Test equipment for AC/DC Drive and Power Electronic Measurements

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The purpose of this document is to review the current requirements for testing and measuring power electronics associated with AC/DC Drive technology. There have been numerous requests on what instrumentation is recommended for field measurements of voltages and currents connected to AC/DC Drives. Variable speed drive technology had been used with DC motors for ten's of years. This technology had always challenged our power measurement techniques and test equipment. Today field engineers are using proven low cost instruments and sound techniques for troubleshooting these DC Drives. Within the last ten years PWM AC Drives are overtaking DC Drive technology in the choice for variable speed motor control. Newer PWM AC Drive technology has incorporated faster switching devices in order to reduce device heat dissipation and drive size. Faster switching devices also increase drive efficiencies.

Fundamental questions for the field engineer still remain. Is the circuit operating as expected? What happens during drive power-up, start-up, and fault conditions? How can I look at reflective wave voltages at the motor? How can I look at output current of a drive? How can I look at the fault current waveform? How can I look at output voltage of a drive? How can I look at electrical noise current and voltages?

To accurately answer the field engineers questions we must review and change our present measurement tools and methods. Our methods must consider the safety issues of ungrounded/floating measurements. Field engineers must measure voltages of greater than 1000 Volts at the same time compare to voltages less than 1 volt. The bandwidth of measurements has increased to up to 100 MHz. Measurements must be made on both current and voltages at the same time. When viewing a waveform there can be no doubt to the accuracy of what is being observed. Any power electronic measurement must handle common-mode noise and differential signal levels and still provide safety to the tester.

The following article reviews methods of voltage and current measurements, followed by a description of operation of PWM AC Drive operation and measurement challenges. Finally some oscilloscope features and specifications are provided to help you select the best possible equipment for PWM AC Drive troubleshooting.

Voltage Measurements.

All voltage measurements are differential since voltage is defined between two points. A voltage at a single point can be measured with respect to earth ground. This is typical in a lot of oscilloscope measurements. In many applications however, it is required to measure the voltage between two points, neither of which is connected to ground. For example the output voltage of the PWM Inverter drive or the voltage across each inverter transistor.

Let's compare voltage measurements methods.

Single-ended passive probe measurements are the most common method of oscilloscope measurement. These probes are standard issue with every scope purchased. An advantage to these probes are they are simple, low cost, and high bandwidth. The disadvantage with these probes is for accurate measurements they are limited to voltage measurements referenced to earth ground. You must be sure the scope earth ground is the same earth ground that the test circuit is at. Any difference will effect the accuracy of the measurement or effect the signal itself. Also when more then one probe is used the probes ground clip may not be referenced to the same ground point. This can create another ground loop and cause inaccurate readings.

In a typical PWM AC drive, power measurements can be measured between two points not tied to ground. This makes single ended passive probe measurements not possible. Different techniques are discussed next. The most commonly known differential measurement technique is the quasi-differential capability built in to every scope. This method connects two scope input channels to each measurement point and isolates the ground input of the scope. Normally one channel is inverted. The scope than subtracts the inputs and displays this difference.

Although this is a sound method for measuring ungrounded referenced signals it does have limitations. Selection of voltage ranges is limited. Common mode rejection is usually pretty low. Accuracy is limited. Sometimes the view will be chopped or alternated. Sometimes it will be hard to obtain a stable trace. This may be a good method for 60HZ signals or SCR DC Drives but may not be adequate for today's PWM AC Drives.

Isolated voltage probes provide another alternative to safe voltage measurements. As the name implies, isolated voltage probes have no direct connection between the measurement probes and the inputs to the scope. The means of isolation is either optical or transformer. This method has a greater common mode rejection ratio and with fiber optics can provide greater physical separation from the circuit being measured. This method however can be effected by the parasitic capacitance between the input and output. The probe isolators are good for the application to low level signals. They are usually used in the Medical Equipment field.

Some battery powered scopes today provide separately isolated input channels. The scope case is electrically isolated from the input channels including the ground lead. Independent input channels enable two separate floating measurements at the same time. With one channel you can be monitoring output voltage of a PWM AC Drive and with the other channel you can be looking at low level signals on the control board. Differential Probes provide a better alternative to isolated probes, and offer some improvements in performance. They are the recommended type probe for AC/DC Drive power electronic measurements. They usually provide two attenuation settings up to 500X. The two probes can be interchanged without effecting the circuit or the accuracy of the measurement. The common mode rejection is very high. The capacitance coupling between the input and output is almost eliminated.

A measurement technique which is sometimes used is the unsafe practice of floating the scope from its protective earth ground. The methods most commonly used is disconnecting the ground plug or using an isolation transformer for the scope. Besides being a very unsafe practice it is not an accurate method for measuring PWM signals associated with AC Drives. This method may damage the scope or any device under test. This method may damage other devices connected to the scope. i.e. plotters, GPIB Port devices, etc. Never float the scope! It is a very dangerous practice!

Let's compare current measurement methods.

There are two methods for measuring current The methods are shunts and isolated transducers. Shunts require you to break open the circuit under test and connect a shunt in series with the circuit. Your usual digital volt meter is a good example. Although the advantage of this current measurement can give high accurate measurements it can also effect the circuit under test and still requires a differential voltage measurement. It can also be prohibitive to open up the circuit to insert the shunt.

Isolated current sensors or current probes provide a more flexible method for measuring current because the circuit under test does not have to be opened. The most common current probes are current transformers for AC current measurement, and Hall effect for AC and DC current measurements. A combination of current transformer and Hall effect probe is a very effective for PWM AC Drive measurements. Current probes must be selected based on the current capability , bandwidth, risetime, impedance and connectability. In general a Bandwidth of DC to 50Mhz is good for the latest drive technology.

Let's review the behavior of an PWM AC drive output current and voltage and the different methods to measure the currents and voltages.

Most PWM drives produce an output of rectangular voltage pulses. The height of each pulse is equal to the Bus voltage of the drive.(650Vdc for 460V Drive). The pulses are created at a regular rate called the carrier frequency. The rate or frequency is somewhere between 400 to 20 thousand per second. The width of each pulse changes to create the RMS voltage at the motor. This is called Pulse Width Modulation (PWM). The output voltage of AC PWM Drives today consist of the rapid turn on and turn off of power transistors. The time it takes a transistor to change from off state to on state can be as fast as 50 nano-seconds. In 50 nano-seconds your are changing the output voltage to the motor from 0 volts to about 650 volts for a 460 volt drive. Then in as little as 20 micro seconds you are going to turn that transistor off and remove that 650 volts from the motor. The voltage will drop to zero in as fast as 50 nano-seconds. Reference figure 1 and 2.

This unique way of applying a PWM voltage to the motor will produce a near sinewave shaped current through the motor windings and therefore produce smooth torque and motor rotation. However unlike the pure sinewave current produced when a motor is applied to normal sinewave voltages, PWM current can be made up of high current pulses in short duration's such as 2 microseconds. Every time these extremely short duration PWM voltages are applied to the motor a current is going to be produced that rises sharply. Reference figure 3

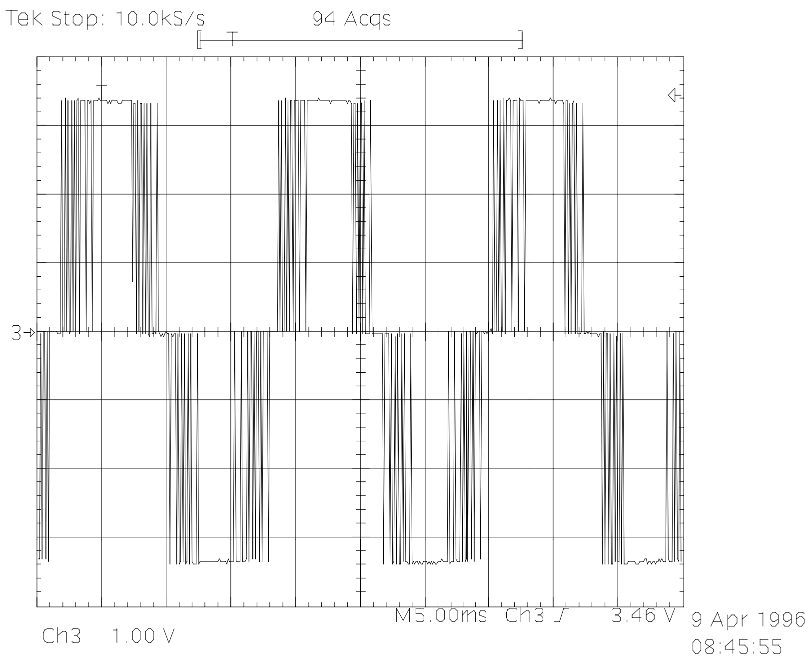

Figure 1 - Output voltage waveform of PWM AC Drive

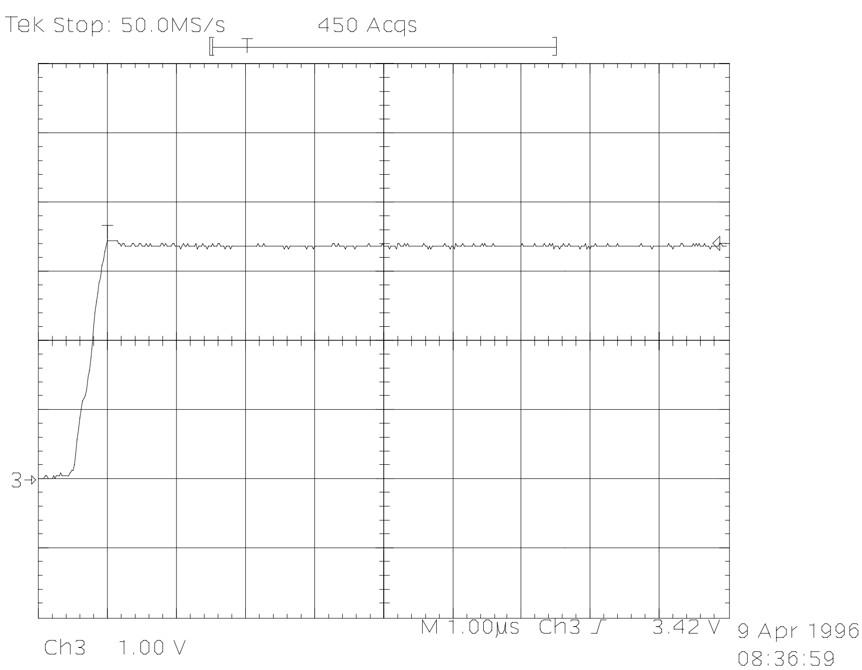

Figure 2 - Output voltage waveform of PWM AC Drive
One rapid turn on of output transistors < 1 micro-sec.

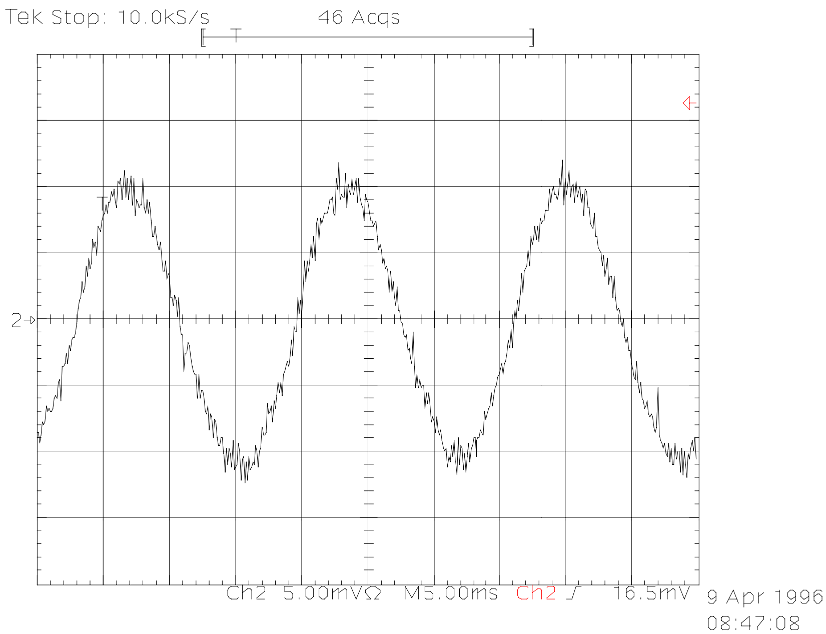

Figure 3 - Output current waveform of PWM AC Drive

Most instrumentation used to measure voltage and current of motors running across the line or instrumentation used for DC drives can not be applied to PWM AC drives. PWM AC drives output voltages do not resemble a sine wave. The wave form looks like a lot of high frequency switching from 0 volts to Bus voltage. The output current waveform of the drive somewhat is sinusoidal but also has some high frequency current pulses riding on the sinewave. The output current waveform can also include very short duration capacitive coupled current.

The following explains why some current instrumentation and methods are not providing us with accurate information of what is going on in the PWM AC Drive.

In order to protect the output transistor devices the drive must sense potentially destructive levels of currents in as little as 2 mico-seconds of time. We assume the drive does this. However the service person often is required to measure the output current of the drive to see if the current is to high. Opening the output circuit of the drive and inserting the Digital Multimeter's current leads is not practical because the meter probably can not accurately measure levels changing in as little as 2 micro-seconds. Portable handheld clamp on current probes that even have peak detect has been shown to be inaccurate at recording and measuring current levels changing in as little as 2 micro-seconds. The accurate means of measuring output current is with high bandwidth isolated current probes and a high bandwidth oscilloscope.

Voltage levels associated with PWM drives can also cause nuisance overvoltage tripping and be destructive to the drive or other devices connected to the drive. The bus voltage can rise to destructive levels in as little as 20 micro-seconds or faster. Output voltage to the motor can rise to destructive levels in as little as 1 micro-second or faster. Digital Multimeters are not quick enough to measure voltages that are changing that quick. Line analyzers are mostly associated for analyzing sine wave voltages from 50 to 60 hertz. Experience has shown most analyzers are not effective for PWM waveforms. A typical grounded scope with the grounded probes can not be used for these voltage measurements. The voltages are typically not referenced to ground and any attempt to measure them with grounded probes can cause damage to the device being measured and/or the scope. Isolating the scope is not a solution because there is usually enough capacitive coupling from the scope to ground that the measurement may be inaccurate. The accurate way to measure PWM AC voltages is with high voltage differential probes with a bandwidth near 25Mhz. You can still leave the scope grounded for safety and get a most accurate reading.

Oscilloscopes in the past have been adequate with SCR DC drives because normally the triggering was based on 60 to 360 hertz. These scopes may not provide good results when trying to capture or sync to voltage level changes in the 100

MHz range. Today's technology in scopes now can give us very easy to use, stable and reliable triggering at high frequencies in medium cost portable test equipment.

The typical instruments today for the use in accurate and speedy determination of PWM AC Drive performance and fault detection may include the following:

- A 2 to 4 channel digital storage oscilloscope with 100 MHZ bandwidth is good. A minimum sample rate of 100 MS/s per channel is required. Some other features of the oscilloscope would include precise triggering on an amplitude or pulse width. Another feature would be the ability to record the signals before and after the trigger event. This is often called memory or record length. The oscilloscope would have waveform and setup storage capability.
- A plotter is an outstanding accessory for immediately collecting and presenting test results at the site or Faxing to a remote tech support location.
- A disk drive in the oscilloscope is becoming even more popular in field scopes today for collecting data.

The oscilloscope is useless without the proper measurement probes needed for testing PWM AC Drives.

- For current measurements at least two clamp on current probes or a current probe system with a bandwidth from DC to over 15 MHz is best. The amperage range can go up to 1000 amps.

- For voltage measurements at least two high voltage differential voltage probes are required. This enables the safe probing of floating voltages where one side of the signal is not ground. These probes are available with usually two attenuation ranges. Maximum voltage that can be measured typically can go as high as 1300V. A method using two high voltage differential probes can be configured to measure up to 2600 volts. The bandwidth of the probes should be from DC to about 25Mhz.

Additional supporting documentation and lists of equipment from test equipment suppliers is available upon request.

ADDENDUM

The following is a list of test equipment including model numbers and approximate cost. This equipment would be adequate to troubleshoot, repair, and determine circuit operation for PWM AC Drive technology. The purpose of this list is not to focus and limit your choice of equipment to only the following. You should only use this as a guide and feel free to compare this equipment to other equipment suppliers.

A relatively low cost list of equipment that could be available for a group of Drive/Power Electronics service persons is the following:

1. One Tektronix Model TDS 3000 Series Digital Phosphor Oscilloscope includes Disk Drive	About 3K-5K
2. One Tektronix Model AM503S Current probe system with additional current amplifier	About 5K
3. One Tektronix A6302 20 Amp current probes	About 1K
4. One Tektronix A6303 100 Amp current probes	About 2K
5. Two Tektronix P5205 Active High Voltage Differential probes	About 2K
6. One Tektronix Wavestar waveform software	About 300
7. Two Power Electronics Measurements(PEM) Rogowski current Transducer Model CWT30	About 2K

A lower cost list of equipment that can achieve 90% of the results of the above equipment should be considered for every Drive/Power Electronics service person is the following:

8. One Tektronix THS 720A Handheld Digital Oscilloscope with Deluxe Meter Kit, Battery Charger, Wavestar Software, Portable printer, Two 10X probes, One A622 100 Amp Current probes, One P5200 Active Differential Probes — About 4K

In addition the following equipment or equivalent should be available for a group of Drive/Power Electronics service person:

9. One Dranetz Model 658 Power Line Analyzer — About 20K
10. One Hioki Model 8830 Four Channel Chart recorder — About 4K