Measuring Closed-Loop Feedback Response

by Ken Salz, Clarke-Hess Communication Research

Switching power supplies rely on feedback control loops to ensure that the required voltage and current are maintained under varying load conditions. Design of the feedback control loop influences many factors including regulation, stability, and transient response.

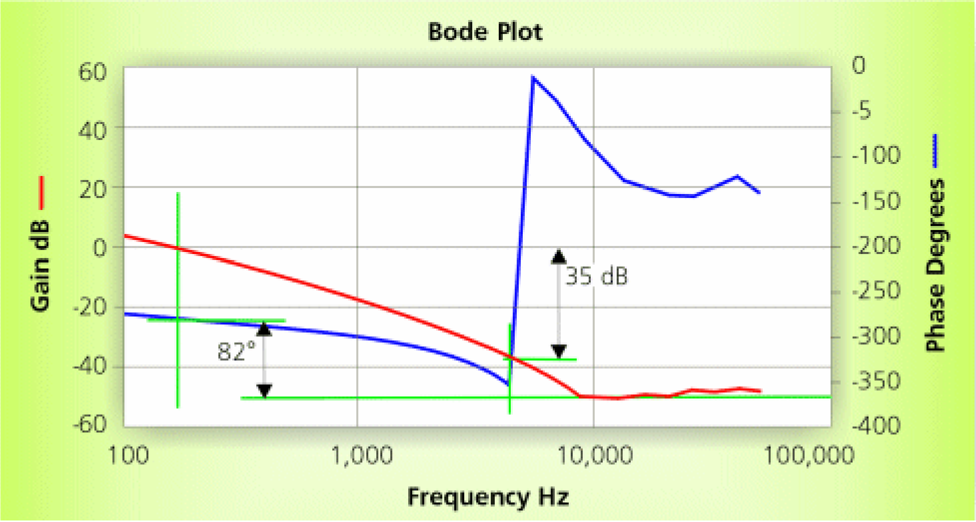
A feedback control loop will oscillate when there is a frequency at which the loop gain is unity or greater and the total phase lag equals 360°. Stability usually is measured by two factors:

- Phase margin, the difference between actual phase lag and 360° when the loop gain is unity, is expressed in degrees.
- Gain margin, the amount the gain has fallen below unity when the total phase lag is 360°, is expressed in decibels.

For most closed-loop feedback control systems, phase margin is greater than 45° (less than 315°) when the loop gain is greater than 0 dB. Gain margin is -20 dB or lower when the loop phase delay reaches 360°.

If these conditions are met, the control loop will have near optimum response; it will be unconditionally stable and neither underdamped nor overdamped. Usually, a frequency response measurement is performed well beyond the control-loop operational bandwidth to ensure all likely conditions are revealed.

The Bode plot shown in **Figure 1** presents control-loop gain and phase-response curves for a single-output switching power supply. Measurements were made using a GP102 Gain Phase Analyzer, a self-contained instrument for assessing control-loop gain and phase margins, then imported into a spreadsheet.



In this case, the phase margin, measured from the 0-dB crossover point to 360°, is 82° (360° to 278°). The gain margin is -35 dB, measured from 0 dB to the point where the phase crosses 360°. Comparing these gain and phase margins to the target values of -20-dB gain margin and 60° phase margin confirms that the transient response and regulation of the power supply tested would be overdamped and unacceptable.

The 0-dB crossover point is 160 Hz, which contributes to the slowness of the loop. Ideally, a positive loop gain at 1 or 2 kHz is desirable, and given the very conservative gain and phase margins, the loop dynamics can be improved without approaching areas of instability. Some small changes to the error-amplifier compensation components are required. After a modification, the control loop can be retested to ensure unconditional stability.

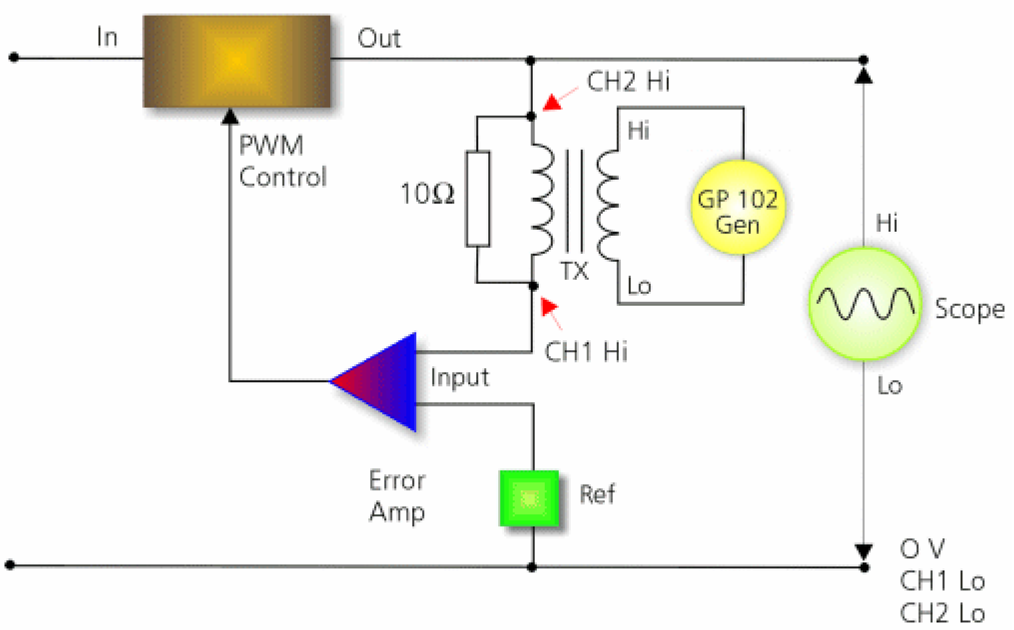
A frequency-response analyzer (FRA) or gain-phase analyzer generally performs these measurements. These instruments use discrete Fourier transform (DFT) techniques because measured signals often are small and masked in noise and distortion produced by the switching stage of the power supply. The DFT is used to extract the signal of interest.

Test-Signal Injection

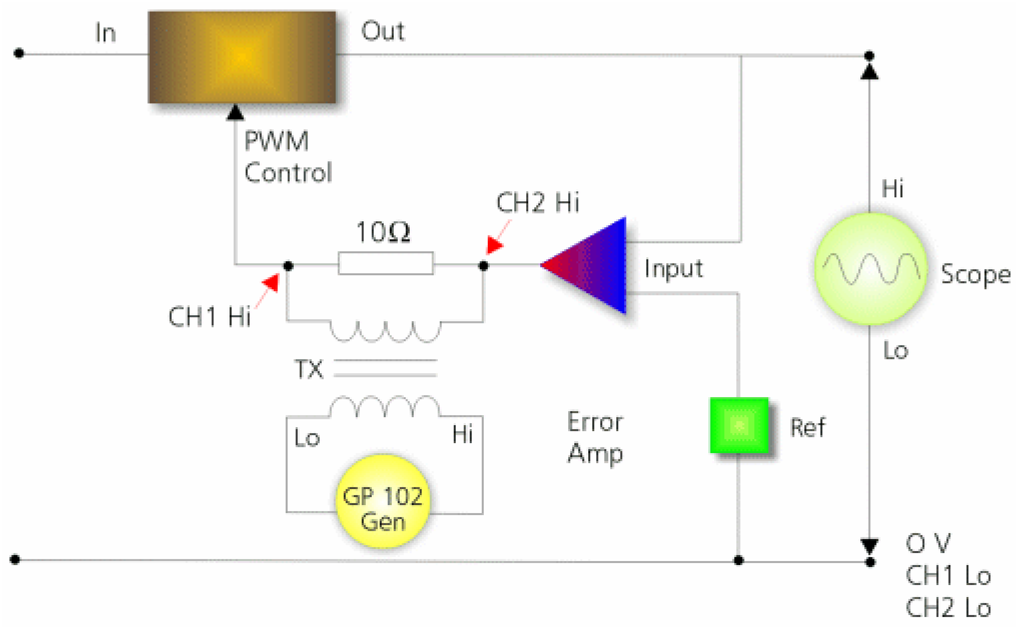
To make a measurement, an FRA injects a disturbance or error signal at a known frequency into the control loop. Two FRA measurement channels are used to determine how long the disturbance takes from the error amplifier input to the power supply output.

The injection should take place where the control-loop feedback signal is confined to a single path and fed from a low-impedance source. The feedback path connection to the power supply output or the error amplifier output are good places to inject a disturbance signal.

Often the signal generator is connected to the circuit under test via an isolation transformer as shown in **Figure 2**, ensuring there is electrical isolation between the FRA signal generator and the circuit under test. The injection method presented in Figure 2 adds the disturbance signal at the input to the error amplifier. This method is appropriate for power supply output voltages within the FRA's maximum input voltage limit.



If the power supply under test produces a high output voltage, then the first injection method does not apply. In **Figure 3**, the disturbance signal has been injected following the error amplifier, where the control-loop voltage to ground is low. This injection method should be used if the power supply output voltage exceeds the FRA input range.



After selecting a suitable injection point, the amplitude of the disturbance signal must be set carefully. The response to the disturbance can be viewed on an oscilloscope connected across the power supply output.

The FRA signal-generator amplitude should be set to zero and a low frequency, usually at the lower part of the control-loop bandwidth. Slowly increase the amplitude of the FRA generator. A good starting point for the FRA signal-generator amplitude is when a small disturbance, around 5% of the nominal power supply output voltage, can be seen on the oscilloscope.

This process should be repeated at the upper part of the control-loop bandwidth to understand if the same drive level can be used over the entire loop bandwidth. The FRA generator must not underdrive or overdrive the control loop. Any measurements made under these conditions will be incorrect.

It is unlikely that the same FRA signal-generator setting can be used over the entire control-loop bandwidth. Under these circumstances, amplitude compression can be used to maintain a steady disturbance signal as the frequency is swept and loop gain changes. This is achieved by controlling the FRA signal-generator amplitude to maintain a constant error amplifier input.

Making a Measurement

The two inputs to the FRA are connected to the two ends of the injection isolation transformer’s secondary winding, as shown in Figures 2 and 3. CH2 measures the control-loop output, and CH1 measures the control-loop input. Measurements are made with respect to ground.

Make a sweep from 10 Hz to 30 kHz and look for gain and phase measurement repeatability as good indicators that the correct level of injection is applied to the control loop. Assess control-loop gain and phase margins, referring to the gain-phase guidelines.

Suitable compensation components can be applied to the error-amplifier stage. Performing a new sweep will show the effect of alterations to the compensation values. Ideally, the loop gain should roll off at -20 dB per decade, particularly where the loop gain passes through unity.

Power-Factor Correction Circuits

Feedback control loops are not confined to the output regulation of a switching power supply. Active power-factor correction (PFC), typically used after the bridge rectifier, uses two control loops to achieve a sinusoidal input current, resulting in a load power factor close to 1.0. PFC circuits generally are based on a dedicated controller IC, a switching device, and an energy storage inductor—a so-called DC link.

The first loop, the voltage loop, tries to maintain a steady DC voltage at the DC link or the output of the PFC circuit. This loop is relatively slow, crossing 0 dB at approximately 10 Hz. The second loop, the current control loop, effectively controls the input current wave shape. This pulse-width modulated (PWM) chopper circuit must track the rectified sinusoidal voltage waveform, so in effect, the reference for the current control loop is dynamic. Because the current control loop has to track the line frequency, the crossover point may be several kilohertz.

Testing the Voltage Control Loop

Testing the slow voltage control loop and the fast current control loop requires different approaches:

PFC Voltage Control Loop

The voltage loop is straightforward. No circuit modifications are required, and in fact, the current control loop is left active during the voltage loop test. The usual rules apply about the choice of the injection point. You should find a place in the loop where the source is a low impedance point and confined to a single path. The value of the injection resistor is likely to be 1,000 Ω.

PFC Current Control Loop

Testing the faster current control loop requires much care and attention because several circuit modifications are needed to obtain a true assessment of gain and phase margins:

1. Use a 0 to 400-VDC source to power the input to the PFC circuit. No AC supply is required and should be disconnected.
2. Disable the voltage control loop but not the entire IC.
3. If required, provide auxiliary power for the PFC controller IC, typically +18 V.
4. Use a 0 to10-VDC supply to control the PFC output current for the corresponding level of input voltage. Effectively, the 0 to 10-VDC supply will control gain within the controller and replace the voltage reference, which normally would be changing at 100 to 120 times a second for 50- or 60-Hz line frequency. The current feedback loop should track the input voltage, hence the use of the 0 to 10-VDC supply to set different conditions.
5. Apply a variable load to the PFC output.
6. Use a 100-Ω injection resistor connected between the current sense resistor and the PFC sense input.
7. Sweep from 50 Hz to about half of the switching frequency. Check the loop response with different settings and combinations described in points 4 and 5. For example, the loop should be tested at zero current, peak current, and midway.

Measurements within the PFC area are hazardous. Isolate the frequency- response analyzer input channels and generator from ground and each other.

About the Authors

Ken Salz is president of Clarke-Hess Communication Research. Before joining the company, he was president and founder of North Atlantic Instruments. Mr. Salz has written numerous articles covering AC measurement and simulation and earned a B.S.E.E. from Hofstra University and an M.B.A. from the New York Institute of Technology. Clarke-Hess Communication Research, 21-09 43rd Ave. Long Island City, NY 11101, 718-784-0445, e-mail: kens@clarke-hess.com