circuit across the chest and through the heart.

WARNING: To avoid electric shock or other injury, when making measurements on CAT III circuits do not use divider probes (e.g. 10:1, 100:1, 1000:1, etc.) that are only rated IEC 1010 CAT I or CAT II. Make sure the scope probe you use is rated for the measurement category environment in which you work.

One final word on safety is covered in the section on **Over-voltage Reflections** – **Troubleshooting** as it will be much better understood and appreciated after the possible condition is explained in more detail.

Overvoltage Category	Examples
CAT IV	 Refers to the "origin of installation", i.e. where low-voltage connection is made to utility power. Electricity meters, primary overcurrent protection equipment. Outside the building and service entrance, service drop from the pole to building, run between the meter and panel. Overhead line to detached building, underground line to well pump.
CAT III	 Equipment in fixed installations, such as switchgear and three phase motors. Bus and feeder in industrial plants. Feeders and short branch circuits, distribution panel devices. Lighting systems in larger buildings. Appliance outlets with short connections to service entrance.
CAT II	 Appliance, portable tools, and other household and similar loads. Receptacle outlets and long branch circuits. Outlets at more than 10 meters (30 feet) from CAT III source. Outlets at more that 20 meters (60 feet) from CAT IV source.
CAT I	 Protected electronic equipment. Equipment connected to source circuits in which measures are taken to limit transient voltages to an appropriately low level. Any high-voltage, low-energy source derived from a high-winding resistance transformer, such as the high-voltage section of a copier.

Table 1. Measurement environment examples

Overvoltage Category	Working Voltage (dc or ac-rms to ground)	Peak Impulse Transient (20 repetitions)	Test Source (Ohm = V/A)
CAT I	600V	2500V	30 ohm source
CAT I	1000V	4000V	30 ohm source
CAT II	600V	4000V	12 ohm source
CAT II	1000V	6000V	12 ohm source
CAT III	600V	6000V	2 ohm source
CAT III	1000V	8000V	2 ohm source

Table 2. Transient test values for overvoltage installation categories

Adjustable Speed Drive Theory

The term adjustable speed drive (ASD) includes a wide variety of mechanical, pneumatic and electronically controlled motors whose speed is adjustable. Another term, variable frequency drive (VFD) is used for electronically controlled ac induction motors as they vary the frequency of the voltage to the motor to change its speed. The term ASD will be used from here on out as this is the conventional term as used in the IEEE standards.

DC motors and other methods of adjusting motor speed and torque will not be discussed in this application note.

Figure 2 shows a simplified block diagram of a typical ASD. There are four main sections. The three sections that are in-line between the ac line inputs and the motor are the Input Converter, dc Link and the Output Inverter. The fourth section, the Control Circuitry, is the "brains" of the drive. Each of these sections has a job to perform, and for most ASDs the task is the same:

- The input converter transforms ac sinusoidal current to dc, as dc is what is required for the electronically controlled power transistors in the output inverter.
- The dc link is the source of power for the output inverter. The larger horsepower drives will have a large bank of capacitors to store voltage from the sine wave input. This section may also contain a series inductor to help regulate the voltage and current.
- The output inverter
 provides a variable ac
 voltage and frequency.
 Voltage and frequency (V/Hz)
 are either varied together to
 provide a constant torque
 with varying speed, or the
 V/Hz is varied at different
 rates to provide variable
 torque at different speeds.



Figure 2. Block diagram of a typical ASD

The control circuitry

of the ASD performs a variety of tasks. It times the switching of the input and output devices. It carries out commands from the operator control panel. It also monitors for and reports malfunctions and improper operating conditions to the operator or troubleshooter. Control circuits shut down the ASD, if necessary, to protect the motor or output inverter and prevent unsafe operating conditions.

		(V x I x Eff)	¥ 5250
Tormio -	Horsepower _	746	x 3230
ioique =	Speed	120 x Hz	
	-	no. of poles	

You can see from the formula above that varying the ratio of horsepower to speed will alter the torque. Therefore, changing the volts/hertz (V/Hz) ratio will change the motor torque. For constant torque applications, the V/Hz ratio is held constant by varying the voltage and frequency together; or for variable torque applications, the voltage and frequency are varied at different rates to accomplish variable torque.

The speed and torque of the motor are usually controlled by 0-5 Vdc, 0-10 Vdc, 0-20 mA, or 4-20 mA control signals applied to the control input block of the ASD. These control signals may come from feed-back sensors and encoders or from a control panel.

The following paragraphs describe in more detail the two most common variations of ASDs, the voltage source inverter, and the pulse width modulated (PWM) inverter.



Figure 3. Simplified diagram of a voltage source inverter with output current and voltage waveforms

Figure 3 shows a simplified diagram of a voltage source inverter. The input section uses thyristors to rectify all, or part of the incoming line-to-line phase voltages to produce varying levels of dc voltage at the dc link capacitor. The dc voltage determines the peak voltage of the drive's output to the motor. The *frequency* of the drive's output voltage is determined by the control signals applied to the SCRs in the output section. To summarize, the voltage part of the V/Hz ratio is controlled by full or partial rectification of the ac to dc in the input section, while the frequency part of the V/Hz ratio is controlled by the frequency of the control signals applied to the inputs of the SCRs (or transistors) in the output section.

Figure 4 shows a simplified diagram of a PWM drive. Notice the input section is using diodes which provide full rectification of the ac line input, thereby charging the dc link capacitor to 1.414 times the input RMS phase-phase voltage (unloaded bus). Unlike the voltage source inverter, the dc voltage remains at a constant level.

However, to provide varying levels of RMS voltage, the voltage waveform is a series of constant magnitude pulses that vary in width. To the motor, one group of positive pulses looks like the positive half of a sine wave, while the negative pulses look like the negative half. The wider the pulses, the higher the RMS voltage. Therefore if narrow pulses are at the beginning of the positive cycle, and wide pulses are towards the middle, it will produce a nearly sinusoidal RMS voltage. Although the voltage waveform looks very

distorted (non-sinusoidal), the large motor inductance will "smooth out" the current waveform so to the motor, it looks more like the dashed lines superimposed on the voltage waveform in Figure 4. The nearly sinusoidal current waveform in the bottom of Figure 4 shows that the motor is in fact only responding to the RMS voltage of the pulses.

To summarize, the voltage part of the V/Hz ratio is controlled by varying the pulse width of the pulses, thereby varying the RMS voltage, even with a constant peak-to-peak voltage. The frequency part of the V/Hz ratio is controlled by the modulation frequency which is the time period comprising one positive set of pulses and one negative set of pulses. It is the modulation frequency that the motor is responding to and only a very small amount of the high frequency pulses can be seen in the motor current waveform.



Figure 4. Simplified diagram of a pulse width modulated inverter with current and voltage waveforms taken at the motor terminals

Simple Things First

Be sure all connections are good. Seems obvious doesn't it? However, *honest* troubleshooters will admit to having overlooked this condition at least once in their career—right?! This troubleshooting step should always be done before anything else. Periodic tightening of connections is often required to maintain a low resistance connection between conductors. Visually inspect all connection points for looseness, corrosion, or conductive paths to ground. Even if the visual inspection looks okay, you should use at least one, or some combination of the following three methods for checking the connections.



Figure 5. The 1 mV/degree output of the Fluke 80T-IR can be used with any DMM capable of reading millivolts. The Fluke ScopeMeter instruments can read out directly in Fahrenheit or Celsius.

Resistance measurements

This is probably the least preferred of the three methods, but will still detect completely open circuits or "leakage" paths to ground that are resistive. Keep in mind however, that most ohmmeters use small amounts of current in their measurements and may read a good connection, when in fact the connection may open circuit when a large amount of current attempts to conduct through it. This is also known as contact resistance.

Voltage drops

Check for voltage drops across the various connections. Compare with the other two phases. Any significant variation between phases, or more than 2-3% (depending on motor current and supply voltage) at each connection, should be suspect.

Temperature measurements

An inexpensive infrared temperature probe used with a handheld DMM is a fast and easy way to check for bad connections. Any significant increase in temperature at the connection terminal will indicate a bad connection or contact resistance due to I2R heat loss. If the temperature of the terminal was not previously recorded onto your system diagram, compare with the other two phases. More on how to use temperature measurements to diagnose motor and drive problems is discussed in the following sections.



Motor Measurements

Temperature measurements

Temperature is a key indicator of a failing, or overloaded motor. Use an infrared temperature probe such as the 80T-IR from Fluke to measure motor temperatures at key points including; bearing locations and motor terminal block connections (if one exists), as well as the motor housing itself. Are the readings close to what was measured when the motor was operating normally? If these readings weren't taken before, is the motor operating temperature within the NEMA classification for that motor? If the answers to these questions are yes, then you may want to move to the ASD controller for the next measurements, or you can go ahead and make the following measurements just to be sure.

Overloading

If the motor is trying to deliver more torque/power to the mechanical load than for which it is rated, an overload condition will exist, i.e., the motor draws current above its nameplate rating. Measure the motor current and check it against the nameplate rating. Be sure to multiply the service factor (SF), if one is shown on the nameplate, times the rated current.

If the motor is at or above its rated capacity and the overload is intermittently tripping the drive, the solution is not to adjust the overload on the drive higher to prevent the tripping! Find out if the motor is rated properly for the application. Sometimes a cheaper, lower rated motor is substituted; or perhaps a miscalculation of the load requirement accounts for the mismatch. It's also possible that the mechanical load being driven by the motor has been increased by an operator or process supervisor who doesn't understand that doing so will put the motor into an overload condition.

What next?

If mechanical load requirements and behavior seem normal, then it's possible some of the motor windings have become shorted and are the source for increased current, heat and loss of torque. Things to check for now are current imbalance, single phasing, voltage imbalance and something unique to PWM drives, overvoltages caused by reflected voltage waves. High motor shaft voltages, a problem also associated with PWM drives, could explain excessive bearing temperatures and premature bearing failure. How to test for these conditions is described in the following paragraphs.

Voltage measurements

As the voltage applied to the motor terminals by the ASD is non-sinusoidal, the voltage readings given by an analog meter, an average responding digital multimeter (DMM) and a true RMS DMM will all be different. Many troubleshooters prefer using an analog meter because the coil in the meter movement responds in the same way as the motor, i.e., to the low frequency component of the waveform, not the high frequency switching component. The analog meter will also correspond to the ASD's programmed V/Hz ratio and the voltage displayed on the ASD housing if one exists.

Most digital multimeters (DMMs) will respond to the high frequency component of the motor drive waveform and will therefore give a higher reading. Even though a true-RMS DMM will give an accurate reading of the *heating effect* of the non-sinusoidal voltage applied to the motor, quite often the analog meter reading is preferred since it gives a (lower) voltage reading similar to the motor's response to the voltage applied. However, it should be noted that even though the motor is not responding to the higher frequencies in terms of torque or work being done, high frequency currents may be flowing outside of the windings due to various capacitances in other parts of the motor. This will be discussed in more detail later on.

The reason for making voltage measurements at the motor terminals is to verify that the voltage is not too high, too low, or is unbalanced. A DMM/Scope with a low pass filter probe or Fluke 41B, can be used to verify that the voltage at the motor terminals corresponds with the calculated voltage readout at the ASD's display. Using a scope or 41B has the advantage in that a simultaneous frequency measurement can be made which is much more meaningful. This is discussed further in the Volts/Hz ratio section. If the voltage at the motor is too low, then bad connections are a likely cause, or the dc bus voltage at the ASD is too low. If the motor terminal voltages are too high, then the dc bus voltage may be too high, which in turn could be due to the ASD input voltage being too high.

Next measure the phaseto-phase voltage between the three motor terminals for voltage imbalance. Voltage imbalances of as little as 3% can cause excessive heating due to unbalanced currents in the stator windings and loss of motor torque. However, some motor installations are more forgiving towards imbalances so be sure to check out the entire motor system for other causes should an imbalance exist. As the relative difference between phase voltages is what is being measured, not absolute voltages, the DMM will give more accurate readings with better resolution than an analog meter. Use the following procedure to calculate voltage imbalance.

Current imbalance measurements

Motor current should be measured to ensure that the continuous load rating on the motor's nameplate is not exceeded and that all three phase currents are balanced. If the measured load current exceeds the nameplate rating, or the current is unbalanced, the life of the motor will be reduced by the resulting high operating temperature. If the voltage imbalance is within acceptable limits, then any excessive current imbalance detected could indicate shorted motor windings. Generally, current imbalance for threephase motors should not exceed 10%.

Percent Voltage Imbalance = <u>Maximum deviation from the average voltages</u> x 100 <u>Average voltage</u>

For example, voltages of 449, 470 and 462 gives an average of 460. The maximum deviation from the average voltage is 11 and percent unbalance would be: $\frac{11}{400} \times 100 = 2.39\%$

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Possible causes of voltage imbalance are: one of the phase drive circuits is only partially conducting, or there is a voltage drop between the ASD's output and the motor terminal on one of the phases due to a poor connection.

There are other concerns about the motor terminal voltages with regard to distortion, but they must be measured and viewed using an oscilloscope and will be discussed in a later section.

As the current measurement will be made in a high energy, electrically noisy environment, be sure the proper current clamp is used as well as good measuring technique. An ac only current transformer (CT) style current clamp will usually work best as it is a low impedance device and less likely to "capture" electrical noise across it. Most ac/dc current clamps are the hall effect style which have a high impedance and are therefore more susceptible to noise. Either style clamp can have problems with noise if not properly shielded and terminated. Clamps using coaxial cable terminated with BNC connectors work best.

Clamps with higher selectable output ranges for current measurements less than 10 or 20 amps will help get the signal-to-noise ratio of the clamp to an acceptable level.

The integrity of the measurement can sometimes be enhanced by **not** touching the clamp or the meter while taking the reading.

To calculate current imbalance, use the same formula as above for voltage but substitute current in amps. For example, currents of 30, 35 and 30 amps would give an average current of 31.7 amps. The maximum deviation from the average current would be 3.3 amps with a current imbalance of 10.4%.





Figure 6. Measure the motor phase currents.



Figure 7. Rotate phase connections to determine whether problem is in the motor or the drive.

If the current in the motor is unbalanced (Figure 6), you can determine if the unbalance is caused by the motor or the ASD by rotating the phase connections on the motor terminals. But first, measure the current in all three phases with the motor under load. Next, rotate the phase conductors from the ASD to the motor terminals.

If the phases A \emptyset , B \emptyset and C \emptyset are connected to motor terminals T1, T2 and T3 respectively, then change the connections so that phases A \emptyset , B \emptyset and C \emptyset are now connected to terminals T2, T3 and T1 (Figure 7). Now measure the phase currents with the motor under load again.

Let's say the first measurement found the current imbalance was on the BØ/T2 connection. If the imbalance moved to the BØ/T3 connection in the second measurement, then the imbalance is coming from the ASD. If the current imbalance in the second measurement was on the AØ/T2 connection then the imbalance is due to the motor.

Single phasing

Single phasing results from the total loss of one of the phase voltages applied to a three phase ac induction motor and can be a tricky problem to detect. In an ASD application, this would usually be caused by an open connection at either end of the cabling between the motor and drive, or an open in one of the conductors in the cable itself. It's also possible one of the insulated gate bipolar transistors (IGBT) which are the devices that drive each phase of the motor, could have become open circuit, although some ASDs are able to detect this condition.

Single phasing is a fairly common cause of failure for three phase induction motors as the other two phase windings must conduct more current, and therefore produce more heat, which eventually leads to premature failure of the motor. What makes single phasing a tricky problem to detect is that the motor will continue to run normally, although there will be an increase in heat, and possibly loss in torque—subtle conditions that may go unnoticed. Another clue to a possible single phasing condition is if the motor is stopped and restarted, it may run backwards.

The measurement side of detecting this problem is also a little tricky. When the voltage measurement is made at the motor terminals, the voltages will read close to normal as motor action is inducing voltage into the open winding. The best way to reliably detect this condition is to make current measurements on all phases until the open phase is detected through an absence of current flow.

Overvoltage Reflections — Theory

For those not interested in the theory of how this phenomenon occurs, skip ahead to the next section on troubleshooting the problem.

The trend with PWM drives has been to make the rise time of the pulses as fast as possible to reduce switching losses and increase the efficiency of the drive. However, fast rise times, coupled with long cable lengths produce an impedance mismatch between the cable and the motor causing reflected waves, or "ringing" as shown in Figure 8. If the rise times are slow enough, or the cable short enough, the reflected waves will not occur. The main problem with this condition is that ordinary motor winding insulation can break down quickly. Additionally, higher than normal shaft voltages can develop causing premature failure of bearings and excessive common mode noise (leakage currents) can interfere with low voltage control signals and cause GFI circuits to trip.



Figure 8. Reflected voltages (ringing) on the modulated pulse

The relationship between cable length, rise time and the resultant increase in peak voltage is illustrated in Figure 9. Basically, the peak voltage at the motor terminals will increase above the dc bus voltage of the ASD as cable length increases and the rise time of the ASD output pulse gets faster.



Figure 9. Impact of rise time and cable length on magnitude of reflected voltages

The magnitude of the voltage that is reflected at the motor terminals back to the ASD and added to the peak voltage, then driven back to the motor, is determined by something called the reflection coefficient, which is a function of the motor resistance, the cable inductance and cable capacitance as shown in the formula below:

$$\Gamma_{\rm L} = \frac{R_{\rm M} - R_{\rm C}}{R_{\rm M} - R_{\rm C}}$$

 $R_M + R_c$ where Γ_L is the reflection coefficient of the load, R_M is the motor resistance and R_c is the characteristic cable resistance expressed by the formula:

$$R_c = \sqrt{L/C}$$

(see cable manufacturer's. specifications for inductance (L) and capacitance (C) per foot)

Most motors less than 10 HP have an Γ_L between 0.9 – 1.0. Some larger horsepower motors may have an Γ_L as low as 0.8, occasionally less. The curves in Figure 9 use an Γ_L of 0.9 in the calculation. There are two different formulas for determining the peak voltage that can be expected at the motor terminals, depending on whether the transit time of the pulse (traveling at half the speed of light) is greater than or equal to 1/3 the rise time (dv/dt) or less than 1/3 the rise time. First let's look at how to determine the transit time (t_t) with regard to cable length (l_c).

 $L_t = \frac{l_c (ft)}{500 (ft/\mu sec)} = 2x 10^{-9} * l_c$

If the transit time of the cable is less than 1/3 the rise time then use the following V_{peak} formula:

$$V_{\text{peak}} = \frac{3t_t}{t_r} * \Gamma_L + 1 * V_{\text{DCB}}$$

When the transit time is greater than or equal to 1/3 the rise time, then the rise time portion of the first V_{peak} formula is not used and the calculation becomes:

 $V_{\text{peak}} = \Gamma_{\text{L}} + 1 * V_{\text{DCB}}$

For example, if we have a 480 Vac L-L voltage with a 648 Vdc bus, 50 feet of cable, and $R_L = 0.9$ we can see the effect of the peak voltage calculation using two different rise times.

With a rise time of 0.5 μ s, the transit time (0.1 μ s) is less than 1/3 the rise time (0.16 μ s) so we use the first V_{peak} formula that takes into account the effect of rise time and the calculation becomes:

 $\frac{.3}{.5}$ x 0.9 + 1*648 Vdc = 998 V_{peak}

With a rise time of 0.1 μ s, the transit time (0.1 μ s) is greater than 1/3 the rise time (0.033 μ s) so we use the second V_{peak} formula which is:

 $0.9 + 1 * 648 \text{ Vdc} = 1,231 \text{V}_{\text{peak}}$

(See the Acknowledgments at the end of this application note for additional information and references)

Overvoltage reflections – troubleshooting

As mentioned earlier, fast rise times on the ASD output pulses and long cable runs between the ASD and the motor will cause overvoltage reflections approaching double the DC bus voltage and even higher. An oscilloscope is required to discover the full extent of this problem, as seen in Figures 10 and 11 below.



Figure 11. Overvoltages due to reflected waves

Figure 10 shows the ASD L-L voltage measurement at the motor terminals with six feet of cable, while Figure 11 shows the ASD L-L voltage with 100 feet of cable. Notice the difference in peak voltage measurements — about 210 volts. Also notice that there is only 5 Vrms difference between the two waveforms (small digits on the display). This means your voltmeter will not find this problem.

Very few scopes will trigger as nicely and easily as the Fluke ScopeMeter* 123 Test Tool did for the measurements in Figures 10 and 11. For other scopes use the procedure outlined below to measure the extent of the overvoltages.



no reflected voltage



Figure 13. Leading edge of PWM pulse with reflected voltage (ringing)

The signals in Figures 12 and 13 were captured by triggering on a single pulse using single shot mode with cursors enabled to make the peak voltage measurement along with rise time. While this measurement requires more button pressing and scope "know how," the automated rise time measurement may be worth the trouble. Manually resetting the single shot trigger periodically will give you a sampling of various peak voltages for the different pulses. Also, slowly raising the trigger voltage will give you an idea of the maximum peak when the scope stops triggering.



Assuming you have identified a true overvoltage, or ringing problem, then something must be done about it. The simplest solution is to shorten the cable. Table 3 shows the maximum length of the cable before the peak voltage goes beyond 1.15 times the dc bus, (highest "safe" motor voltage) for various rise times and reflection coefficients (Γ_L) of 0.9 and 0.8 (see previous section for more details).

The table only shows where the peak overvoltages start for a given rise time and length of cable. The peak overvoltages will continue to increase to almost double the dc bus voltage as the cable lengthens or rise time gets faster. The peak voltages can even exceed voltage doubling if the reflected voltage occurs on top of existing ringing due to the distributed leakage inductance and coupling capacitance.

The real danger of this overvoltage condition is the damage it can do to the motor windings over a period of time, which may not show up as a problem when the PWM drive is first installed. Many PWM drives are installed without taking into consideration the overvoltage effects of long cabling between the PWM output and the motor. And while improved efficiency of the newest and latest PWM drives are achieved by making the rise times faster on the output pulses, this can make the overvoltage problem even worse, and the need for shorter cabling even greater.

If your motor has already failed and has to be rebuilt, better insulated wire such as Thermaleze Q^s, or TZ Q^s (by Phelps-Dodge), should be used to rewind the motor. The main advantage is that it provides significantly more protection against overvoltages without adding insulation thickness and the same stator can be used without modification. If the motor has been damaged beyond repair then a motor designed to meet NEMA MG-31 specifications (sustained V_{peak} \leq 1600 volts and rise time 0.1 μ s) should be used as a replacement motor for PWM applications where sustained overvoltages may be occurring.

PWM Pulse Rise Time	Length where Vpeak >1.15 x DC bus voltage and $\Gamma_{\rm L} = 0.9$	Length where Vpeak >1.15 x DC bus voltage and $\Gamma_{\rm L} = 0.8$
0.1 µs	2.8 feet	3.1 feet
0.2 μs	5.5 feet	6.3 feet
0.5 µs	14 feet	16 feet
0.7 μs	19 feet	22 feet
1 μs	28 feet	31 feet
1.5 µs	42 feet	47 feet
2 μs	55 feet	63 feet
3 μs	83 feet	94 feet
4 μs	111 feet	125 feet
5 µs	138 feet	156 feet
6 µs	166 feet	188 feet
7 μs	194 feet	219 feet
8 μs	221 feet	250 feet
9 µs	249 feet	281 feet
10 µs	277 feet	313 feet

Table 3. Maximum cable lengths for various rise times and reflection coefficients before peak voltages begin to exceed 1.15 times the DC bus voltage



Figure 14

Motor Terminal Filter	Inverter Output Filter	Series Reactor
Parallel connected at the motor terminals.	Series connected to the PWM output terminals.	Series connected to the PWM output terminals.
Designed to match the characteristic cable impedance.	Designed to slow rise time (dv/dt) below a critical value.	Acts as current limiter and also slows rise time.
Not cable length dependent.	Dependent on cable length.	Dependent on size of system.
Losses are more or less fixed.	Losses dependent on motor kVA	Losses dependent on motor kVA
Size/cost more or less fixed.	Size/cost dependent on motor kVA.	Size/cost dependent on motor kVA.

Table 4.

If the cabling in your PWM application cannot be shortened then use **one** of the three ways to fix the problem as shown in Figure 14:

- 1. An external "add-on" low pass filter can be installed between the PWM output terminals and the cable to the motor, as one way to slow the rise time.
- 2. Another approach is to install an R-C impedance matching filter at the motor terminals to minimize the overvoltages, or ringing effect.
- 3. In some applications, such as submersible pumps or drilling machines, it is not possible to access the motor terminals and other methods of minimizing overvoltages are required. One way is to apply series reactors between the PWM output terminals and the cable to the motor. While this is a fairly simple solution, the reactors may be fairly large, bulky and expensive for large horsepower applications.

The trade-offs between these three alternatives for minimizing overvoltages can be summarized in Table 4. All the solutions suggested above should be designed for your specific application by a qualified engineer.

Safety Note: Reflective voltage phenomenon can mean peak voltages 2–3 times the DC bus voltage. For 480V line voltage this means a DC bus voltage of 648V and possible peak overvoltages of 1300V-2000V and possibly higher given +10% line voltage variance. Therefore it is recommended that the measurement at the motor terminals be made with the highest rated probe available and for the shortest time possible where reflected voltages are likely to be present.

Bearing currents

When motor shaft voltages exceed the insulating capability of the bearing grease, flashover currents to the outer bearing will occur, thereby causing pitting and grooving to the bearing races. The first signs of this problem will be noise and overheating as the bearings begin to lose their original shape and metal fragments mix with the grease and increase bearing friction. This can lead to bearing destruction within a few months of ASD operation and is thus expensive in motor repair and downtime.

There is a normal, unavoidable shaft voltage created from the stator winding to the rotor shaft due to small dissymmetries of the magnetic field in the air gap that are inherent in the design of the motor. Most induction motors are designed to have a maximum shaft voltage to frame ground of < 1 Vrms.

Another source of motor shaft voltages are from internal electrostatic coupled sources including; belt driven couplings, ionized air passing over rotor fan blades, or high velocity air passing over rotor fan blades such as in steam turbines.

Under 60 Hz sine wave operation, the bearing breakdown voltage is approximately 0.4-0.7 volts. However, with the fast edges of the transient voltages found with PWM drives, the breakdown of the insulating capacity of the grease actually occurs at a higher voltage — about 8-15 volts. This higher breakdown voltage creates higher bearing flashover currents, which causes increased damage to the bearings in a shorter amount of time.

Research in this area has shown that shaft voltages below 0.3 volts are safe and would not be high enough for destructive bearing currents to occur. However, voltages from 0.5-1.0 volts may cause harmful bearing currents (>3A) and shaft voltages > 2 volts may destroy the bearing.

Care must be taken when making this measurement. Connect the probe tip to a piece of twisted stranded wire, or a carbon brush which in turn makes contact with the motor shaft, while the common is connected to the motor frame ground. As the shaft voltages are caused by fast rise times of the PWM drive pulses, the voltages will appear as inconsistent peaks and should be measured using an oscilloscope and not a DMM. Even if the DMM has peak detect, there is enough variation between peaks to render the reading unreliable. Another measurement tip is to make the shaft to frame ground voltage measurement after the motor has warmed to its normal operating temperature as shaft voltages may not even be present when the motor is cold.

The most simple solution to this problem is to reduce the carrier (pulse) frequency to less than 10 kHz, or ideally around 4 kHz if possible. If the carrier frequency is already in this range than alternative solutions can be employed such as: shaft grounding devices, bearing insulation, faraday shield in the motor, conductive grease, the use of ceramic bearings or filtering between the ASD and the motor.

Leakage currents

Leakage currents (common mode noise) capacitively coupled between the stator winding and frame ground will increase with PWM drives as the capacitive reactance of the winding insulation is reduced with the high frequency output of the drive. Therefore, faster rise times and higher switching frequencies will only make the problem worse. It should also be noted the potential increase in leakage currents should warrant close attention to established and safe grounding practices for the motor frame. The increase in leakage currents can also cause nuisance tripping of ground fault protection relays, override 4-20 mA control signals, and interfere with PLC communications lines.

Measure common mode noise by placing the current clamp around all three motor conductors. The resultant signal will be the leakage current.

A common mode choke along with a damping resistor can be used to reduce leakage currents (Figure 15). Also, special EMI suppression cables can be used between the drive output and the motor terminals. The copper conductors of the cable are covered with ferrite granules which absorb the RF energy and convert it to heat. Isolation transformers on the ac inputs will also reduce common mode noise.



Figure 15. Common mode choke with dampening resistor to reduce leakage currents

Measurements at the Inverter

Control circuit noise

Induced electrical noise can significantly affect sensitive control circuits such as speed, torque and control logic, position feedback sensors, as well as outputs to display indicators and system control computers. As many of the control inputs are scaled 0 to 5 or 10 Vdc maximum, with typical resolutions of one part in 1,000, only a few millivolts can cause improper operation. Significant amounts of noise can actually damage the drive and/or motor.

À common source of electrical noise is from the coils of relay and contactor coils. Transients caused by the opening of the coil circuits can generate spikes of several hundred volts which in turn can induce several volts of noise in adjacent wiring. Follow good installation practices by using twisted pair, shielded wiring for sensitive control circuits and separate them from relay and contactor coil circuit wiring.

Additionally, adding snubber circuits to the relay and con-tactor coils will eliminate arcing and reduce noise induced in adjacent wiring. For most ac coils, a 33 k Ω resistor connected in series with .047 μ F capacitor can be connected across each ac relay and contactor coil. For dc coils, use a reverse biased diode across the coil to achieve similar results as the RC snubber for ac coils.



Noise on the line inputs caused by SCR controlled dc drives, current source inverters, six-step drives, and other noisy loads in the building can also induce unwanted noise in adjacent control wiring. The high energy, fast switching PWM signals on the motor cabling will also contribute to this problem if it is unshielded and within close proximity of control wiring. The best way to minimize this problem is to be sure line input wires and motor cabling are contained in separate grounded, rigid metal conduit.

Verifying whether noise problems exist in control circuit wiring will require the use of a scope. Special care should be taken when using a scope to make low voltage measurements so that noise is not coupled into the scope and is then mistaken as noise on the control signal wiring. Using 10x probes with short ground leads will minimize noise introduced by the scope probes into the measurement.

Volts/hertz ratio

As discussed earlier, the ratio of voltage to frequency determines the amount of motor torque produced by a given ac induction motor. If the motor experiences a loss in torque, then this measurement may give some clues as to what is happening.

While the V/Hz ratio is not something that normally needs to be adjusted after installation, this measurement can be quite useful for diagnostic purposes. The Fluke 39 or 41B power meters work well for this measurement as they have a built-in low frequency response which gives a voltage reading comparable to what the motor responds to. Additionally, the frequency can be viewed on the same screen as the voltage. Using an oscilloscope with a built-in, or an external low pass filter such as the PM 8918/301 low pass filter probe from Fluke, can give similar results.

If the frequency of the reading is stable, but the voltage is low, high or unstable, it could indicate a problem with the dc bus circuit. If the frequency is unstable, but the voltage is okay, then something might be wrong with the IGBT control circuit. If the V/Hz are fluctuating together, or the speed of the motor is off, but the V/Hz ratio is correct, then one of the speed inputs to the control board may be bad. Vector drives that employ torque control by regulating current in a nonlinear fashion over the entire speed range are an exception to this however, as the V/Hz ratio will vary considerably, be hard to predict, and should therefore not be used for diagnostic purposes.

Inverter drive circuits

Voltage source inverters

While PWM drives are becoming more and more popular, and are commonly being used to replace the voltage source inverters (more commonly called the six-step drive because of the stepped shape of its output) there are still many of these six-step drives in operation that require maintenance. While all the other checks outlined in this section-voltage and current imbalance, single phasing and overheating-certainly apply to six-step drives, there are problems unique to this kind of drive as well.

A "shorted" transistor on some six-step drives can be detected by measuring across the transistor with a scope. A good transistor will have a nicely formed square wave with sharp edges, while a bad transistor will be rounded at the peak of the leading edge.

Figure 16.ACand DC coil noise suppression



If the shorted transistor is causing the drive's protection circuit to trip, then the converter section that rectifies the ac into dc can be disconnected and the inverter circuit can be run with the 10 volts or so of leakage voltage that is present on the dc bus. The input driver circuit will still turn on the transistors but at a much lower voltage level and the bad transistor is easily detected.

Likewise, the inverter section can be disabled while troubleshooting the ac to dc converter circuit. The speed control can be varied while monitoring the dc bus voltage to see if it varies with the speed control. Important note: The voltage feedback resistors must remain connected to the dc bus to insure the converter section is still controlled with the speed potentiometer. Be sure to disconnect the ac inverter section after the voltage feedback resistors. If this procedure is not followed, the dc converter will turn full on immediately upon starting the drive.

If the converter section is not functioning properly SCRs can be checked individually, **out of circuit**, using the following procedure (Figure 17).

- 1. Put the DMM or ScopeMeter in Diode Test.
- Place the red lead on the Anode and the black lead on the Cathode. This puts about 3.5 Vdc across the device.
- 3. Solder some alligator leads to a 1 K Ω resister and connect one end to the anode and the other to the gate.



This should turn on the SCR and a voltage drop of about 1.0 volt should be measured across it. If the SCR is not conducting, you will continue to see OL on the DMM's display. Note: some SCRs may require a higher voltage to turn on. If this is the case. then connect a test lamp in series with the SCR and connect a 9 or 12 Vdc battery across the test lamp and SCR. Connect the resistor between the gate and the anode of the SCR. The SCR is conducting if the lamp turns on.

PWM inverters

Many of the newer fractional horsepower PWM drives are integrated to the point where the input diode block and IGBTs are "potted" into a single throwaway module that is bolted to the heat sink. The cost of these units rarely justify the time to repair, if replacement parts are even available. However, the larger horsepower drives starting in the 5-25 horsepower range, have components that are accessible and become economically feasible to repair.

If it has been determined that the drive inverter is the source of an improper voltage being applied to the motor, then use the following procedure to isolate which IGBT(s) is failing in the output section.

- To check the positive conducting IGBTs, connect the scope common lead to the DC+ bus and measure each of the three phases at the inverter's motor output terminals. Check for nice, clean-edged square waves without any visible noise inside the pulses, and that all three phases have the same appearance.
- To check the negative conducting IGBTs, connect the common lead to the DC- bus and perform the same measurements as in step one above, on each of the three phases at the inverter's motor output terminals.
- Check for "leaky" IGBTs by measuring the voltage from earth ground to the inverter's motor output terminals with the drive powered on, but the speed set to zero (motor stopped). Some drives may have a normal earth ground to motor terminal voltage of about 60 volts, with a reading of over 200 volts indicating a leaky IGBT. Perform this measurement on a known good drive to determine what is normal for that drive.



Figure 18. Single shot transient time stamped with ScopeMeter freeware

The dc bus

DC voltage too high

Transients (less than .5 cycle) and swells (.5-180 cycles) on the AC line inputs and motor regeneration are the two most common causes of "nuisance" tripping of the overvoltage fault circuit on ASD inverters. Transients and swells can be caused by events happening outside the building like lightning or utilities switching KVAR capacitors or transformer taps, as well as other loads inside the building being switched on (capacitive) or off (inductive). To test for this, use an oscilloscope or power line monitor with at least 10 µsec/ div. resolution, and capable of time-stamping the event.

The Fluke ScopeMeter® 123 Test Tool is a good choice for this measurement as it has plenty of single shot resolution, and most importantly can timestamp the event so it can be time correlated to whatever source-lightning, utility or electrical equipment-is causing the problem. Additionally, it has the IEC 1010-1 600V CAT III safety rating which should be an important consideration when purposely measuring high magnitude impulses in a high energy environment.

If the drive is installed in a part of the country that is prone to lightning activity, be sure the building has proper surge protection that is functioning

properly. Additionally, the building's grounding system must be properly installed and functioning to help dissipate lightning strikes safely to earth, rather than through some path in the building's power distribution system. Steps can and should be taken to minimize their effects on your electrical and electronic equipment, since a building that is susceptible to transients, sags and swells, is usually a building that is deficient in proper wiring and grounding.

If a transient voltage is expected, then an oscilloscope like the Fluke ScopeMeter^{*} can be used to measure, and more importantly, *time stamp* the transient so it can time correlated to whatever event caused the ASD fault. A "freeware" software package is available which was especially designed for the ScopeMeter "B" series to capture, time-stamp and reset single shot measurements.² It is especially well suited for logging and time-stamping elusive transient events. See Figure 18.

The ScopeMeter 123 can also time stamp a single shot event which can later be retrieved using FlukeView* for ScopeMeter* software version 2.0 (this feature only available with ScopeMeter 123). This eliminates the need to have a PC connected to ScopeMeter 123 while it's waiting to trigger on the transient (Figure 19).

If the tripping is caused by a transient, then an isolation transformer or series line reactors can be placed in series with the front end of the ASD. An alternate solution would be to place a surge protection device (SPD) at the motor control center, or the primary side of the distribution transformer feeding the ASD. However, if the source of the transient is coming from another load on the same secondary feed as the ASD, then a separate isolation transformer or series line reactor may need to be used directly in front of the ASD, or better yet, put the ASD on it's own feed.

Voltage swells >30 cycles can be monitored using the ScopeMeter TrendPlot[™] mode (see Figure 20) or using some other type of line monitor. One way to mitigate the swell is to

ScopeMeter freeware available at: www.fluke.com/scopemeter/



Figure 19. Transient time and date stamp retrieved using FlukeView software

install a temporary dropout relay for as many cycles as the swell, but that can still be tolerated by the drive. The viability of this solution will be determined by the amount of "ride-through" the ASD's input circuit can handle before the dc bus voltage drops to an undervoltage condition. Another possible solution is to use a voltage regulation device like an uninterruptable power supply (UPS), but it should be noted that most UPSs are designed to handle voltage sags and momentary interruptions and may not handle voltage swell conditions unless specifically designed to do so. Carefully check the UPS manufacturer specifications.

Overvoltages or long term voltage drift can be caused by very large loads being turned off within the building or a slow response of the utility's voltage regulation system to large reductions in demand on the power grid. This condition is easily discovered using the ScopeMeter TrendPlot[™] feature. The best way to deal with this problem is to employ local voltage regulation with a device like a UPS that is designed to handle overvoltage as well as sags and dropouts.

Another common source for overvoltage on the dc bus is motor regeneration. This occurs when the motor load is



Figure 20. Trend of voltage swell

"coasting" and begins to spin the motor shaft rather than getting spun by the motor. which causes the motor to change into a voltage generator and returns energy to the dc bus. Excessive regeneration can be measured by checking for a change in the direction of the dc current back into the dc bus while simultaneously checking the dc bus voltage for an increase above the trip point. If regeneration is causing the overvoltage tripping, something called "dynamic braking" can be employed which limits how fast the regenerative current is allowed to feed back into the dc bus capacitors.

If the dynamic braking has already been employed and is not functioning properly, then it can be tested according to the manufacturer's specifications. If the brake is the resistor type, it can be visually inspected for signs of overheating; discoloration, cracking, or even smell for that distinctive aroma of an overheated component. The resistance value can also be measured against the manufacturer's specifications. If the dynamic brake uses the transistor type, then the silicon junctions can be tested using diode test as described earlier. Also, the braking current can be measured and the current waveform compared with that of a known good system.



Figure 21. Voltage sag caused by a "downstream" load

DC voltage too low

There are several possibilities for "nuisance" tripping of the low voltage fault circuit on ASD inverters. Voltage sags (.5-180 cycles) and undervoltages (>180 cycles) on the line input to the drive are common conditions associated with this problem. Sags are quite often caused by another load within the building's distribution system being turned on, or perhaps from a neighboring building starting a large electrical load.

Make the measurement with an instrument that can time stamp the sag or where the undervoltage causes the ASD low voltage fault to trip. You may want to start making this measurement at the service entrance. This way you can quickly isolate whether the sag is being caused from within the building or outside. Be sure to monitor the voltage and current simultaneously so you can tell whether the problem is downstream from the service entrance as indicated in Figure 21 where the surge in current is coincident with the voltage sag. An upstream (outside the building) problem would show the voltage sag without a corresponding surge in current. If the problem is within the building, continue making the measurement at different load centers until you have isolated the load with the corresponding voltage sag and current surge.

Another possibility is a motor that is drawing enough current to cause the dc bus voltage to drop below the undervoltage fault setting, but not enough to trip the current overload. You will need to check the motor current for overloading (compare with motor nameplate) as well as verify whether the program settings of the drive are correct for the motor nameplate ratings, including the application for which the motor and drive were intended. Look at the line input voltage waveform to the ASD. The wave-shape should be a nicely shaped sine wave. Severe "flat-topping" of the waveform (see Figure 22) can prevent the dc bus capacitors from fully charging to the peak value, which lowers the dc bus voltage as well as the amount of current available to the ASD output circuit.

AC line input

Many of the problems associated with the ac line input that have been discussed in the previous section, have a direct and immediate effect on the dc bus. However, there are a few issues unique to the input circuit that still need to be discussed.

Diode bridge

The diode bridges used in PWM drives are pretty straightforward to troubleshoot. The normal failure mode for a diode is from transient overvoltages or over-current conditions. If the shorted diode trips the breaker before it has a chance to burn into an open circuit, then a DMM with diode test will uncover this problem quite easily. Use diode test as the ohms mode may not put out a high enough voltage to get the diode to conduct.

PRNT VØ AUTO RMS 60.0Hz 222 V +500 -500 9 180° 360°

Figure 22. Voltage flat-topping caused by harmonic currents

Once power has been completely disconnected from the ASD line inputs, use diode test to check from both the -DC and the +DC bus to each of the line input connections. Starting with the positive lead on the +DC bus, probe each of the line inputs with the negative lead. Each reading should indicate OL (overload), or a reverse bias condition. Take the readings again, only now with the negative lead on the +DC bus and measure each line input with the positive lead. This will forward bias the diodes and cause them to conduct with about 0.5-0.7 volts dropped across them. Use this same procedure for the other three diodes connected to the -DC bus. The only difference is that the positive lead on the -DC bus will cause the diodes to conduct, and the negative lead on the -DC bus will reverse bias the diodes and cause an OL reading on the DMM. Shorted diodes will read as 0 volts while open diodes will read OL when they should be conducting.

Most modern ASDs will also employ some kind of a pre-charge circuit to the dc bus capacitors to reduce the inrush current. This will prevent tripping of protection circuits, not to mention significant reduction in wiring and transformer size that would normally be required to handle the inrush. Some drives will employ a pre-charge resistor that limits the inrush current until the dc bus charges to about 60%, then a relay cuts in to remove the resistor from the circuit. When troubleshooting the input circuit, be sure the pre-charge resistor and relay are not overlooked as possible causes first.

Other drives employ SCRs on the front end that will "chop" the ac voltage that is allowed to be rectified. This slowly charges the dc bus capacitors until the dc bus comes up to a predetermined level, then the SCRs goes into full rectification. Use the following procedure to check for a bad SCR or one that doesn't go into full conduction in the pre-charge circuit. Use measurements made on a known good drive for reference waveforms.

 Connect the scope common lead to the DC+ bus and measure each of the three phases at the line inputs one at a time. There will be a large voltage drop across each input SCR at the beginning of the pre-charge cycle which will drop down to nearly zero volts once the





Figure 23. Checking for open and shorted diodes in-circuit

dc bus capacitor is charged and the SCR is fully conducting. The time it takes to go to nearly zero volts can be measured and compared against the manufacturer's specification or a known good drive.

2. Repeat the same procedure for the other three SCRs by placing the scope common lead on the DC- bus and make the same measurements as explained in step one above.

Voltage notching

The older six-step drives usually use SCRs instead of diodes as in the PWM drives to rectify the input line voltage and convert it to dc. The reason for this is the SCRs can be made to rectify only a portion of the incoming sine wave, thereby reducing or increasing the peak voltage seen by the dc bus capacitor. Remember, by raising or lowering the dc bus voltage we are raising or lowering the peak voltage of the output circuit signal applied to the motor and therefore the RMS voltage as well.

As you can see in Figure 24, the voltage contains notches caused by the firing of the SCRs from the control circuit, which



Figure 24. Notching of the line voltage caused by "chopping" of the line input SCRs

can be a real problem if this distorted voltage makes its way into the distribution system and is applied to other sensitive electronic loads.

The most common way to deal with voltage notching from six step drives is to use line reactors in series with the line input to the drive, or use an isolation transformer. The advantage to an isolation transformer is it will also reduce common mode noise.

This should be done with caution however, as the addition of line reactors and isolation transformers will increase the source impedance which can cause problems for other loads sharing the same branch circuit. The reason for this is the ASD will be drawing nonlinear (harmonic) currents in addition to chopping the voltage, and the harmonic currents may produce additional voltage distortion due to the increased line impedance. Additionally, there may be loads such as KVAR correction capacitors that become resonant and draw excessive current at a certain harmonic frequency, depending on the inductance of the distribution wiring and other "upstream" devices that may exist like line reactors and isolation transformers (see Fluke Harmonics application note and video³ for more information).

³ Understanding and Managing Harmonics Video, P/N 609096. In Tune With Power Harmonics Application Note Literature code B0221C.

Voltage unbalance

While voltage unbalance at the motor terminals (discussed earlier) can adversely affect motor operation, it can also cause problems at the line side of the drive. ANSI C84.1-1989 recommends 3% maximum voltage unbalance at the point of common coupling (PCC) with the utility under no load conditions, while the IEC recommends 2% (see previous section to determine % voltage unbalance). However, as little as 0.3% voltage unbalance on the input to a PWM inverter can cause voltage notching and excessive current to flow in one or more phases which can cause tripping of the ASD's current overload fault protection.

While the 0.3% voltage unbalance is an extreme case compounded by a lightly loaded motor, an oscilloscope will be required to view the notching problem. An accurate DMM will be needed to make the voltage measurements required for the % voltage unbalance calculation. The Fluke 87, 863 and 867B are good choices for this measurement because of their accuracy and resolution.

A common cause of this problem is single phase loads dropping in or out on the same feed as the three phase ASD. The trend mode of the Fluke ScopeMeter Test Tool can be used to help isolate which single phase load is causing the most problem. Additionally, providing a stiffer source by increasing the kVA rating of the transformer, or by providing a separate feed for the ASD will minimize or eliminate this problem.

There are two basic issues concerning harmonics and ASDs:

1) the ASD operating in a harmonic environment created by other loads, and 2) creating a harmonic environment for loads both within and outside the building. That is, how the ASD is itself affected and how the ASD can create problems for other loads. The latter condition, creating problems for other loads is what the IEEE-519 recommended practice is all about and is discussed further in the following paragraphs.

The main problem with installing the ASD in a harmonics environment is voltage flattopping. As discussed earlier, the conversion of ac to dc means that there is current drawn only at the peak of the voltage waveform (see Figure 25) as the ac line voltage exceeds the dc bus capacitor voltage. This burst of current into the capacitor is what causes the voltage to drop at its peak. Flat-topping of the line voltage caused by other electronic loads in the building means the dc bus capacitor in the ASD cannot charge to its maximum capacity. This can make for dramatic drops in the DC bus voltage should either the motor load suddenly increase, or if there is a sudden sag on the line voltage inputs. Stiffening the source (increasing allowed to travel outside of transformer kVA and distribution conductors) or adding voltage regulation such as with a UPS should alleviate this problem.



Figure 25. Nonlinear (harmonic) currents cause flat-topping of the voltage waveform

The second condition, when the installation of the ASD creates harmonic problems for other loads, is an issue primarily for large horsepower drives, or a large number of small horsepower drives, an increasingly common situation. If your ASD installation exceeds the capability of your building's distribution transformer and/or distribution wiring, then flattopping may occur and cause problems for other nonlinear loads in the building such as personal computers and other electronic (nonlinear) loads.

Another concern is when a large ASD installation generates harmonic currents that exceed guidelines set forth in the IEEE-519 document. The purpose of IEEE-519 is to provide guidelines for how much harmonic current should be your building onto the utilities distribution system. The limits will depend on the "stiffness" of the utility system (see Tables 5 and 6).

Remember, harmonic currents are only a problem if they encounter some kind of source impedance. In other words, if the utility transformer has too little V/A capacity for the level of harmonic currents present, the source voltage begins to distort. Since the utility is responsible for supplying distortion free voltage to all its customers, they will probably let you know, and possibly penalize you if your ASDs and other nonlinear loads are generating more harmonic currents than the distribution system can handle.

The IEEE-519 guidelines set limits for harmonic voltage and current distortion as measured at the point of common coupling or PCC (usually at the revenue meter), not individual loads. Some ASD manufacturers will promote their drives as being "IEEE-519 compliant." This is a rather dubious claim as there is no way to accurately predict how even a low distortion ASD load will affect the buildings ability to meet IEEE-519 guidelines, unless of course ASD manufacturers discover a way for the drive converters to draw current in a sinusoidal (linear) fashion.

No matter which harmonic problem you are trying to correct, it will be necessary to use a power harmonics analyzer such as the Fluke 41B, or fast fourier transformation (FFT) software with the oscilloscope waveform to analyze harmonic content and voltage distortion. This measurement should be made at the PCC with the ASD operating at full load, then with the ASD powered down, so the impact of the ASD installation on the buildings ability to meet the IEEE-519 guidelines can be known.



The short circuit current ratio (SCR), is basically the "stiffness" of the system to which the building is connected. Table 5 shows both the total harmonic distortion limit as well as the distortion limit for each individual harmonic for bus voltages below 69kV. Table 6 shows what the maximum current distortion is for different SCRs and for the different ranges of harmonics.

Figure 26 below shows how the harmonic voltage distortion data is presented on the Fluke 41B power harmonics analyzer. Two screens are also available for current and power. This measurement was made at the input to the drive and shows the total harmonic distortion (THD) as above 5%. If the same measurement results had been made at the PCC, then this building would be out of compliance with the IEEE-519 guidelines. However, some harmonic cancellation with other loads in the distribution system often occurs which will usually mean lower THD readings at the PCC. Refer to the Fluke Harmonics application note and video³ for more information on how to solve your harmonics problems.

³ Understanding and Managing Harmonics Video, P/N 609096. In Tune With Power Harmonics Application Note, Literature code B0221UEN.

Table 5: Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion (%)	
Below 69 kV	3.0	5.0	

Table 6: Maximum Harmonic Current Distortion in % iL (120V - 69 kV)

SCR	h<11	11-16	17-23	23-34	h>34	TDD	Related Assumption	
<20	4.0	2.0	1.5	0.6	0.3	5.0	Dedicated system	
20<50	7.0	3.5	2.5	1.0	0.5	8.0	1-2 large customers	
50<100	10.0	4.5	4.0	1.5	0.7	12.0	A few relatively large customers	
100<1000	12.0	5.5	5.0	2.0	1.0	15.0	5–20 medium size customers	
>1000	15.0	7.0	6.0	2.5	1.4	20.0	Many small customers	



Figure 26. Voltage waveform, harmonics graph and text data from the Fluke 41B Power Harmonics Analyzer

ASD Measurement Guide

The following table summarizes the ASD measurements discussed previously and the recommended Fluke scopes, meters and power analyzers that can be used for each measurement.

Measurement Type	Fluke 87 CAT III 1000V	867 "B" GMM CAT III 1000V	ScopeMeter "B" Series CAT III 600V	ScopeMeter 123 CAT III 600V	Fluke 39/41B Power Analyzer CAT III 600V
Resistance	Х	Х	Х	Х	
Low Voltage	Х	Х	Х	Х	
Temperature	w/accessory	w/accessory	w/accessory	w/accessory	
Motor Voltage without overvoltages present	Use only for voltage imbalance	X	Use PM 8918/301 low pass filter probe for "motor eqv." ms voltage. Use standard probe for waveform detail.		X
Motor Voltage overvoltages present	Use only for voltage imbalance	Х	DP120 CAT III 600V/CAT II DP120 CAT III 600V/CAT II 000V probe recommended 1000V probe recommended		Х
Motor Current	clamps with current output only	clamps with current output only	80i-1000s, 80i-500s, or 80i-110s current probes recommended	80i-1000s, 80i-500s, or 80i-110s current probes recommended	X
Volts/Hz			Use PM 8918/301 low pass filter probe for "motor" rms voltage.	Use PM 8918/301 low pass filter probe for "motor" rms voltage.	Х
DC Bus	Х	Х	For DC volts > 600 use DP120 differential probe - CAT II measurements only	For DC volts > 600 use DP120 differential probe - CAT II measurements only	
Voltage Distortion		Limited	Х	Х	< 2 kHz only
Harmonics			With FlukeView software With FlukeView software		X
Component tests	X	X	X	X	
Transients and Surges	>1 msec	>1 µsec	>40 ns	>40 ns	

Table 7. Instrument recommendations for various ASD measurements

Measurement Type	80i-1000s AC current clamp 1 mV, 10 mV or 100 mV/Amp	80i-500s AC current clamp 1 mV/Amp	80i-110s AC/DC current clamp 10 mV, 100 mV/Amp	80I-400 AC current clamp 1 mA/Amp
DC			To 100 amps	
AC RMS	To 1,000 amps	To 500 amps	To 100 amps	To 400 amps
Waveform Details	To 100 kHz	To 10 kHz	To 100 kHz	To 5 kHz

Table 8. Recommended Fluke current probes for ASD current measurements





Fluke 89-IV

- 50.000-count resolution with instant readings
- 0.025% basic dc accuracy
- 100 kHc ac bandwidth
- Internal memory allows for stand-alone logging and storage of up to 1000 measurements
- Time-stamped MIN/MAX/ AVG
- · Real-time clock
- Temerature readings in °C or °F
- Lifetime warranty
- CAT III 1000V safety
- Optional FlukeView software





- Optional accessory. AC current 100 mA to 1000A rms continuous, 1400A rms peak. BNC connection.
- Use with 39/41B or ScopeMeter





Fluke 87

- 0.1% basic dc accuracy • 100 mV to 1000V ac &
- dc • 0.1 mA to 10A, all fused
- 3³/₄ digit, 4000 count
- digital display
- Analog bar graph pointer
- Min/Max/Avg recording • Frequency, duty cycle, capacitance
- Input Alert[™]
- True-rms, backlit display, 1 ms peak hold, $4^{1/2}$ digit mode
- Touch Hold[®] and Relative modes
- Lifetime warranty



80i-500s AC

• Included with both the Fluke 39 and 41B. AC current up to 500A rms, 700A rms peak, with best accuracy of 2% of reading from 45 Hz to 65 Hz. BNC connection.

80T-IR

For fast non-contact temperature measurements. Range: -18°C to 260°C (0°F to 500°F). Accuracy: $\pm 3\%$ of reading or ±3°C (5°F) whichever is greater. Internal switch selection for °C or °F. For use with DMMs or ScopeMeter.



ScopeMeter®190 Series

- Bench-level performance in a rugged, reliable handheld oscilloscope
- 200 MHz bandwidth
- length
- Advanced trigger modes
- Up to 1000V isolated inputs
- 4 hour battery life
- Built-in meter and recorder



80i-110s

 Optional accessory. Measures ac and dc current in two ranges from 50 mA to 100A. Best accuracy is 3% and frequency response is dc to 100 kHz. BNC connection.



- 80i-400
- 1-400A
- $\pm 3\%$ of Rdg
- 30 mm (1.18 in)
- 1 mA/Amp



ScopeMeter[®] 123

- 0.5% basic dc accuracy
- 5 mV to 600V ac & dc
- 20 MHz bandwidth
- $3^{2}/_{3}$ digit, >5000 count display
- 2 channel Min/Max/ Trend Plot recording
- Frequency, duty cycle, pulse width
- Direct readout in amps and °C/°F
- True-rms, backlit display, 40 nS glitch capture
- Touch Hold and Relative modes
- Print Screen capability
- Three-year warranty



Fluke 43

The Fluke 42 Power Quality Analyzer performs the measurements you need to maintain power systems, troubleshoot power problems and diagnose equipment failures. All in a rugged handheld package.

- Combines the most useful capabilities of a power quality analyzer, multimeter and scope
- Measure power, harmonics, and catch intermittents
- Monitoring functions help track intermittent problems and power system performance
- Menus use familiar electrical terminology
- Complete package with voltage and current probes, PC software and cables
- Applications manual, power quality troubleshooting video and users manual explain measurements step-by-step



FlukeView[®] Software

- · Capture screen images or waveforms to document and archive measurements
- Use data in spreadsheet programs for detailed analysis
- · Save and retrieve setups for fast preparation of measurement routines
- Supports popular PC file formats (BMP) and PCX) for image storage





Application Notes

In Tune with Power Harmonics Literature #BO221UEN

Electrical Power Circuit Measurements for ScopeMeter Literature #B0241UEN

ABCs of Multimeter Safety Literature #BO317UEN

Electrical Troubleshooting with Fluke Multimeters Literature #B0171UEN

Educational Videos

ABCs of Digital Multimeter Safety P/N 609104 Understanding and Managing Harmonics P/N 609096

Acknowledgments

- A. von Jouanne, P. Enjeti, V. Stefanovic, "Adjustable Speed AC Motor Drives: Application Problems and Solutions", Seminar notes, pp. 3.1-6.20, PowerSystems World Conf. 1996
- [2] IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems - Std 519, New York, NY: IEEE Inc., 1992
- [3] EC&M, "Practical Guide to Motors and Motor Controllers", pp. 9–16, Intertec Electrical Group, 1991

Special thanks to Dr. Annette von Jouanne for her assistance preparing this application note and to Oregon State University for the use of their Motor Systems Resource Facility.

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