Testing a power supply - Stability (Part 3)

Robert Hanrahan - April 17, 2013

Read an introduction to this series in Part 1, and Part 2, which covers noise.

Introduction

This is the third and final part in a three-part series which discusses how to properly test a power supply to ensure it will work reliably over various operating conditions. The series is intended to provide the design engineer with a sufficient understanding about some, but not necessarily all, of the testing needed to verify a reliable power supply design.

Part 1 addressed how to accurately measure power supply efficiency. In Part 2 we covered various noise sources and how to properly measure them with an oscilloscope. We also discussed output errors created by line and load transients.

This Part 3 discusses power supply control loops and how to measure stability. We discuss Bode plots and what to look for when testing stability.

See Video 4 below

Why measure stability?

A power supply is a closed loop amplifier; it takes in electrical energy and converts it to electrical energy in another form, at a specific regulated voltage and/or current. Power supplies regulate by sensing the output and comparing a portion of it to a reference voltage. The difference between the sense signal and the reference is amplified and then used to control the power stage of the regulator to keep the voltage (or current) constant (Figure 1).
Power supplies employ negative feedback from the output back to an error amplifier to ensure proper regulation over various operating conditions (load changes, temp changes, input voltage changes, etc.). As with any stable closed-loop system, one must ensure the closed-loop gain is less than one at frequencies of operation or risk oscillation and/or other non-desirable characteristics.

Negative (or degenerative) feedback works in opposition to external influences such as changes in output voltage caused by load changes or drift of component values. The negative feedback term of a power supply must be sufficiently out of phase with the input or establish a gain of less than one to ensure proper operation.

The traditional method of ensuring stability in a closed feedback circuit is to measure and plot the gain and phase for the complete path around the loop. From this measurement a safety margin can be calculated and determined if it is acceptable for the system under test. Phase and gain margin will be expanded upon below.

While loop characteristics can be simulated, real world system level characteristics such as PCB and connector impedances are difficult to accurately model, especially with lower cost simulation tools. So an actual stability measurement is necessary to understand actual loop stability.

**When can control loop stability be ignored?**

Some power supply ICs were designed to help minimize the concerns related to stability. Using these ICs assumes a stable design, if one follows strict design guidelines and maintains specific operating conditions. For example, the Simple Switchers™ or Swift™ product families from TI are designed for ease of use and operate properly over clearly defined ranges of input and output conditions with a specific implementation. If a design is held within the defined application limits and the designer follows printed circuit board (PCB) examples, the circuit should be stable.

Some regulator architectures do not employ traditional amplifier feedback loops, but use level comparators with hysteresis to maintain the output voltage. These hysteretic control loop regulators,
often called DCAP or constant-on-time (COT), employ an inherently stable control loop. Though not always necessary, it’s always a good practice to measure stability in any closed-loop power system.

**Measure stability at different system operating points**

In situations where the load, input voltage, or system characteristics vary over time and or temperature, it is necessary to measure loop stability over agreed upon test limits. Though a regulator might appear stable during initial bench testing, it can become unstable under other operating conditions or when built with components at an outside tolerance. Stability of a power supply must be measured across all worst case system configurations, including high/low input voltage and high/low output impedance. At a system level, analyze a power supply load to accurately produce the worst case load conditions including additional output capacitance and/or inductance which may appear.

**Measuring power supply stability**

Power supply loop stability is a very important criterion and can be easily measured. The fundamental idea is to inject a small error signal into the loop to see how the loop behaves. Though other methods to measure stability exist (and are well documented), a traditional method is to sweep an error signal across the frequency range of interest while measuring the phase and gain response on the output. The data measured is then used to draw a Bode plot graph, which clearly depicts the stability margins of the system. Low-frequency network analyzers (up to ~20 MHz) are available from various test equipment manufacturers to perform this exact function.

All network analyzers (or frequency response analyzers) are different, yet have common functions. Reference the manufacturer’s recommendations for the exact operation of the specific equipment you are using.

A network analyzer is connected differentially across a small shunt resistor as described in Part 1, “Preparing for tests.” **Figure 5** shows a typical network analyzer connection. As you can see, the low impedance source signal is injected across the shunt and the high impedance input probes are connected across the shunt.

The source signal is normally isolated from the power supply so not to disturb the circuit under test or inject energy back into the analyzer, potentially resulting in damage to the equipment. While some network analyzers include circuitry which isolates the output signal, others require external isolation such as the isolation transformer shown in **Figure 2**. Reference the specific network analyzer user’s manual before making any connections to the power supply.
The network analyzer must disturb the feedback loop, yet not to the extent that the disturbance causes problems. For this reason the amplitude of the injected signal will vary, depending on system characteristics. Generally, the higher the injected signal, the higher the signal-to-noise of that measurement (cleaner plot), but at some point the injected signal causes loop problems, resulting in instability and poor results. Hence, the actual amplitude will be adjusted during the bench measurement itself. Keep in mind that this is a differential measurement, thus, the actual level being injected is not significant, only the differential signal itself (output/input).

For higher frequency measurements the source probe capacitance, as well as the input probe capacitance, can have destabilizing effects. The probe capacitance can be reduced by adding series resistors. You may increase the source resistor value to as large as needed, then increase the signal amplitude to obtain a noise free plot.

As mentioned earlier, the stability of a power supply should be measured under all operating conditions. A power supply may be stable under some conditions while unstable under others. That is why it is best to produce all operating extremes, including maximum and minimum output.
impedance and input voltages. Keep in mind that some systems may see a wide variation of capacitance and/or inductance on the output, which can significantly impact the stability of the power circuit.

Be aware that an electronic load may add a reactive load component, which may have a slight effect on your stability measurements. This also holds true if wire wound resistors are used for these tests. Be sure to also measure stability with your actual system load in place, and possibly in parallel with an added load to simulate a worst case.

The following procedure should be repeated for all operating extremes, as well as a typical system configuration:

1. Before connecting the DC power supply to your power circuit, set the proper input voltage and verify correct polarity.
2. Connect the DC power supply to the input.
3. Connect the electronic load to the output and/or connect the actual system load.
4. Calibrate the network analyzer as described in the network analyzer user’s manual. Make sure to include the isolation transformer, if used.
5. Verify calibration by connecting the source with isolation directly to the receiver inputs. Connect grounds together, run a scan and verify a horizontal line for both gain and phase.
6. Connect the network analyzer source and input probes (Figure 2). Connect both receiver input probe grounds to the system under test ground close to the shunt resistor. Connect the isolation transformer to the shunt with short leads. Now connect the source side to the source from the analyzer and the return connected to the analyzer ground (or probe, if used).
7. Set the analyzer’s frequency range to sweep from ~100 Hz to the switching frequency of a switch mode power supply, or around 1 MHz with a linear power supply. With a switch-mode power supply, the frequency below 10 Hz or above the switching frequency will not provide any significant information about the control loop.
8. Set the scales to logarithmic gain with a gain of approximately +/-60 dB and the phase to display +/-180 degree. Set the midscale Y axis to 0 dB gain and zero degrees phase (if not default).
9. Set the analyzer to scan continuously. Adjust the source gain to display a clean undistorted plot within the area of interest. Caution: an amplitude that is too high may result in an unstable control loop, which may require power cycling of the power supply being tested.
10. Most network analyzers provide markers to allow clear measurement of the phase and gain margins (described later).
11. Save the Bode plot for analysis.
12. Repeat the procedure with other system configurations as explained above.

**Power supply phase and gain margins**

Phase and gain margins are industry standard measurements used to determine the stability of a control loop. As explained earlier, a regulated power supply uses a control loop to monitor and control its output characteristics. As with any control loop, if not properly designed, it can quickly become unstable resulting in oscillations, overshoot, droop, and other undesirable characteristics leading to system malfunction.

When a feedback loop exists with a gain greater than one, and a phase delay of zero degrees, oscillation occurs. We do not cover control loop theory here, but focus on the concept of using phase and gain margin to establish the criteria for a stable and safe design.
The feedback amplifier of a power supply provides negative gain. As the input voltage increases, the forward loop gain decreases. In other words, as the output voltage decreases (load increases), the forward gain increases. This is easy to understand at DC or low frequency of operation. But, the negative feedback must react with some reasonable frequency response or the output voltage will change (droop or overshoot). This could result in potential system problems.

The loop frequency response, or the frequency where the control loop still has positive gain, must be high enough to support expected system changes (load steps, line changes, etc.). But, it cannot be too high where the loop’s phase delay approaches 360 degrees (in-phase). Power supply control loops usually employ a filter (called the compensation filter) to attenuate the loop gain and control where the frequency response of the loop falls below one (or 0 dB input/output). This frequency is called the crossover frequency of the loop (Figure 3). Setting an ideal crossover frequency for a power supply is beyond the scope of this article but suffice to say it depends on system characteristics and requirements, some of which I touched on above.

![Switch Mode Bode Plot](image)

Figure 3. Power supply bode plot.

As explained earlier, the control loop gain decays at an established rate and crosses a gain of one (0 dB) at some established “crossover” frequency. The control loop phase delay must be sufficiently maintained until the crossover frequency is reached. Phase margin is the measured output phase delay related to the error amplifiers input at the crossover frequency (phase output – phase input) (Figures 1, 3). Sufficient phase margin for a specific design depends on system requirements including operating margins, load response requirements, design tolerances, to name a few.

Some industry experts use 45 degrees of phase margin as a safe system target specification, though others may suggest as low as 30 degrees. Lower phase margin often results in faster loop response time, which is desirable in some situations. Generally speaking, a phase margin below these values risks the possibility of instability in the control loop.

If the control loop input-to-output gain crosses zero dB, but does not sufficiently decrease before the loop phase delay reaches zero degrees (in-phase), the control loop risks oscillation and/or other undesirable characteristics. Gain margin is the absolute value of the magnitude of output gain divided by the input gain (Figure 3).
Some industry experts use 10 dB of gain margin as a safe value, though as low as 5 dB has been used safely. Generally speaking, a phase margin below these values risk the possibility of instability in the control loop. A relationship exists between phase and gain margin targets. Usually, the lower the phase margin, the lower the gain margin one can expect.

Many papers and books exist on control loop theory and safety margins in real world systems. It is recommended that the reader reference external work in order to establish a sufficient phase and gain margin for your specific system requirements.

EMI

Conducted and radiated electromagnetic interference (EMI) is normally tested at a system level, yet often relates back to power supply noise. Industry techniques exist for determining sources of EMI within a power supply, yet is beyond the scope of this article.

Conclusion

Today power supplies can be designed with the help of automated simulation tools. For instance, tools such as TI’s WEBENCH™ or TINA-TI design and simulate a power supply right down to thermal analysis before ever turning on a soldering iron. Usually the design works as expected. Yet because all simulators make assumptions, the simulators results will differ from the actual system operation. Good engineering practice always includes a thorough hands-on analysis of the actual system operation.

This series provided an overview of some, but not all of the testing one should plan on to ensure a reliable power supply design. The writer urges designers to create a thorough power supply test specification and test plan and execute to that plan to rest assured your system is operating as expected, and will continue to do so long past the expected life of the product.

Join the conversation about testing power supplies on TI’s E2E™ Community

References


About the author

Robert M. Hanrahan currently is Member Group Technical Staff at TI where he is involved with analog field applications. He has more than 20 years of experience in digital and analog design, applications engineering, and management. Robert has published numerous application notes and articles in electronics and aviation trade magazines and has a patent in his name. His degrees include a BS from The University of the State of New York, and he holds a commercial pilot and flight instructor certificate, as well as a ham radio license. Robert can be reached at ti_rhanrahan@list.ti.com.

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