Number 2870

Stabilizing Fast Transient Response Power Supply/Load Circuits

Introduction

Keithley's Series 2300 Battery/Charger Simulators (fast transient response power supplies) are specifically designed for powering RFIC power amplifiers, mobile phone handsets, and other portable, battery-operated products in R&D and manufacturing environments. These battery-simulating power supplies are designed to recover very quickly from short-duration pulse load current changes as large as 1000% (i.e., a 10× increase in load current) and to measure the peak of the load current pulse. In order to maintain the output voltage at the programmed output level despite near instantaneous pulse load changes and to capture information on pulses as short as 600μs, the power supply must combine a fast voltage recovery time with minimal voltage droop from the transient perturbation caused by the fast load current change. Power supplies like the Series 2300 battery/charger simulators must have a fast-responding, wide-bandwidth (beyond 200kHz and up to 2MHz) output stage. While this wide-bandwidth supply recovers quickly from large load current changes, the wide-bandwidth output stage is much more susceptible to the impedance of the external load circuit than conventional narrow-bandwidth DC power supplies. Certain high reactance load conditions, such as long wire runs and capacitive loads with low equivalent series resistance (ESR), can cause the power supply output to begin oscillating. This paper will describe the various load circuit conditions that can cause oscillation and provide methods for stabilizing the load circuit.

The DC Power Supply/ Load Circuit Combination

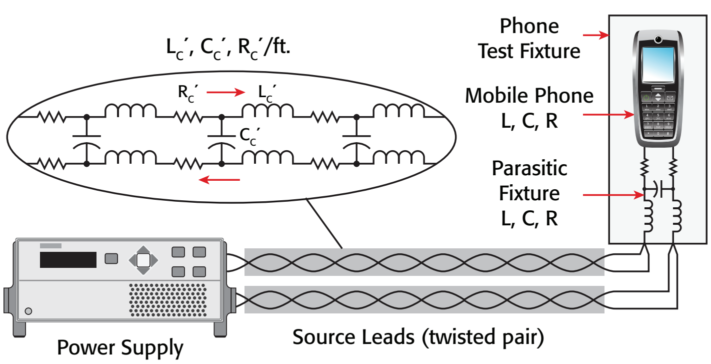

Figure 1. Typical connections between a power supply and a DUT. The power supply is using remote-sense feedback.

Figure 1 illustrates a typical load power circuit in which a power supply is energizing a device under test (DUT), in this case, a mobile phone in a test fixture. The power supply is using a four-wire connection scheme consisting of a pair of power sourcing wires and a pair of load voltage sensing wires. The wires in each pair are twisted together to minimize spurious voltages resulting from induced magnetic fields. The test fixtures often employ bypass capacitors to minimize AC noise. To understand how the load circuit performs for analysis of short load current pulses (effectively an AC signal), the two pair of wires must be modeled as an AC network of distributed resistive, series inductive, and parallel capacitive components. The test fixture and DUT must be modeled as an AC network as well. The cable capacitance, the parallel capacitance between the wires, is usually much smaller than the bypass capacitors added around the DUT, which are typically on the order of 10μF or larger.

Stability Analysis of the Power Supply/Load Circuit Combination

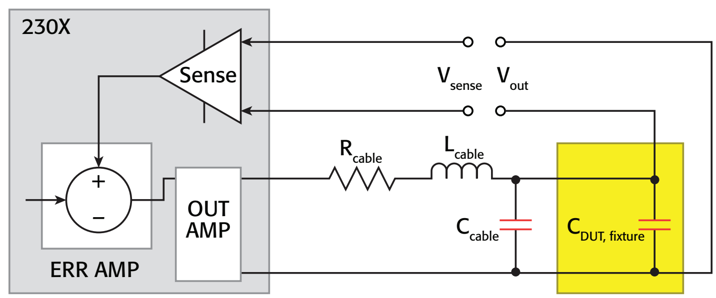

Figure 2. Simplified Series 2300 measurement schematic with reactive load and remote-sense feedback

To analyze the Series 2300 power supply/load circuit combination, the overall power supply is modeled as a feedback network consisting of an ideal error-correcting amplifier, an ideal output amplifier stage, and an ideal feedback sense amplifier (see ***Figure 2***). The sense amplifier measures the voltage directly at the load to force the power supply output to increase its voltage to overcome the losses in the test leads and fixture to ensure the desired (or programmed) voltage is applied to the load. The cables and test fixture connections/DUT are modeled as lumped-element components with the DUT and test fixture as defined by the dominant component, the parallel capacitance of the DUT.

A feedback network's performance is characterized by a Bode plot, which shows the gain and phase performance as a function of frequency. ***Figure 3*** shows the loop gain and phase performance of a Model 2306 power supply into an open circuit—effectively, a well-behaved resistive load. The loop gain falls to 0dB (unity gain) at a frequency slightly greater than 1MHz. If the loop gain is equal to one, and the output phase is 0° (positive feedback), the output will be unstable (consult the references in notes 1 and 3 and any electronics text that discusses the theory of feedback circuit design for more information). In the case of the open circuit load, the Model 2306 has a phase margin of about 90° above 0°, which ensures the output is stable. Circuit design rules recommend a phase margin greater than 45° to guarantee circuit stability under all conditions.

The actual power supply/R-L-C load circuit combination has a multi-pole transfer function with the bandwidth and the unity gain point determined by the power supply control loop and the parameters of the R-L-C load. The L-C load components also determine the resonant frequency, which is near the frequency of oscillation. The resonant frequency (fres) is defined as follows:

$$f_{res} = \frac{1}{2\pi\sqrt{L_{cable}C_{total}}}$$

If the phase margin is near 0° at this frequency, the power supply output will oscillate. Similarly, at the resonant frequency, the pole Q factor is:

$$Q = \frac{\omega_{res} L_{cable}}{R_{Cable}} = \frac{1}{\omega_{res} R_{Cable} C_{Total}} = \frac{1}{R_{Cable}}\sqrt{\frac{L_{Cable}}{C_{Total}}}$$

To maximize the transient response and ensure stability, fres needs to be greater than the bandwidth of the power supply output circuit, and Q needs to be as small as possible.

The following sections describe methods to ensure a stable load circuit by effectively extending fres beyond the bandwidth of the power supply and to minimize Q. The four methods are:

1. Decreasing L_{cable}: Using good wiring techniques and low impedance cable
2. Decreasing C_{Total}: Eliminating unnecessary capacitors, typically on the test fixture
3. Increasing R_{Cable}: Adding resistance to the load circuit
4. Adding a compensation network to the load circuit.

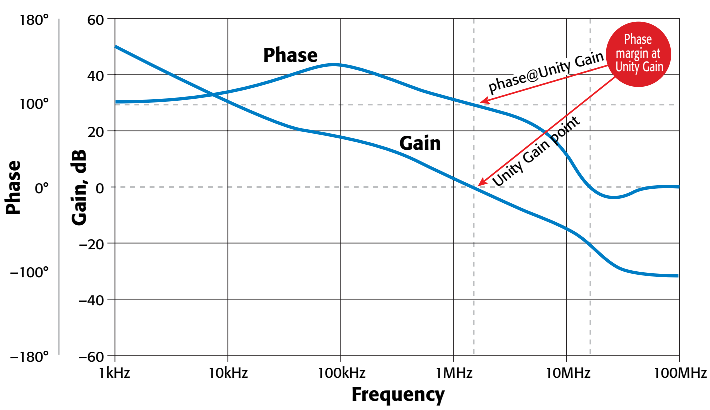

Figure 3. Model 2306 battery channel/2302 closed-loop gain and phase with no load

Using Good Wiring Techniques and Low Impedance Cable

Good wiring techniques minimize the coupling of external noise into a circuit and should be used in all applications. These techniques are essential for controlling instability in wide-band-

Compensating for Inadequate Power Supply Transient Response with a Large Load Capacitor

When large capacitors are placed in parallel with the DUT, the capacitance does improve stability, but there are significant performance trade-offs involved. Prior to the availability of fast transient power supplies like the Series 2300, manufacturers of portable devices such as mobile phones had to work with conventional power supplies, which do not have the bandwidth to respond effectively to large, near-instantaneous load current changes. The solution to maintaining a near-constant output voltage was to put a large capacitor in parallel with the load, essentially to add a second voltage source in the load circuit (see ***Figure 4***). Large capacitors with values of 100μF to 4700μF typically have a large equivalent series resistance (ESR) that reduces the Q of the load circuit. Furthermore, the equivalent series resistance of the capacitor increases at higher frequencies and effectively adds additional resistance to the circuit. The increased resistance at high frequencies also acts to reduce Q and greatly enhance circuit stability. However, there are two disadvantages of using a large capacitor at the load:

1. The power supply current readback circuit can no longer be used to measure a pulse load current because the capacitor is supplying current to the load to hold the voltage at the load steady.

2. Large electrolytic and tantalum capacitors have large leakage currents, which prevents the power supply current readback circuit from reading sleep mode or off-state currents accurately.

Although adding a large capacitor at the load can increase system stability, it is not a desirable solution. Using a fast transient power supply and removing the capacitor at the DUT provides the best overall circuit performance.

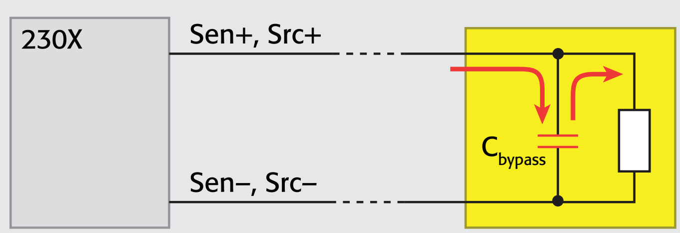

Figure 4. The impact of a large bypass capacitor at the load when the DUT load current increases.

width power supply/load circuits. Twisted-pair source and sense leads should be used to reduce unwanted coupling from nearby interference sources and offer immunity to both electric and magnetic fields. Twisting the conductor pair between source and load minimizes the loop area, which limits the magnitude of induced voltages and cancels these noise voltages because they are of equal magnitude and opposite polarity in adjacent twists. Consequently, twisted wire pairs provide better immunity to magnetic fields than two closely spaced parallel conductors. Moreover, twisted wire pairs reduce the emission of magnetic fields. The current flow in the two close proximity wires is equal and opposite, so the resulting magnetic fields effectively cancel each other within a few inches of the pair. The twisted wire pair has lower inductance than an untwisted pair of wires of equal length. Typically, the inductance of a 15-foot-long (4.6m) twisted-pair cable is 2–4μH.

To minimize inductance in a given length of twisted-pair wire, use wire with thin Teflon® insulation. Thin insulation minimizes the loop area of the twists; and, Teflon is an insulator with a low dielectric constant, which provides the added benefit of minimizing the cable's capacitance and reduces total cable impedance.

Another way to lower cable inductance is to keep the cable as short as possible. The closer the fixture/DUT is to the power supply, the lower the total cable inductance. Obviously, there are physical limitations on how close the DUT can be to the power supply, but routing the cabling as directly as possible to keep the cable length as short as possible helps ensure system stability.

If using twisted-pair wire and the shortest possible cables is not sufficient to ensure stability, low inductance cables can be used. Keithley's Model SC-182 low inductance coaxial cable with Teflon insulation has a 10Ω characteristic impedance. A 4.6m length of this cable has 150–250nH of inductance. When compared with standard twisted cable, this is a reduction in inductance of an order of magnitude.

Using Teflon®-insulated twisted-pair wires, minimizing wire length, and using the SC-182 low inductance cable help reduce L_{Cable} and enhance load circuit stability. However, using these solutions does not alter the performance of the power supply/load circuit combination.

Decreasing the Capacitance in the Load Circuit

Wherever possible, eliminate any capacitors in parallel with the DUT. The Series 2300 power supplies have the wide bandwidth and resulting fast transient response needed to maintain the voltage at the DUT during state transitions without the help of a parallel capacitor at the DUT. Eliminating capacitors reduces the total capacitance in the load circuit, so removing a parallel capacitor at the DUT will improve the load circuit's performance.

Adding Resistance to the Load Circuit

Increasing the resistance in the load circuit reduces Q and can enhance stability. ***Figure 5*** shows the recommended location for the addition of two resistors to the load circuit. A recommended maximum value is 1Ω for each resistor. Using the least resistance necessary to achieve stability is optimal; thus, if 1Ω stabilizes the load circuit, experiment with lesser-value resistors to find the smallest acceptable value. A small additional voltage drop in each source lead can be overcome by the sense detection feedback network and the error correction circuitry that ensures the voltage at the load is maintained at the programmed value. Another way to increase the load circuit resistance is to use thinner gauge wire. Either method for increasing R adds damping to the circuit. Therefore, although added resistance can improve stability, it also increases the load circuit time constant and the power supply settling time.

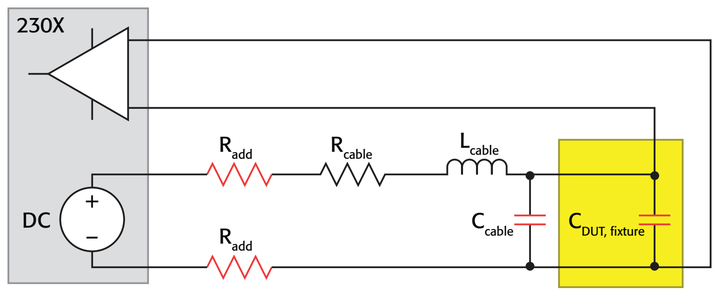

Figure 5. Adding two resistors to Series 2300 source leads to improve stability.

Adding a Compensation Network to the Load Circuit

A third method for improving stability involves adding two R-C compensation networks near the power supply between corresponding sense leads and source leads (see ***Figure 6***). This technique bypasses the cable inductance and load capacitance of the feedback network for frequencies higher than the circuit resonant frequency (f_{res}). The compensation capacitors (Cc) act as a low impedance path for the high frequency components of the voltage waveform as it changes due to the load current transitions. Compensating capacitors effectively close the feedback loop of the power supply/load circuit combination at approximately fres and stabilize the circuit.

To compensate the power supply/load circuit combination with this network, the 3dB point of the low pass compensation network filter must be less than f_{res}. Thus,

$$f_{network} = \frac{1}{2\pi RcCc} < f_{res}$$

A recommended staring point is to set Rc to 100Ω, then determine an appropriate value of Cc to stop oscillation. Given that the sense feedback amplifier draws very little current, the 100Ω resistors create minimal error in the voltage at the DUT. While this is an effective method for improving stability,

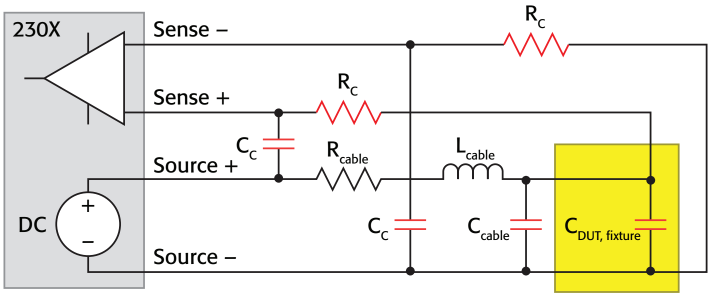

Figure 6. Adding two compensation networks

this method reduces the effective bandwidth and the transient response of the power supply/load circuit network.

In addition to the external compensation network, the Model 2302 and Model 2306 power supplies offer internal bandwidth control to improve load circuit stability. The HIGH bandwidth setting produces the fastest transient response with dynamic loads. The LOW bandwidth setting (default instrument state) will have a slower response but will be more stable for most loads. The LOW bandwidth setting internally implements the compensation capacitance technique shown in ***Figure 6***.

Actual Instability Problem and the Stabilizing Solution

Figure 7 depicts the actual system voltage response (lower curve) to a 1A load current pulse. The load is resistive and cable length is negligible (the load is connected directly at the power supply output terminals). The voltage at the load exhibits a 10mV droop and 10mV overshoot in response to the rising edge and falling edge of the load current pulse. This is as close to the ideal response as can possibly be achieved.

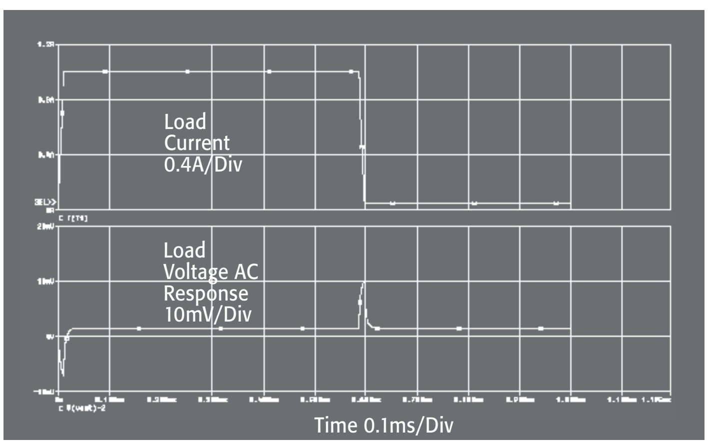

Figure 7. Transient response with resistive load and negligible cable length.

A more realistic situation involves cable lengths between the power supply and the DUT that can range from hundreds of nanohenrys to several microhenrys. In addition, the capacitance on the fixture and the DUT input capacitance can be as high as tens of microfarads. At these impedance levels, the system can be unstable. For example, with L_{cable} =1μH and C_{DUT} = 2μF, the power supply/load circuit combination will be unstable and the voltage at the load will oscillate as shown in ***Figure 8***.

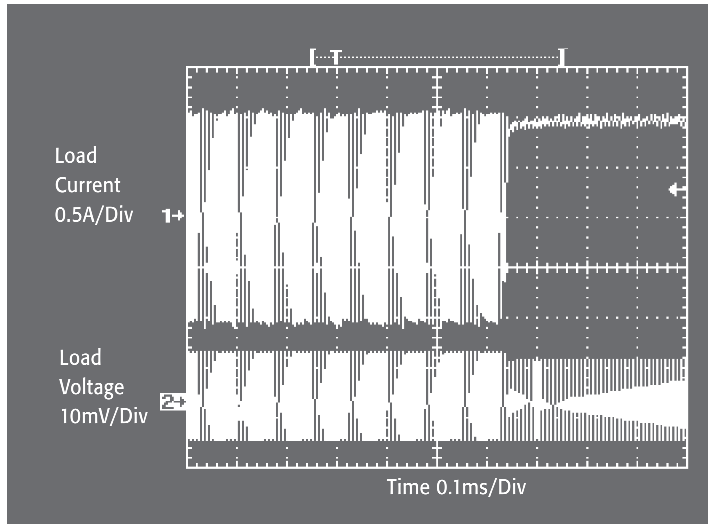

Figure 8. System instability (Lcable=1µH , C_{DUT} = 2µF)

In this case, replacing the power supply load wire pair with the Keithley Model SC-182 Low Inductance Cable reduces the load impedance sufficiently to stabilize the circuit. ***Figure 9*** shows the resulting response to the load current pulse.

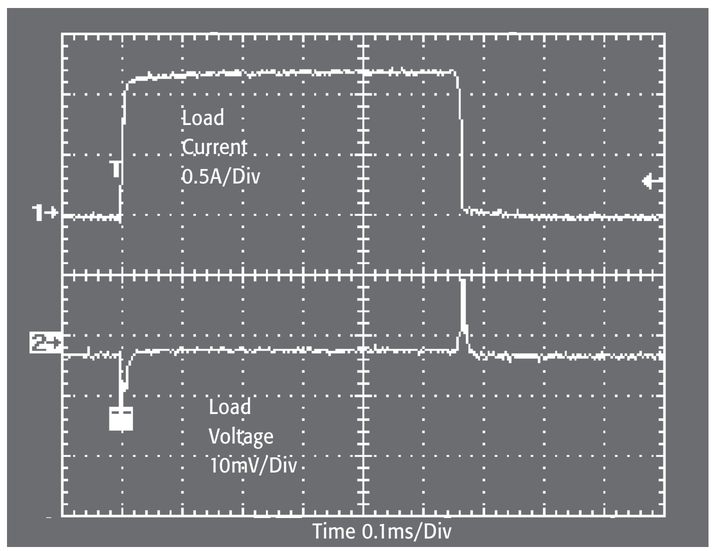

Figure 9. System stabilized (122cm. SC-182 cable, C = 2µF)

Suggested Solution Sequence for Stabilizing the Power Supply/Load Circuit Combination

Following this suggested order of steps can help solve power supply/load circuit stability problems:

1. Eliminate any capacitors on the test fixture and across the DUT wherever possible.
2. Reduce the inductance of the power supply wiring by using wiring with Teflon insulation where possible. Alternatively, use the SC-182 coaxial cable with Teflon insulation. Use good wiring techniques and minimize the length of the wiring to the DUT.
3. If using either a Model 2302 or a Model 2306, try switching to the LOW bandwidth setting to activate the internal compensation network.
4. If an oscillation is occurring at a frequency lower than 100kHz (when using the Model 2303) or lower than 500kHz (when using the Model 2306), then try using an external compensation network.
5. If an oscillation is occurring at a frequency higher than 100kHz (when using the Model 2303) or higher than 500kHz (when using the Model 2306), try adding resistance to the power supply/load circuit. Start with 1Ω in each source wire. If the 1Ω resistor stabilizes the circuit, experiment with smaller values until the circuit becomes unstable again, then choose a slightly larger value that re-stabilizes the circuit. The objective is to minimize the level of additional resistance in the circuit to optimize transient response. Remember that using a thinner gauge lead wire could add sufficient resistance to accomplish the same goal as adding resistors to the circuit.

The order of these steps is such that the initial steps have the least impact on circuit performance. Any of the techniques can be used in conjunction with others to resolve more difficult power supply/load circuit combinations.

Summary

While fast transient response power supplies provide the necessary performance to quickly recover from large pulse load currents, the wide bandwidth of these supplies makes them susceptible to instability in high reactance load circuits. The load circuit reactance is a function of the type of lead wire used, the length of the wire leads, components on the fixture, and the input reactance of the DUT. The combined reactance of these circuit elements must be minimized to obtain the full performance of the fast transient power supply. Methods to reduce the reactance include reducing cable inductance by minimizing the length of the cable or, for best results, using the Model SC-182 low inductance cable. Increasing the load circuit resistance is a second technique to improve stability. Using a thinner gauge cable or adding a small resistor in each source line accomplishes the objective of increasing the resistance in the load circuit. Eliminating unnecessary fixture capacitors reduces total circuit reactance and is the third technique. The fourth technique for improving stability involves adding a compensation network to the circuit to reduce the effective bandwidth of the circuit. Used individually or together, these four techniques can ensure power supply/load circuit stability and provide both a voltage output with minimal variation during dynamic load changes and measurements of DC and pulse load currents. The advantages of fast transient response power supplies far outweigh the additional effort in load circuit configuration to ensure stable performance.

Endnotes

1. Keithley Instruments White Paper, *Optimizing Test Performance Of Digital Cellular Products With Ultra-High Speed Power Supplies*, 2001, available at www.keithley.com/data?asset=4643, retrieved July 26, 2007.
2. Campbell Scientific, Inc. White Paper, *Preventing and Attacking Measurement Noise Problems*, 2001, available at www.campbellsci.com/documents/whitepapers/mnoise.pdf, retrieved July 26, 2007.
3. Spectrum Software, *Plotting Loop Gain And Phase Margin*, available at http://www.spectrum-soft.com/news/winter2001/loopgain.shtm, 2001, retrieved July 26, 2007.

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