

Chapter 6: *Verification of Power Converter Performance*

The electronic power supply must perform to specification in the system. In order to verify performance, it is critically important that the system designer measures parameters accurately. For example, because of track resistances, a converter operating at 90% efficiency may be measured as 87% if the voltage measurements are made in the wrong position. Many other parameters such as output noise require specialised measurement techniques for accurate, repeatable results.

6.1 Introduction

In previous chapters we have looked at the first stages of power system development, beginning with defining the power requirements, selecting appropriate power converters and designing them into the system. For most OEMs, the next step is to verify that these steps have been successful by means of power system performance measurements. Some of these measurements can be very straightforward and easy to implement, while others will require specialized techniques, test equipment, and experienced personnel. In this chapter we will address the areas of performance measurement that historically have been confusing, difficult to implement, or subject to inconsistent results. We will focus on DC measurements, ripple and noise, and transient response.

Most of this chapter will describe measurement techniques used on actual operating hardware in a laboratory environment. There is, however, an alternative that the reader should be aware of. Artesyn has developed an interactive simulation facility on our website that can be used to make many 'measurements' on Artesyn converters in a simulated system environment. This facility is called "SimScope", and is available for use by our customers at no charge. Several of the most popular Artesyn products are already modeled, with more being added on a continual basis. SimScope can be used to simulate both DC and AC (noise and ripple) measurements as well as transient response and stability analysis. Reference to using SimScope as a guide to what one may expect from manual measurements will be made when appropriate in the following discussion.

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6.2 Fundamental Principles

Measurements of DC voltages and currents are fairly straightforward to make and high levels of accuracy are possible due to the sophisticated test equipment that is now available. Only a few basic precautions are required in order to achieve accurate and repeatable results. We will discuss how to best perform the most commonly made measurements, including suggestions on types of test equipment and setups.

The most common source of error in DC measurements is unwanted voltage drops due to inadequately sized conductors or to poor placement of measurement points. This problem has become more severe recently because of the high levels of DC current now required at the low circuit voltages frequently encountered. As an example, consider the test setup shown in Figure 6.1. Here we are trying to measure the load regulation of a 150W 2.5V DC/DC converter. The converter load regulation specification is 1% from 20A to 60A output current - i.e. 25mV change in voltage over this current range. The converter is located one foot away from the load and the two are connected with heavy AWG10 wire. We have shown two possible measurement points, A and B. If point A is used, the resistance of even the heavy AWG 10 wire will create a problem. The wire resistance is approximately 1m Ω per foot. The resulting 2m Ω will cause a voltage drop of 80mV due to the 40A change in current flowing through it. So, even if the converter had perfect load regulation, the measurement would indicate a value of 80mV, well in excess of the 25mV maximum specification. This problem can be avoided simply by moving the DVM probes to measurement point B. Here, the reading will reflect the actual load regulation of the converter. In general, voltage readings should always be made either at the output terminals of the converter or at

the sense point if remote sensing is used.

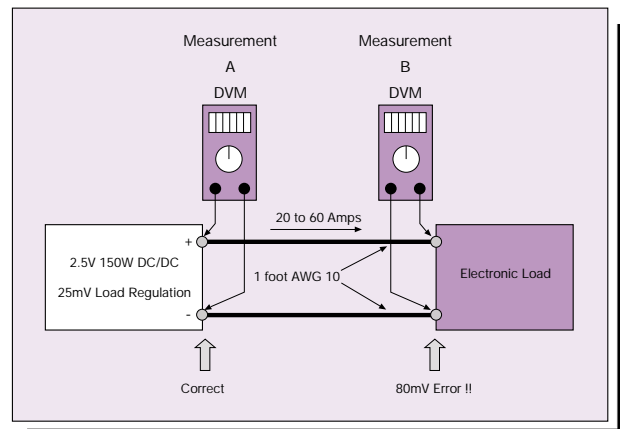


Figure 6.1 - Load Regulation Measurement

We have emphasized in several places that power converter efficiency is an extremely important parameter, and has a strong influence on thermal performance, physical size and cost of the power system. Because of its importance, efficiency measurements are almost always made either in the system or under simulated system conditions in order to verify that the actual efficiency meets the system requirements and the specifications of the converter manufacturer. It is important to obtain an accurate measurement for this important parameter, and we will present here some hints on how to achieve a successful result.

Efficiency is determined by dividing the converter's measured output power by its measured input power. In order to determine each of these, a current must be measured in addition to a voltage, as shown in Figure 6.2. Determining current is an additional complication because every method of measuring current will impose some sort of impedance in series with both the input and output of the converter being measured. Like lead resistance, this inserted impedance can cause errors if

the measurement is not made correctly. For an accurate efficiency measurement, the current measurement device must be located 'outside' the voltage measurement point as indicated in Figure 6.2b. If the current meter is located "inside" the voltage measurement point, as shown in Figure 6.2a, its impedance will cause the input voltage and power measurement to be high and the output voltage and power measurement to be low and the efficiency calculation to be lower than the actual efficiency. Consequently, it is important to always use the arrangement shown in the second drawing, with the voltage measurements made directly at the terminals of the power converter.

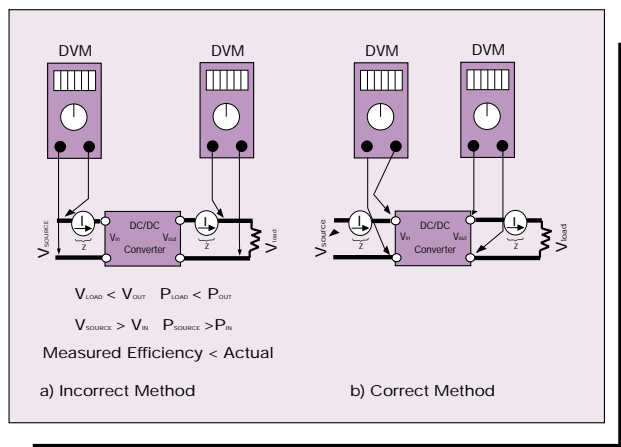


Figure 6.2 - Efficiency Measurement

There are several methods of measuring the current levels, and we will comment upon the most commonly used instrumentation. If the available current ranges are adequate to accommodate the expected current, a DVM can be used in the current mode to directly measure the current. This will be a very accurate result, but will entail breaking the connection in order to insert the meter. The DVM will have an associated voltage drop which can be determined from the manufacturer's manual.

A second method is to use some sort of low value shunt

resistance inserted in series with the current to be measured and reading the voltage drop across the shunt with a DVM. This is a commonly used technique when measuring large values of current, where shunts of a fraction of an ohm can create enough voltage drop to be conveniently measured with sufficient accuracy. With the shunt, of course, the inserted resistance is known with certainty, and the overall accuracy is determined mostly by the tolerance of the shunt resistance. When using a shunt, it is important to design it so that it either has a minimal temperature rise or uses a resistive material with a very small temperature coefficient of resistance. Sometimes a power system designer attempts to use a section of the trace resistance of the printed circuit board connecting the input and output of the converter as a shunt resistance. This is not recommended as a technique for obtaining an accurate result, as the copper of the PCB trace has a very large temperature coefficient and will give large errors as it heats up with the current flowing through it. Also, a Kelvin connection should be used, with the current monitoring DVM connected only across the shunt resistive element so that it does not read any voltage drops across the interconnecting leads or terminals.

Another way to measure the current is to use a clamp-on type of meter using a Hall effect sensor to measure DC current. This has the advantage of convenience in situations using discrete wire connections rather than PCB traces because it is not necessary to break the connection to insert a current meter. The disadvantage is that the clamp-on meters and probes are not as accurate as the other measurement techniques discussed and perhaps not suitable if a highly accurate result is desired. The insertion impedance of these probes will appear to be primarily inductive to the circuit being measured.

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So far, we have assumed a DC input to the converter. In the case of an AC/DC converter, we must measure AC voltage and current at the input. These measurements will, in general, be less accurate than the corresponding DC measurements. Because of the non-sinusoidal current waveform at the input of a switchmode converter and the possibility of distortion on the input voltage waveform, high bandwidth instruments should always be used when making both the voltage and current measurements. Since the displacement factor of the converter is typically unity, these RMS voltage and current readings can then be multiplied to arrive at the measured input power.

6.3 Noise and Ripple

After efficiency, output noise and ripple are perhaps the most commonly measured performance parameters of a power supply. They are also parameters that are the most subject to variation due to differences in measurement techniques. This is especially true for high frequency noise - measurements taken by ten people will almost always result in ten different answers. There are many reasons for this variability, and we will discuss them here. They include pickup of radiated noise, common-mode currents, impedance mismatches, bandwidth issues, ground currents, and differential vs. single-ended measurements. We will also address how to measure the input ripple current for DC/DC converters.

For background purposes, we will first review the distinction between differential and common-mode noise and how they become issues with power converters. Power converters, unfortunately, are not simple four terminal devices operating with only DC currents. If they

were, life would indeed be much less complex. Instead, every switchmode converter includes internal circuitry that switches high levels of current very quickly. This di/dt activity creates induced voltages and currents in parasitic inductances in components and the converter package itself. Since the converter package is coupled to earth ground either directly by a DC path or by capacitance, these induced currents can propagate out into the system on all of the converter interfaces - input lines, outputs, grounds and signal lines.

Since the output power and ground paths tend to be the lowest in impedance, they will have relatively high levels of common-mode currents on them. This situation is shown in Figure 6.3. Along with these undesirable currents, there exists the desired differential output current to the load, which is also shown in the figure. The basic objective for the system designer is to minimize the level of the common-mode currents. The basic concern in terms of making output noise and ripple measurements is to prevent the common-mode current that does exist from invalidating the measurement results of the desired differential parameters.

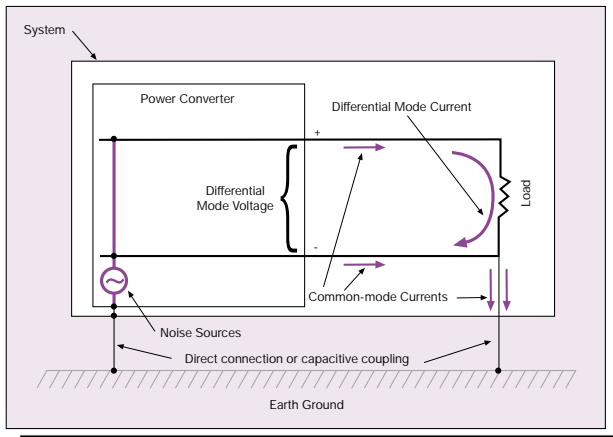


Figure 6.3 - Common-mode vs. Differential Current

Because of the high level of switching activity in and around power converters, there are sometimes radiated fields that can create problems when trying to make measurements. Even if the power converter is perfectly shielded, fields can still be caused by input and output distribution traces and wiring. The scope probes used to measure ripple and noise usually need to be placed in the vicinity of these noise sources. The most straightforward approach for probing the output of a converter is shown in Figure 6.4a. Here a conventional X1 or X10 scope probe is used with the tip attached to the positive converter output and the clip on the ground lead placed on the output return. Loop antennas are especially effective at picking up radiated noise, and the probe and ground lead form a very nice loop with an area of up to 40 cm². Radiated pickup induced in this loop will add to the actual signal being measured and result in an inaccurate and unpredictable result. The radiated pickup problem can be minimized by getting rid of the ground lead and clip and instead using a slip-on type probe adapter that contacts the ground sheath of the probe. This can be soldered in place to the traces on the output of the converter as shown in Figure 6.4b, and then the probe slipped into it when a measurement is desired.

Note the much smaller loop area - as little as 1cm². This will drastically reduce the amount of radiated pickup.

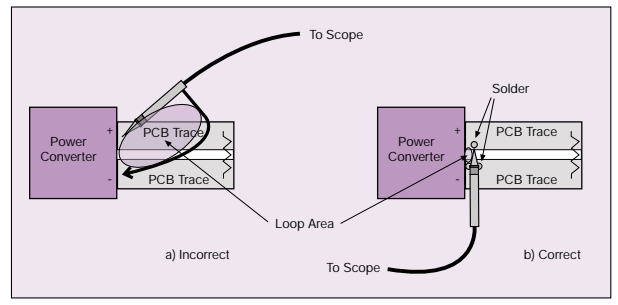


Figure 6.4 - Radiated Noise Pickup

Another associated problem is ringing. Let's examine the probing circuit formed in Figure 6.4a. The scope probe ground lead will have an inductance of approximately 250nH. The input capacitance of the scope probe is perhaps 15pF, and the probe input resistance approximately 10mΩ. This forms a high Q series resonant circuit with a resonant frequency of about 80 MHz. This circuit can be excited by the signal voltage being measured, and can result in ringing superimposed on the desired waveform, confusing the results. If the setup shown in Figure 6.4b is used instead, the capacitance and resistance remain the same, but the inductance is significantly reduced - perhaps 10nH for the probe tip and another 10nH for the sheath connection for a total of 20nH. This moves the resonant frequency up to around 300MHz where any ringing is less easily confused with the signal being measured and is more easily filtered by the techniques to be described later.

Another source of measurement error is common-mode current. As we described previously, this high frequency current will appear to some degree on all of the low impedance outputs of a power converter, although

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Artesyn optimizes their designs so that it is minimized. The common-mode current will create voltage drops across any inductive elements in the measurement network according to the $L di/dt$ relationship. The most common source of inductance is the roughly 250nH inherent in a scope ground lead and clip. Figure 6.5 shows how this inductance can create a large error voltage as the common-mode current flows through the scope probe and the scope chassis and returns to earth through the powerline. This error can be made smaller by using the probe connection arrangement shown in Figure 6.4b, with its 20nH inductance, but there will still be some error due to the differential-mode voltage generated across this small inductance.

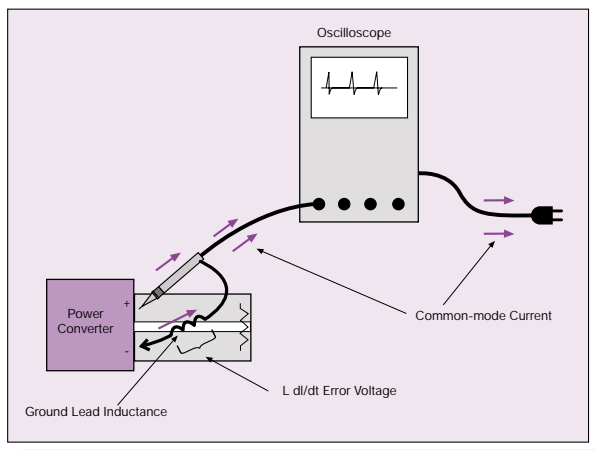


Figure 6.5 - Common-mode Current

It may be tempting to attempt to solve this problem by disconnecting the earth ground connection at the oscilloscope power plug. DO NOT DO THIS! You will be creating a safety hazard. In addition, the common-mode current will still return to earth ground through the large values of capacitance from the powerline to earth ground, resulting in a very small reduction in the error.

There are better ways to minimize the effects of the

common-mode current. One possibility is to use a battery-powered oscilloscope that is carefully isolated from all paths to earth ground. Trigger probes and connections to other test equipment must be carefully inspected and eliminated if they can provide any direct or capacitive return paths to earth ground. Another very effective and convenient method is to use a common-mode choke on the oscilloscope probe. With this approach, as shown in Figure 6.6, line-powered scopes can be used. Simply wrapping a few (3 to 6) turns of the scope probe cable through a high permeability toroid core forms the choke. One core that is commonly available and very effective is a Philips TX36/23/15 in 3E25 material. This approach will create a high impedance path for the common-mode noise and prevent it from flowing through the inductances inherent in the scope probe connections and creating an error voltage.

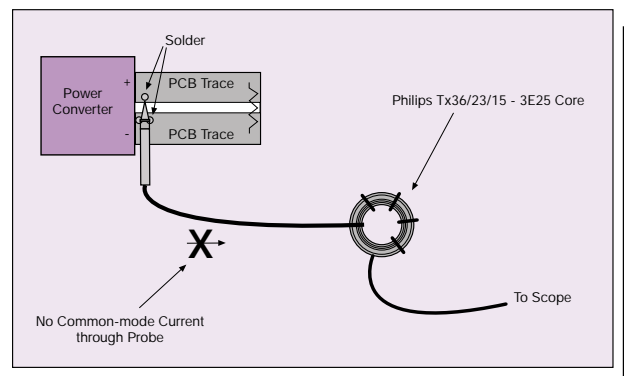


Figure 6.6 - Common-mode Choke

Eliminating the scope probe entirely by using a direct coaxial connection can have advantages. The simplest way of doing this is shown in Figure 6.7. But note the **impedance mismatches** that result from such a connection. The source impedance of the power converter is typically less than 0.1Ω . The line impedance of the coaxial cable is 50Ω . The input impedance of the

oscilloscope is at least $1\text{M}\Omega$. These mismatches will result in reflection and ringing at each junction and an entirely unacceptable measurement result. The solution for the impedance mismatches is shown in Figure 6.8. The scope is terminated with a 50Ω resistor so that the cable sees 50Ω at the termination end. A 50Ω resistor is inserted in series at the power converter so that the effective source impedance becomes 50Ω , matching the cable impedance. The overall result is a matched 50Ω coaxial connection with no reflections or ringing. A series capacitor, approximately 100nF in value, is also inserted at the power converter end. This capacitor will block the DC level and low line frequency ripple but allow the high frequency power converter ripple and noise to pass through to the scope. The 100nF capacitor will result in a lower corner frequency of about 30KHz , so the capacitor value may need to be increased if you are working with a converter with a fundamental operating frequency of 50KHz or less. Note that the two resistors form a 2:1 Voltage divider and that the scope reading will be $1/2$ of the actual value of ripple and noise!

The setup shown in Figure 6.8 is the recommended probing arrangement for measuring high frequency ripple and noise. Here are a few notes on its implementation and usage:

- The setup assumes that the output impedance of the power converter is $\ll 50\Omega$. For low power converters with higher output impedances, the resistor value at the power converter end may need to be reduced so that the sum is 50Ω . For example, if the converter output impedance is 10Ω , use a 40Ω resistor.
- The capacitor and resistors should be high quality low inductance components. Use very short leads to minimize inductance and loop areas when assembling

them, with SMD packaging technology being ideal. If you are forced to use components of large size, enclose them in a completely shielded box.

- The termination at the scope end is easily accomplished by using a BNC 'T' connector and a 50Ω terminator. Or, you can use the internal 50Ω termination option if it exists on your scope.
- Make sure to use high quality 50Ω coaxial cable with excellent screen integrity.
- Remember that you need to **double** the scope reading to obtain the actual value of ripple and noise!

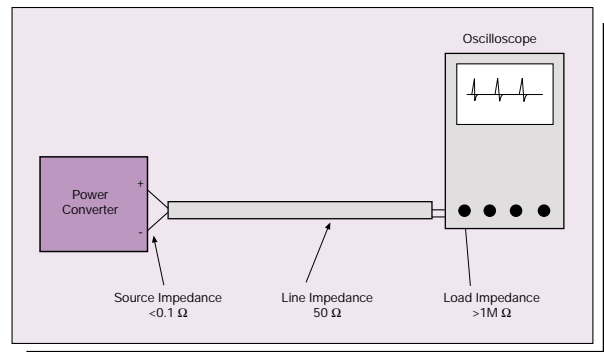


Figure 6.7 - Impedance Mismatches

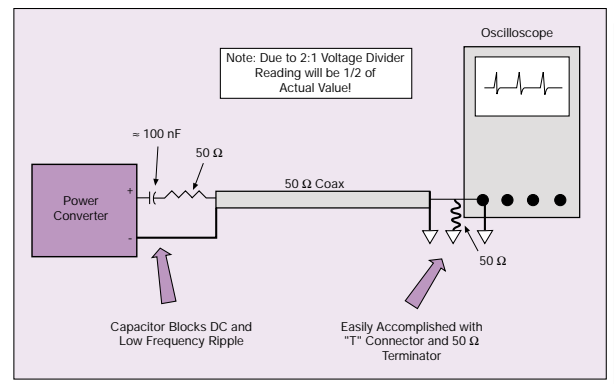


Figure 6.8 - Matched Coaxial Connection

Most manufacturers, including Artesyn, recommend an **upper bandwidth limitation** when making ripple and

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noise measurements. This is done to eliminate very high frequency ringing and noise spikes which either are not actually emanating from the power converter or would be attenuated by the high frequency decoupling capacitance and PCB layer-to-layer capacitance in the actual system. A value of 20MHz is typically used for this upper bandwidth limitation. The '20MHz bandwidth' option on the input amplifiers on most scopes will work quite well for this purpose, as they are well-designed filters with smooth responses and well-matched input and output impedances. External low pass filter boxes, especially homemade ones should be treated as very suspect. They are notorious for poorly controlled responses and mismatched impedances. If you want to use an external filter, make sure that you completely characterize it first for bandwidth, input and output impedance and roll-off response.

Sometimes, when two or more probes are used on the same circuit, there can be a problem with circulating ground currents between probes. The easiest solution is to remove all of the probe ground connections except for one. Leave the ground connection at the circuit point where you are measuring the smallest voltage.

In our discussion of measurements in the presence of common-mode noise, we concluded that the best alternatives are:

- Eliminate the noise at the source.
- Attenuate it with filters and/or low inductance connections
- Divert it with a common-mode choke

If the above techniques are not successful, the next alternative is to attempt to use a differential-mode

measurement technique. In theory, this should work, but, as we will see shortly, there are often practical difficulties. Most scope input amplifiers are specified with a common mode rejection ratio (CMRR) of about 60dB. On the surface, it would seem like there would be about a 1000 times reduction in common-mode noise when using just a regular probe with such a scope. But read the scope specification closely - the 60dB only applies at DC. In the frequency range of interest (50KHz to 20MHz or so), the CMRR can be close to zero! So this approach cannot be relied upon to give an accurate measurement result. There are two possible ways to improve the overall scope CMRR and the differential-mode measurement performance.

The first option is to use an external active differential probe. These probes have a high frequency instrumentation differential amplifier internal to the unit and have two probe tips so that the differential voltage between them can be measured. When used very carefully by a skilled operator, these units can give reasonable results, but they have inherent problems as well, which prevent an overall endorsement:

- They are expensive
- They are very fragile - easy to break tips, compromise the shielding and blow the input
- It is difficult to place the probe tips at the desired locations (time-consuming and frustrating to use)
- They must be carefully calibrated and adjusted prior to each use to insure that the high CMRR is actually present.

The second method is to use two matched amplifiers connected to a battery-powered oscilloscope. The differential measurement is made by connecting the two

measurement points to the amplifiers using two matched coaxial lines as per Figure 6.8, and setting the scope to 'A-B' mode. The lines should be the same length. For this approach to be successful, the two amplifiers must have good CMRR and be very well matched in terms of both phase and gain. This should be confirmed prior to each measurement by connecting both measurement probes to a common point that contains a high level of noise in the frequency range of interest. Ideally, the scope display should be 'zero'. A more likely scenario is a noticeable artifact of the common-mode noise. You can try to reduce this to a minimal amount by adjustment of the variable gain controls on the amplifiers. If it can be reduced to a reasonable amount, you can then proceed with the measurement. Because of these types of difficulties, the differential measurement is not recommended except as a last resort.

In order to illustrate the amount of improvement obtainable with the techniques described here, we have made ripple and noise measurements on the same converter using several of these methods. An Artesyn BXA40-48S05 converter was used, providing an output of 5V at 8A. A bandwidth of 100MHz was used so that the amount of common-mode noise at higher frequencies could be evaluated. In the measurements using the common-mode choke, 5 turns of the scope probe were taken in the referenced core.

The best measurement is that obtained when using the matched coaxial connection of Figure 6.8. This results in a value of 88mV peak-to-peak (after doubling the scope reading to account for the voltage divider). Other techniques used resulted in values of up to 560mV! The five measurement approaches, the resulting peak-to-peak measurement and a reference to a figure displaying each waveform is given in the following table.

Comparing the clean look of Figure 6.13 to the high levels of ringing on the other waveforms will help to understand why the matched coaxial technique is recommended.

Technique	p-p Noise - mV	Waveform
X10 Probe with Ground Lead and Clip per Fig. 6.4a CM Choke per Fig. 6.6	560	Figure 6.9
X1 Probe with Tip and Sheath per Fig. 6.4 b No CM Choke	382	Figure 6.10
X1 Probe with Tip and Sheath per Fig. 6.4 b CM Choke per Fig. 6.6	266	Figure 6.11
X10 Probe with Tip and Sheath per Fig. 6.4 b CM Choke per Fig. 6.6	114	Figure 6.12
50Ω Terminated Coaxial Cable Per Fig. 6.8	88	Figure 6.13

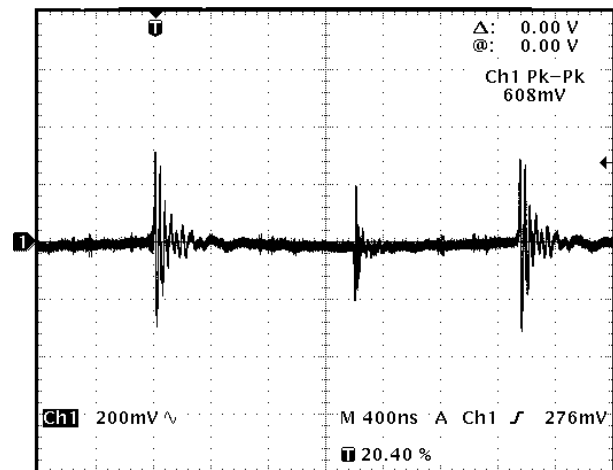


Figure 6.9 - X10 Probe with Ground Lead and CM Choke

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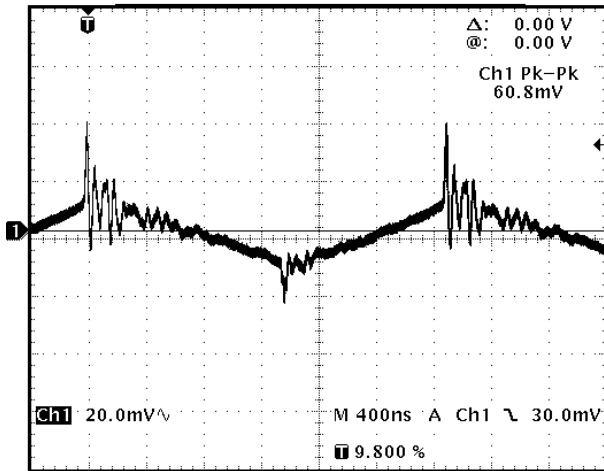


Figure 6.10 - X1 Probe with Tip and Sheath - No CM Choke

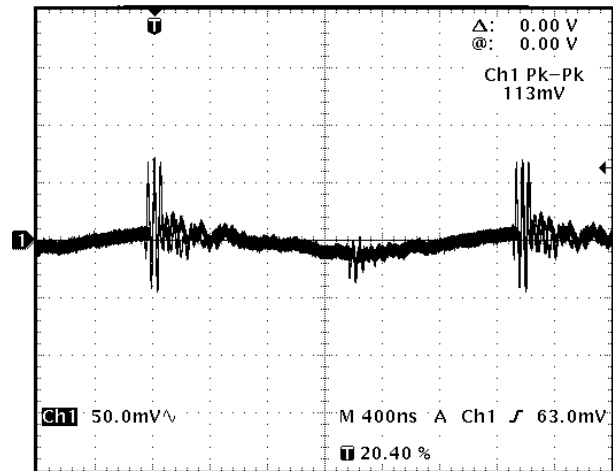


Figure 6.12 - X10 Probe with Tip and Sheath and CM Choke

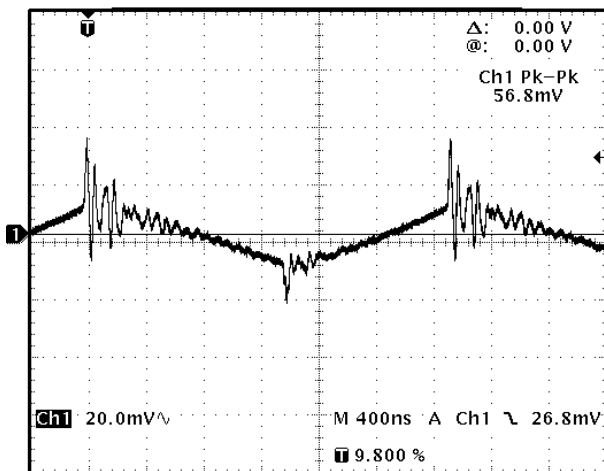
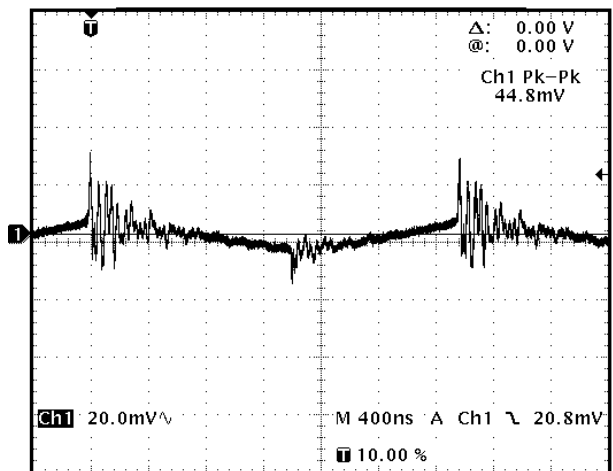


Figure 6.11 - X1 Probe with Tip and Sheath and CM Choke



Note: Result must be multiplied by 2, giving 88.8mV

Figure 6.13 - 50 Ω Terminated Coaxial Cable

The Simscope tool, available on the Artesyn website (www.artesyn.com) can be used to simulate output noise measurements for supported DC/DC converters. The simulated ripple prediction should match a good measurement fairly accurately, while the noise portion of the simulation may exhibit more variation. In the case of DC/DC converters, the input ripple current is also

sometimes measured. This is a fairly easy measurement to make using the basic setup shown in Figure 6.14. The measurement is made in one of the DC input lines to the power converter, either by means of a low value (perhaps 0.1Ω) resistive shunt or a clamp-on type current probe. The AC current waveform is then read from the scope display. It is important to use either a battery or a low noise AC/DC converter as a source so that the reading is not confused by noise or ripple emanating from the front-end power source. SimScope also supports simulated prediction of input ripple current and is a good alternative to actual measurement.

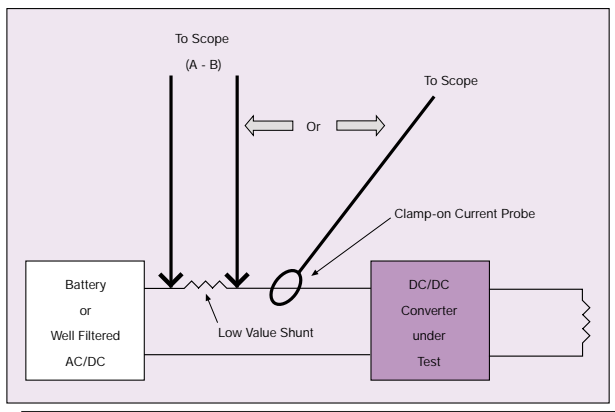


Figure 6.14 - Input Ripple Current Measurement

6.4 Transient Response and Stability Analysis

The transient response of a power converter is a time domain characteristic that determines how its output voltage fluctuates when the converter is subjected to a dynamic load current. The changing output voltage can affect the operation of load circuitry, so it is desirable to keep the voltage deviation within reasonable limits. As we will see later, the voltage waveform during the current transitions can also offer clues as to the stability of the converter's control loop in the system configuration.

Transient response testing is done by using a dynamic load. This load can be a commercially available electronic load with dynamic capability, or can be configured by connecting a pulsed semiconductor switch in parallel with a static passive or active load. The basic test setup is shown in Fig. 6.15. For the most meaningful results, the output capacitance on the converter should be similar, in both value and capacitor type, to the capacitance of the final system. If remote sensing is used, it should be connected at the same location in the DC distribution network as it would be in the final system. The oscilloscope used to monitor the transient response should be connected to the same point. It is important to use large conductor sizes when connecting the converter to the electronic load so that DC drops are negligible and do not detract from the dynamic performance of the converter.

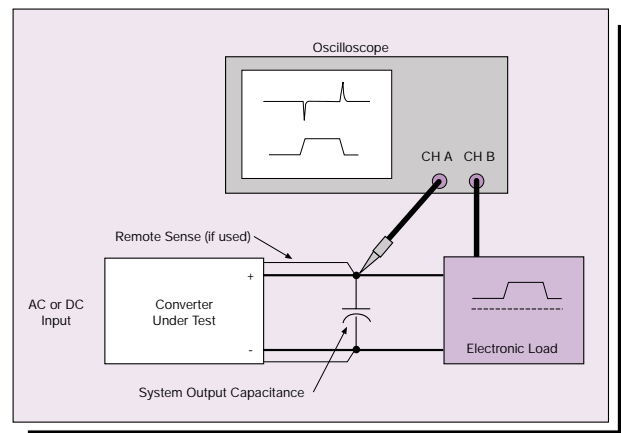


Figure 6.15 - Transient Response Test Setup

Several parameters of the current waveform must be controlled in order to achieve repeatable and meaningful results:

- Static Load Current - this is the initial or starting value of the load current transition. It should be set to

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represent a typical static system current.

- ΔI - The increase (or decrease) in load current from the static value. This should be representative of actual load changes in the system.
- Δt - The time period over which the load current changes. This, too, should be representative of what is expected in the actual system application. For a given value of ΔI , smaller values of Δt will result in a more difficult dynamic requirement and a larger output voltage deviation from the converter under test. For repeatable measurements, this parameter must be controlled. It is often overlooked, leading to inconsistent dynamic response measurements.

Refer to Fig. 6.16 for a graphical representation of these definitions.

The typical output voltage response is also shown in Fig. 6.16. The increasing current transition will result in a temporary reduction in output voltage followed by a recovery period. The decreasing current transition will result in a recovery of the output voltage back to its original DC value after a spike of increasing voltage. The voltage waveform during the recovery period will be somewhat of an indicator as to the stability of the converter in the system. A smooth recovery or a single damped overshoot indicates a relatively stable system. Continued high amplitude ringing during the recovery period indicates a system with little stability margin. Unstable systems will exhibit large undamped oscillations.

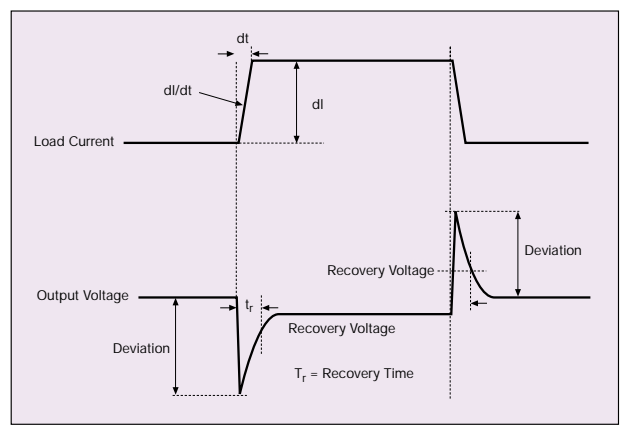


Figure 6.16 - Dynamic Response

SimScope can be used to predict the dynamic performance of supported Artesyn products. It is very easy to quickly accumulate simulation results for any desired conditions of static current, ΔI and Δt . Changes in system capacitance and remote sensing can also be experimented with to determine how this will affect the dynamic response. Using SimScope for this purpose will save many hours of laboratory time, but remember to verify the final result with an actual measurement. A detailed view of an output voltage response to a dynamic load obtained from SimScope is shown in Fig. 6.17. The figure demonstrates how any voltage change, ΔV , and any time span, ΔT , can be measured directly on screen. This allows the user calculate rates of change in the same manner as from an oscilloscope screen.

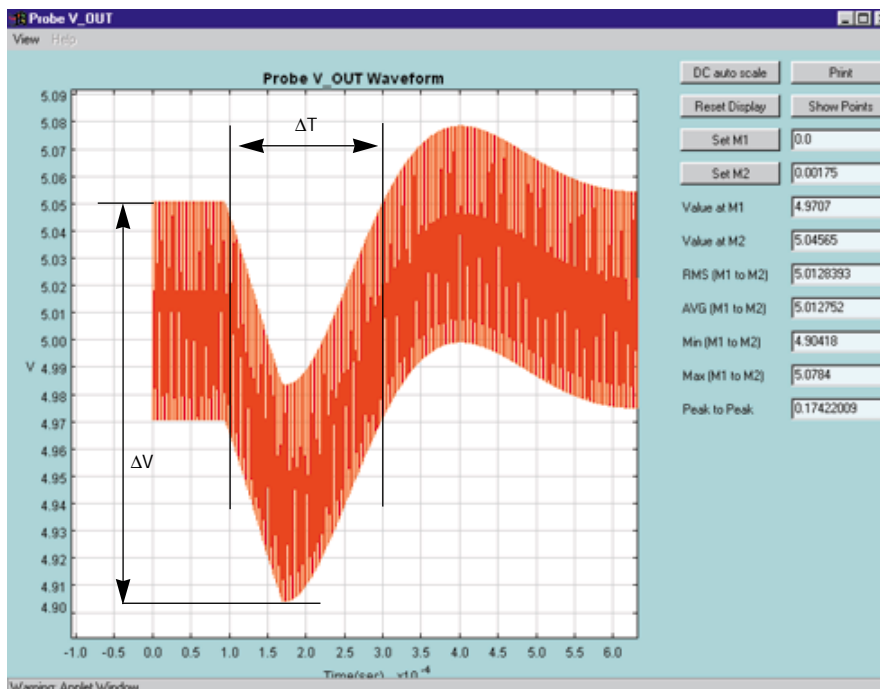


Figure 6.17 - Dynamic Response Measurement

Stability Analysis - The stability of a power converter (its freedom from oscillation when subjected to transient loads) is determined by plotting the phase and gain margins (to be defined below) of the converter in its system configuration as a function of frequency. These plots are referred to as 'Bode plots'. This is a small signal analysis and is traditionally performed during the converter development process by opening the feedback loop and injecting a signal of the desired frequency into the converter. This is difficult to do with a purchased standard converter, so the user of such converters often need to accept the general stability design guidelines of the converter manufacturer and their recommendations on external components. Artesyn offers their customers

a more sophisticated and flexible option by including a stability analysis function within SimScope. The SimScope implementation effectively opens the feedback loop and provides a plot of total loop gain and phase vs.

frequency. By analyzing this plot for a given operating condition and set of external components, and obtaining the phase and gain margin, predictions can be made as to the stability of the power system. The stability criteria can then be used to optimize the value of external components or to do trade-off studies between stability and other desired system performance parameters. SimScope is available for use on a no cost basis, and is the recommended method of determining the stability performance of supported Artesyn power converters.

Figure 6.18 shows an example of a Bode plot obtained from SimScope. It displays a curve of the gain in dB in red with the vertical axis on the left side, and a curve of the phase shift in blue with the vertical axis on the right side. The horizontal axis is frequency and is displayed on a logarithmic scale. There are two markers, M1 and M2, that can be set to read specific points on the plot.

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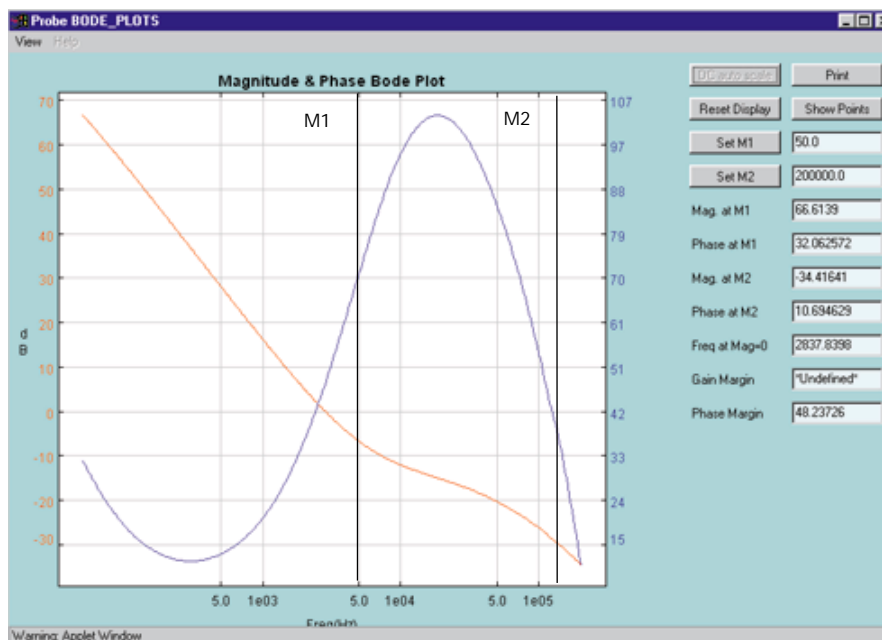


Figure 6.18 - Example of Bode Plot

These markers will display the frequency selected along with the gain and phase at each marker in the corresponding marker boxes. To assist in the evaluation of system performance, three performance criteria data boxes are also shown along the right side of the display. These are the 'Freq at mag = 0' or control loop crossover at zero dB box, the "Gain Margin" and the 'Phase Margin' box. 'Freq at mag = 0' is the frequency at which the red gain curve crosses zero dB. At frequencies above this point, the loop gain will be negative.

'Gain Margin' is defined as the negative gain at the point where the phase shift crosses zero degrees. If the gain were positive at this point, the system would be unstable. Therefore, the amount of negative gain is an indicator of the stability margin inherent in the system. In the example shown in Fig. 6.18 the gain margin is about 40.2 DB at marker location M2.

'Phase Margin' is defined as the phase shift at the point

where the gain crosses the zero dB line. This, too, is an indicator of system stability. The phase margin for the example in Fig. 6.18 is 31.7 degrees at marker location M1.

The phase and gain margins are indicators of system stability. There are many factors that reduce the phase and gain margins but generally minimizing the distribution inductance and determining the distribution capacitance, parasitic resistance and inductance will be most beneficial in analyzing and maintaining system stability. The influence of Phase and Gain margins as indicators of system stability can be summarized as follows:

<u>Phase Margin</u>	<u>Gain Margin</u>	<u>System Stability</u>
Positive	Positive	Stable
Positive	Negative	Conditionally Stable
Negative	Negative	Unstable

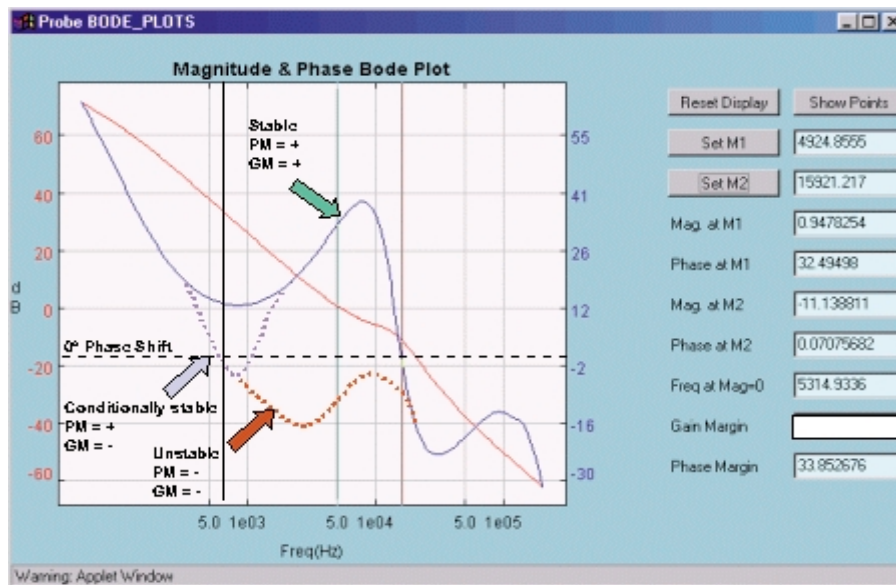


Figure 6.19 - Stability Criteria

A graphical representation of the above possibilities is shown in Figure 6.19.

Note that margin must be included for component variation and aging. That is, a system with a 1 degree positive phase and gain margin, while theoretically stable, would not be robust in the sense of guaranteeing success over a large volume production run. As a general rule of thumb, a phase margin in the range of 40 to 60 degrees should prove acceptable stability. The gain margin should be at least 6 to 10dB. Conditionally stable systems, although operating satisfactorily under most static conditions, should be avoided if possible. This is because they can become unstable under some transient or start-up conditions if the loop gain should decrease.

The ESR of capacitors is not fixed, but varies with frequency. For the most accurate results when running a stability analysis, the ESR of externally connected capacitors should be specified at the loop crossover

frequency - that is, the 'Freq at Mag = 0' value. To do this, run the Bode plot simulation first using an estimate of capacitor ESR, and obtain the zero gain crossover frequency. Then, using this value, look up the ESR at this frequency in the data provided by the capacitor vendor. This new value of ESR should then be entered into the SimScope model, and a new Bode analysis run to obtain the best estimate of system stability.

Frequency response analysis will help determine power system stability. A note of caution is in order, however. An actual transient response analysis should always be performed in addition to the Bode plot to verify system stability. There is still no substitute for performing the measurements on the converter - Simscope should be used as a design tool but its results need to be confirmed by measurements.

The frequency response plots may indicate the system is stable but the selection of input filter components can

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cause the input to be unstable. The Bode plots are showing output loop stability, and consequently input filter instability may not be evident with this test. Running a transient response and looking at both the input voltage and output voltage will show signs of instability if that is the case. Examples of the time-domain responses of stable, less stable and unstable systems are shown in Figs 6.20, 6.21 and 6.22 respectively. There is additional detail on stability criteria along with examples of using the SimScope analysis tools available on the SimScope help screens.

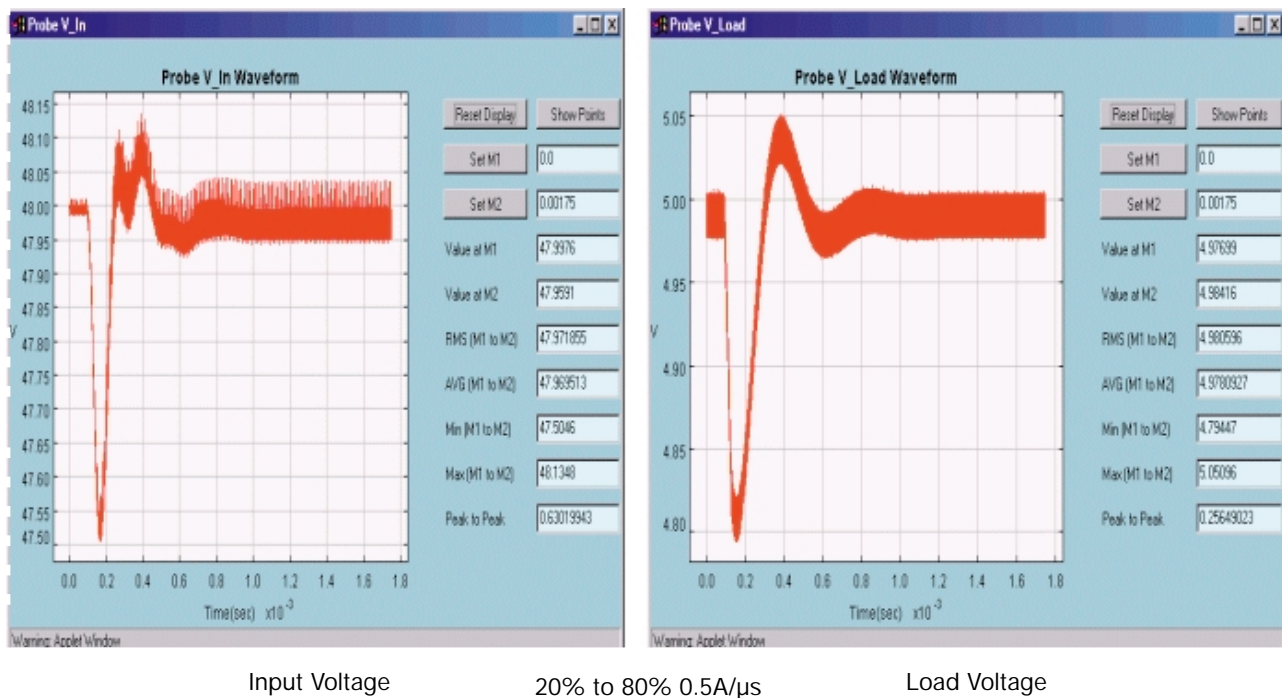
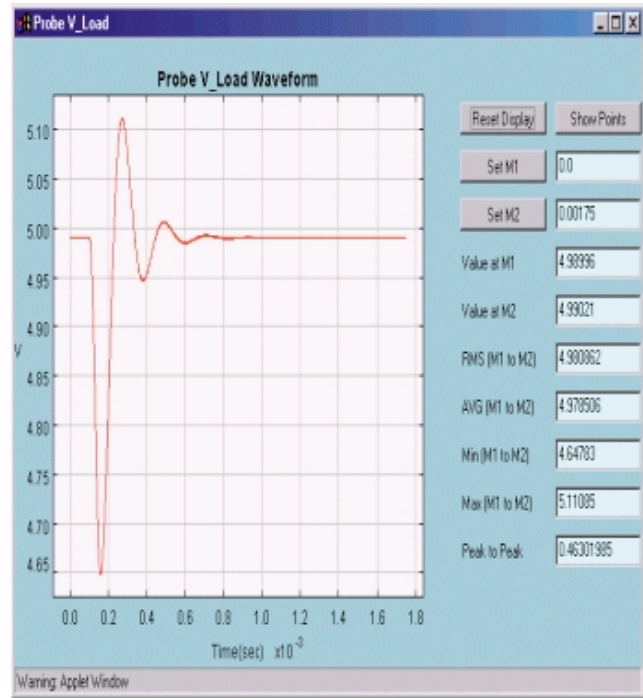
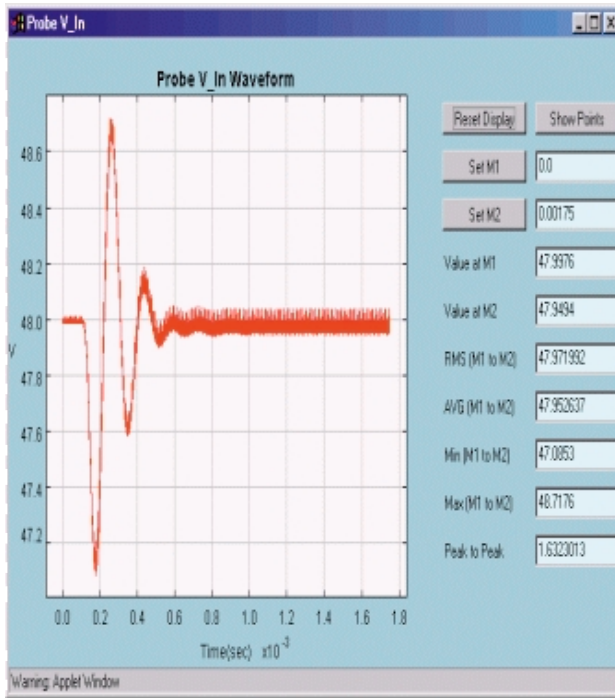
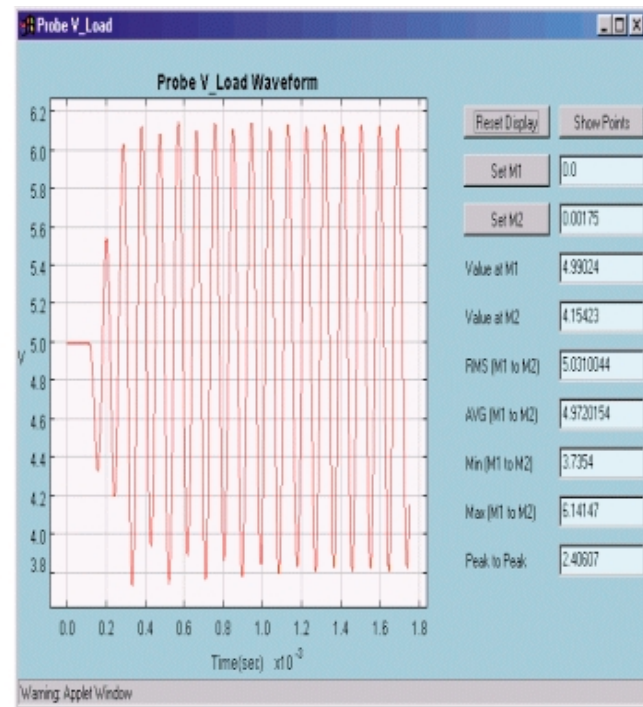
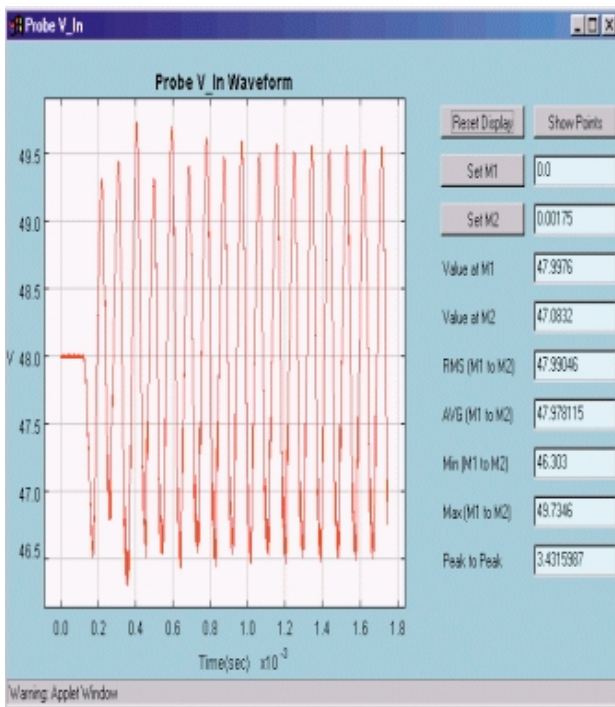


Figure 6.20 - Stable System - Transient Response



Input Voltage 20% to 80% 0.5A/μs Load Voltage

Figure 6.21 - Stable System with less Stability Margins - Transient Response



Input Voltage 20% to 80% 0.5A/μs Load Voltage

Figure 6.22 - Unstable System - Transient Response