designfeature *By Stuart Chappell, Newtons4th Ltd*

TODAY'S INSTRUMENTATION EASES EFFECTIVE REAL-WORLD TESTS.

Measurements of loop stability go beyond PC simulation

AFTER DESIGNING a control loop within a power supply, motor drive, or almost any power-electronics product, engineers must establish that they have achieved their target specifications for loop stability. Unlike measuring ripple, noise, voltage deviation, or recovery time after you impose a transient load, you cannot effectively test loop stability with traditional test instruments, such as a voltmeter or an oscilloscope.

Engineers who face lengthy and complex testing, using many separate instruments or costly, specialized equipment, instead often assume that circuit simulations truly reflect the characteristics of the finished product. However, despite having an apparently stable design based on their software simulation, they find that the effect of pc-board parasitic reactances, component tolerances in production, or varying load conditions in normal operation can result in finished products that may perform more poorly than expected and exhibit instability or even failure.

Although software simulation provides a useful engineering tool, it can offer only an approximation of system response based on the information the programmer enters into the program. Therefore, it can be an unreliable substitute for real measurements. Techniques of modern instrumentation now provide engineers with cost-effective test instruments that provide direct measurement of this critical design characteristic. The well-established subject of loop stability now has practical and cost-effective techniques available to simplify testing (see **sidebar** "Control theory is the place to start").

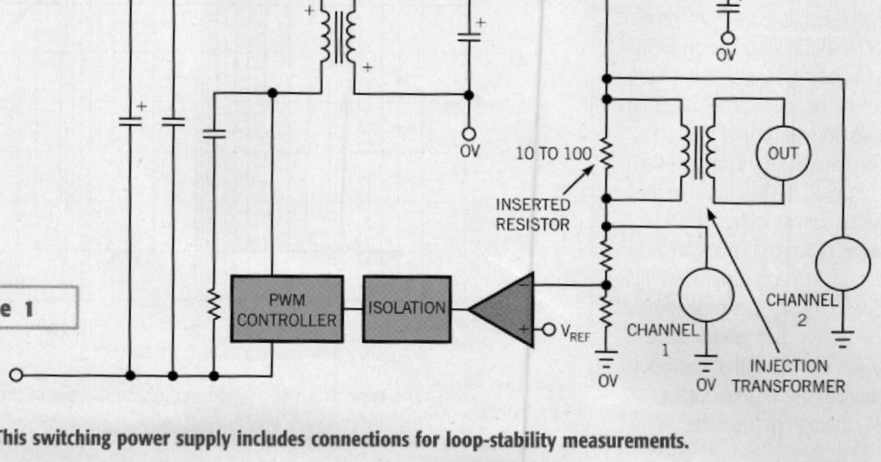
BEGIN WITH TEST POINTS

The first step in making real measurements in a closed-loop environment is to inject a disturbance signal. To achieve this goal, insert a resistor with a value of 10 to 100Ω into the loop at a point at which the small resistance has negligible effect, such as in series with the feedback resistors (**Figure 1**). If you are laying out a new pc board, it is worth permanently adding the resistor as part of the board layout, so that you can perform these tests at any time without disturbing the wiring.

To establish the gain and phase margin of the control loop, apply a sweep of discrete-frequency disturbance signals across the inserted resistor via an isolation transformer to ensure that the control loop does not pull down to ground (**Figure 2**). At each injected frequency point, measure the relative amplitude in decibels and the relative phase in degrees on either side of the inserted resistor. These values reflect the closed-loop gain and loop delay at the respective test frequencies and produce a frequency response plot of the loop, from which you can establish loop stability.

To effectively measure the relative gain and phase of the injected signal, the instrumentation must reject frequency components other than those in the injected frequency. The best way to achieve this rejection is to perform a DFT (Discrete Fourier Transform) on the measured data, taken at high the side of the sensing resistor with respect to ground, Channel 1, and the low side of the resistor, Channel 2, as you inject each selected frequency (**Figure 3**). By directly plotting the post-DFT measurement results from channels 1 and 2 into a graphics display dur-

Figure 1



This switching power supply includes connections for loop-stability measurements.

ing the frequency sweep, you need not use PC processing to obtain a complete frequency-response bode plot. For example, despite good gain and phase-margin values, the system in **Figure 4** has low gain and crossover frequency, resulting in poor regulation and reduced stability with a rapid load change. In contrast, with full load applied, although the gain margin is lower than it is under low-load conditions, it is still adequate, and much greater gain exists over a wide frequency range (**Figure 5**). This gain re-

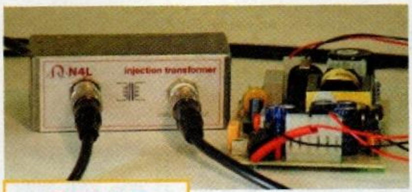


Figure 2 An injection transformer injects a disturbance signal into the control loop of an open-frame switched-mode power supply. At each injected frequency point, measure the relative amplitude in decibels and the relative phase in degrees.

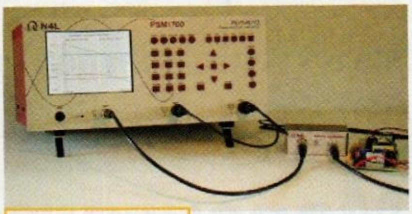


Figure 3 A typical test configuration for testing a switch-mode power supply has a phase-sensitive multimeter with two voltage-sensing measurement channels and a built-in signal generator that connects to the control loop via an injection transformer.

CONTROL THEORY IS THE PLACE TO START

Control-loop theory deals with the behavior of systems that are changing in time. For a brief review of fundamental principals, consider one of the most common examples of this theory, the control loop within a power supply (**Figure A**).

A regulated power supply should provide its load with a stable output voltage, and, to do so, it must be able to adjust the characteristics of the system to maintain the desired output voltage under changing load conditions. You achieve this regulation using a control circuit that feeds back a proportion of the power- supply output for comparison with a known reference signal. This comparison produces an error signal that you then use to adjust gain within the power-supply system so you maintain the desired output.

By considering the elements in this control loop, you can derive a basic mathematical relationship that represents the effect that the loop has on an input and use this relationship to calculate the output controlled variable from any input reference. The control loop comprises a reference, R, the key input to the system; an amplifier or gain stage, A, which is the system under control; a controlled variable, C, which is the desired output of the system; a feedback stage, B, which is a signal that is proportional to the system output; BC, the output from the feedback stage into the summing junction; the summing junction or comparator, $\otimes$, which, in this case, you derive by subtracting BC from R; and the error signal, E, the output from the comparator. Therefore, E=R−BC, and C=AE; C=A(R−BC)=AR−ABC; and C(1+AB)=AR. Therefore,

$$\frac{C}{R}=\frac{A}{(1+AB)}.$$

The term

$$\frac{A}{(1+AB)}.$$

is the transfer function of the system, and you find the output of any control system by multiplying the input to the system by the transfer function. Therefore,

$$C=\frac{A}{(1+AB)}\times R.$$

Despite the apparent simplicity of control theory, analysis of loop stability under conditions that are changing in time becomes complex. Any closed-loop-feedback system can become unstable if, at any frequency, the phase delay around the loop is 360° or more when the loop gain is greater than 1 (0 dB). At values close to 360° and 0 dB, the system can exhibit erratic behavior, even though it does not have sustainable oscillations. To preserve controlled behavior of the closed-loop system, designers typically apply gain- and phase-margin criteria. The loop gain should be −20 dB or lower when the loop phase delay reaches 360°. The phase delay around the loop should be less than 315° with a 45° margin when the loop gain is greater than 0 dB.

The most convenient way to view the frequency response or transfer function of a control loop is a bode plot, from which you can establish the gain and phase margin. **Figure B** illustrates a typical plot from simulation software and shows margin and crossover points.

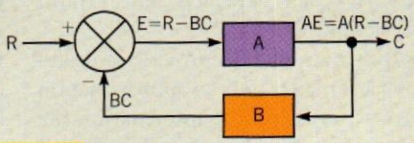


Figure A The key signal points in a closed-loop system are the bases for defining control-loop performance.

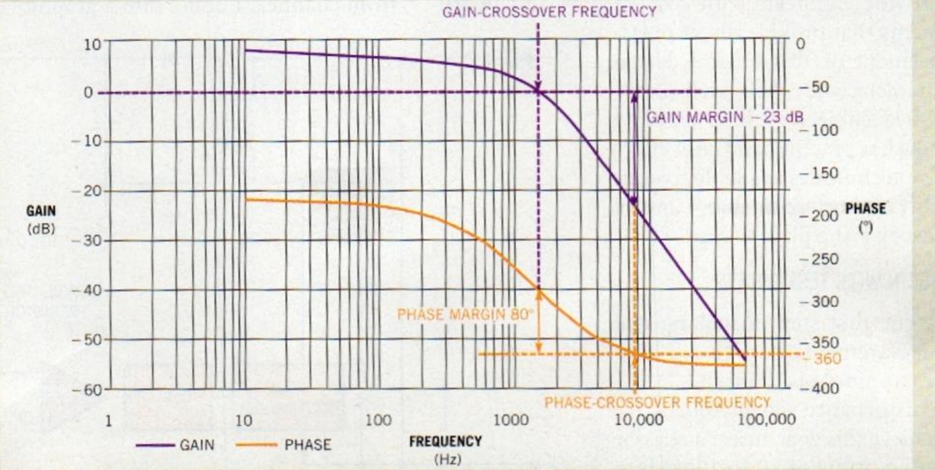
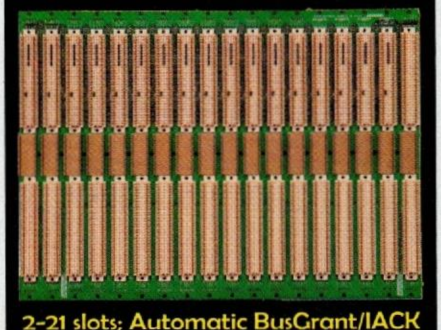


Figure B The bode plot shows gain and phase margin of the control loop and is the starting point for performance analysis.



sults in superior regulation and greater stability even with rapid load change.

To establish meaningful performance characteristics of a power supply, you must measure the transfer function over the range of load conditions under which you expect the power supply to operate (**figures 4** and **5**). Then, once you establish the transfer function under the chosen load conditions, consider design changes affecting the pole and zero elements within the complete transfer function to achieve the best overall performance.

A pole element introduces attenuation of −20 dB per decade and negative phase shift, whereas a zero element introduces gain of 20 dB per decade and positive phase shift. The complete transfer function comprises the pole and zero elements within the control loop. Because nearly all systems exhibit attenuation at higher frequencies, more poles than zeros usually exist in the transfer function.

In the low-load transfer function shown in **Figure 4**, the attenuation at frequencies up to the gain crossover frequency is consistent and in the order of 20 dB per decade, which suggests the presence of a single dominant pole. Although **Figure 1** does not show a full schematic of the power supply, for the purpose of illustrating a principal, consider this dominant pole to be associated with capacitance in the error-amplifier stage of the control loop. Reducing the value of capacitance within this stage would increase the pole frequency and, therefore, the gain, improving the low-frequency regulation. The change in transfer function associated with this modification will influence the gain and phase under all load conditions, so you must repeat tests over the complete load range to ensure that gain and phase margins remain within target limits.

Although PC simulation is a valuable tool at the early stage of a control-loop design, designers can achieve an understanding of true control-loop characteristics only with real measurements on the completed design. Modern instrumentation can now provide an accurate and economic approach to this challenge.□

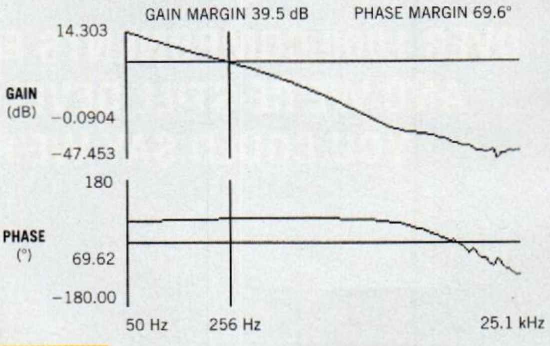


Figure 4

A power-supply bode plot under low-load conditions, with gain and phase margin readings selected and a cursor at the gain-crossover point, shows poor regulation.

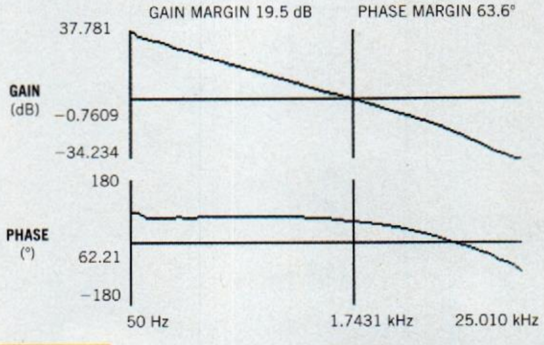


Figure 5

This analysis of a power-supply bode plot under full-load conditions shows adequate margin under operating conditions.

AUTHOR'S BIOGRAPHY

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