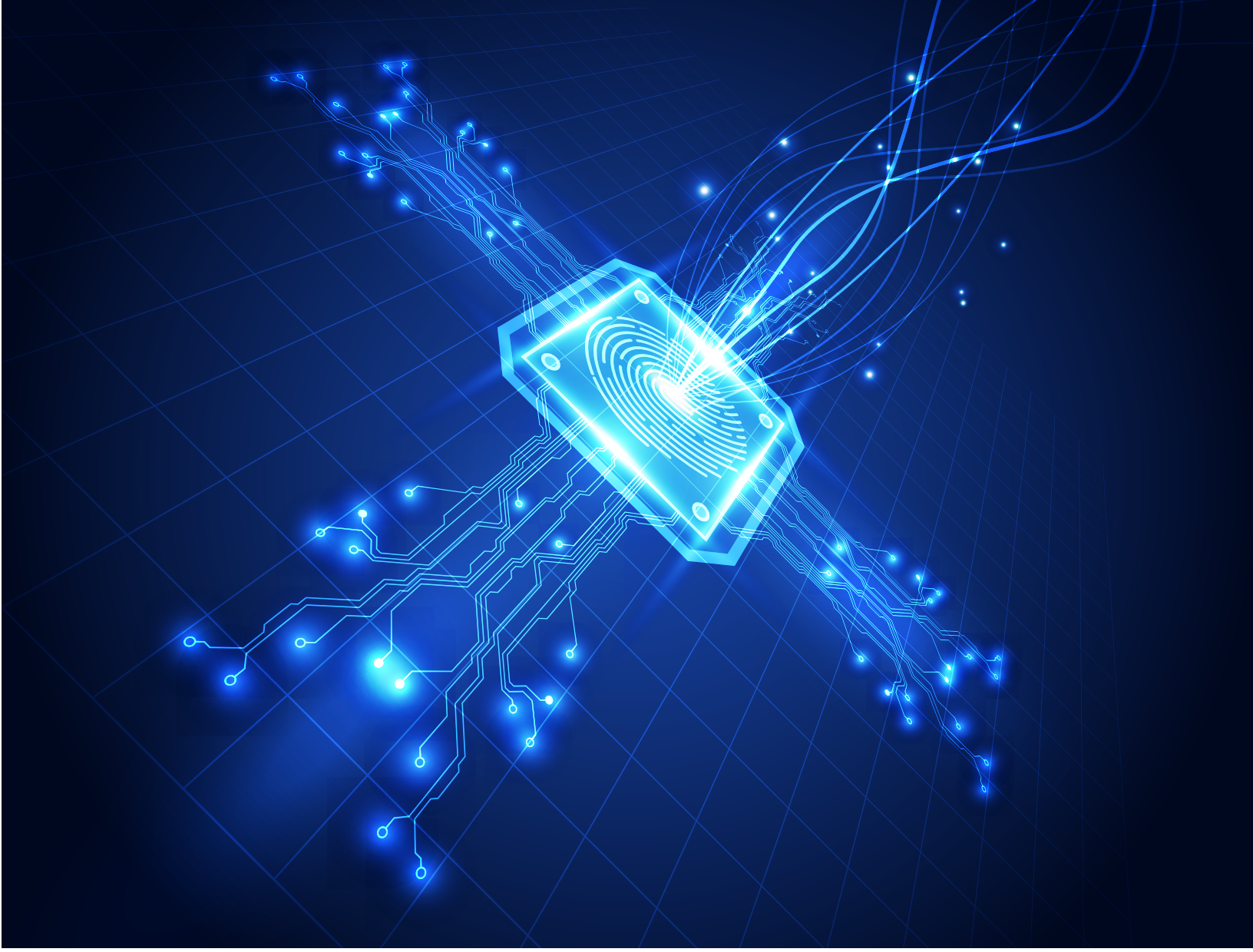

NEW SIGNAL INJECTION TECHNIQUE SIMPLIFIES POWER SUPPLY FEEDBACK LOOP MEASUREMENTS

H. Dean Venable • Venable Instruments

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New Signal Injection Technique Simplifies Power Supply Feedback Loop Measurements

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New, easy to implement signal injection point simplifies frequency response measurement in complex power supplies.

Abstract

New power supply designs are becoming harder and harder to measure for gain margin and phase margin. This measurement is important because step load testing does not measure critical parameters such as conditional stability. Measuring gain and phase of the feedback versus frequency requires finding a point in the loop to inject a test signal. One such point is the connection between the voltage error amplifier and the pulse width modulator (PWM) comparator, but that point has been moved inside most PWM integrated circuits, and is no longer accessible. A second point is in series with the output of single-output supplies, but this point is rapidly becoming inaccessible or invalid with the inclusion of multiple output voltages feeding one summing node. A new technique has been developed which does not suffer from either of these limitations and which can be implemented on virtually any PWM chip. This article describes this technique and gives examples of how to apply it to various types of integrated circuits.

Why Measure Feedback Loops?

Most people are interested in the transient response of a power supply, i.e., how fast it responds to changes in load or line voltage. A common method of determining transient response is to do step load testing. Unfortunately, step load testing does not tell the whole story. Step load testing does not reveal conditionally stable loops (loops where the total phase shift reaches 360° at a frequency when there is still gain around the loop). Sometimes, step load testing does not reveal the stability of the loop at all, particularly when the loop is fast and the rise time of the step is slow. This slow step rise time is not unusual in the built-in step generators in many electronic loads.

A Bode plot (plot of log gain versus log frequency and linear phase versus log frequency) gives all the information necessary to evaluate a loop. Gain and phase margins are taken

directly from the plot. Conditionally stable loops are instantly revealed. The transient response time is proportional to the reciprocal of the loop bandwidth and the amount of ringing is easily predictable from the measured phase margin. Figure 1 shows an unconditionally stable loop and Figure 2 shows a conditionally stable loop.

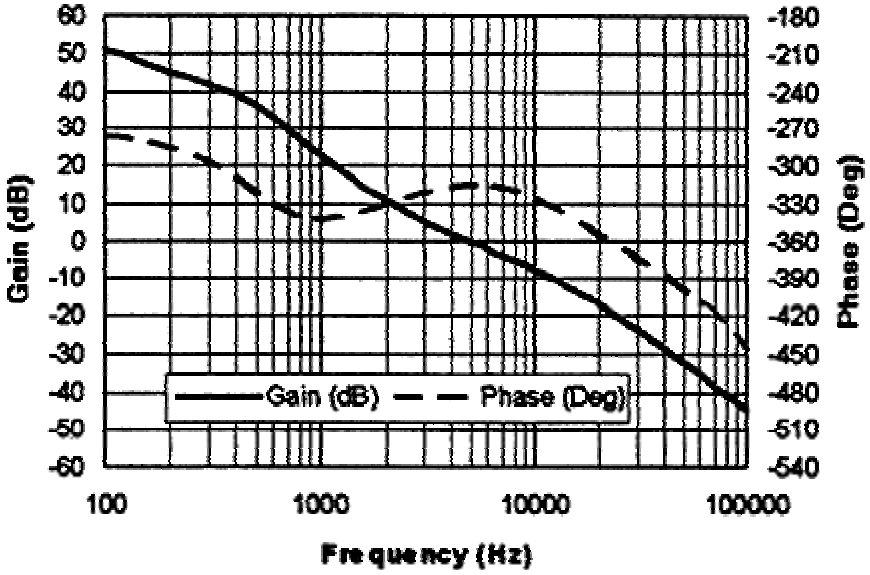

Figure 1. Unconditionally stable loop

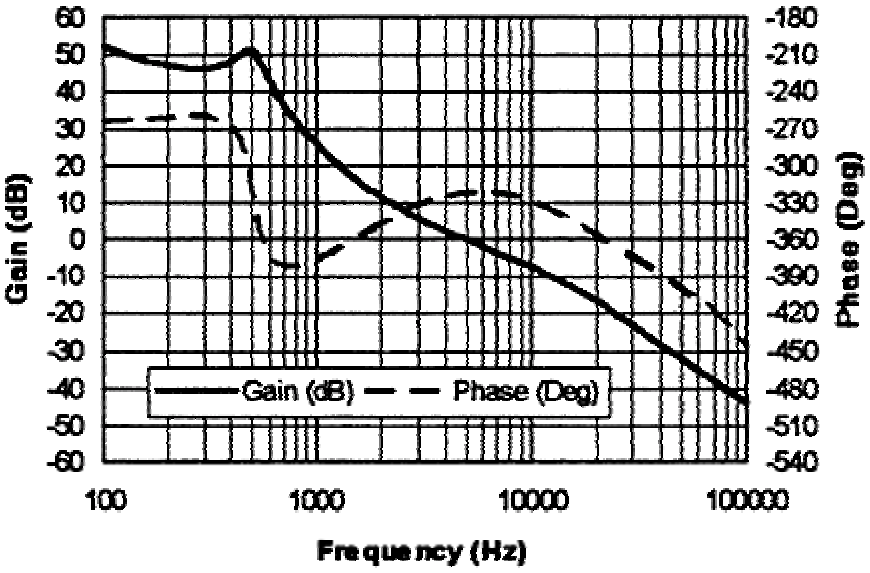

Figure 2. Conditionally stable loop

How Loops Were Measured

When power supplies were built from discrete components, every point in the circuit was accessible. The criteria for making a loop measurement was to find a place in the loop where the signal was confined to a single path and the impedance looking into the circuit input was much higher than the impedance of the circuit output. There were two of these points in most switching power supplies. One was at the connection between the voltage error amplifier and the comparator which set the pulse width. (This point exists in both voltage mode and current mode circuits.) The other point was the connection between the output of the power supply and the input of the voltage error amplifier.
simplified schematic showing the two possible injection points.

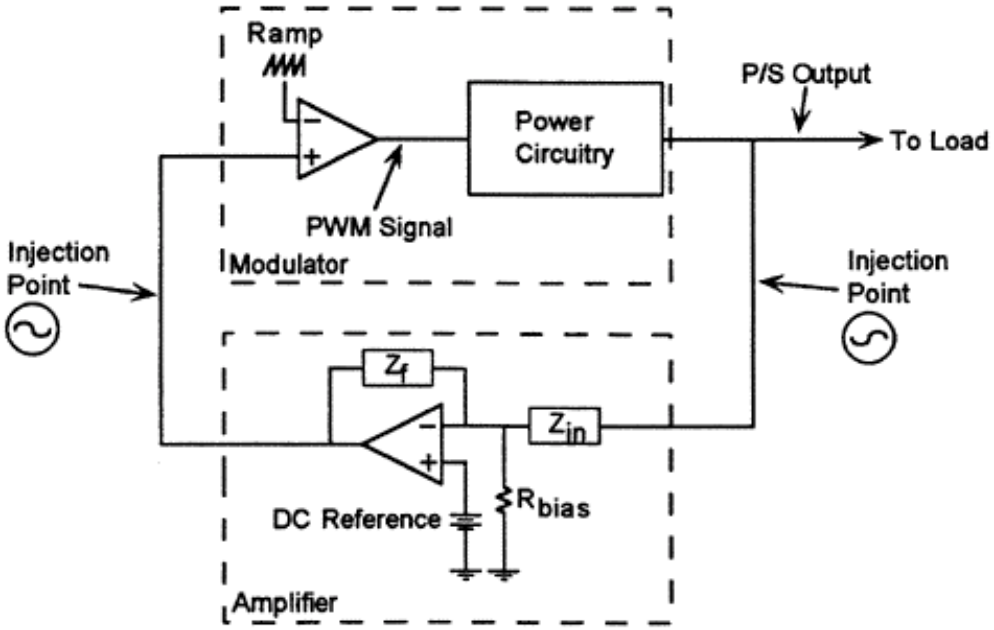

Figure 3. Simplified schematic showing possible injection points

Impedance Criteria

Meeting the impedance criteria of high input impedance and low output impedance made testing easy, but meeting the impedance criteria was not absolutely necessary if the right software tools were available. The actual equation for loop gain is

$$Truegain = \frac{Gain + \frac{Z_{out}}{Z_{in}}}{1 + \frac{Z_{out}}{Z_{in}}}$$

Equation 1.

where Gain is the measured loop gain, $Z_{in}$is the input impedance and Z_{out} is the output impedance.

If the input and output impedances can be measured or calculated and if software tools are available for doing complex multiplication and division of the various transfer functions, this limitation can be circumvented.

Signal Injection in a Simple Power Supply

Measuring loop gain and phase shift consists of inserting an error voltage in series with the loop and then measuring the voltage with respect to signal ground on each side of the injection voltage. The ratio of the output voltage to input voltage (in both magnitude and phase) is the loop gain, and this measurement has to be repeated at enough points across the frequency band of interest to create a smooth plot. The specific technique for inserting this error voltage is to put a small resistor in series with the loop (small compared to the input impedance) and then to connect a voltage source across this resistor, usually in the form of a transformer output winding where the transformer input winding is driven from a variable frequency oscillator. Figure 4 shows the signal injection technique.

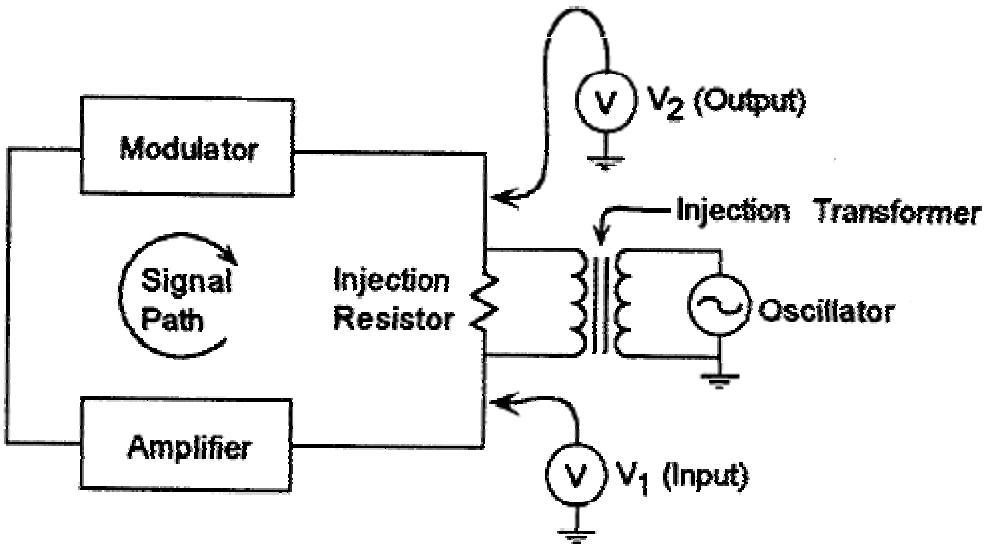

Figure 4. Signal injection technique

Signal Injection in a Complex Power Supply

New power supply designs are becoming more and more difficult to test as the single path needed for injection is either inside an integrated circuit or changed into multiple paths by new circuit topologies. Figure 5 shows a "worst case" scenario that is a very common topology in contemporary power supplies. This topology uses a TL431 or equivalent "programmable zener" to sense the output voltage.

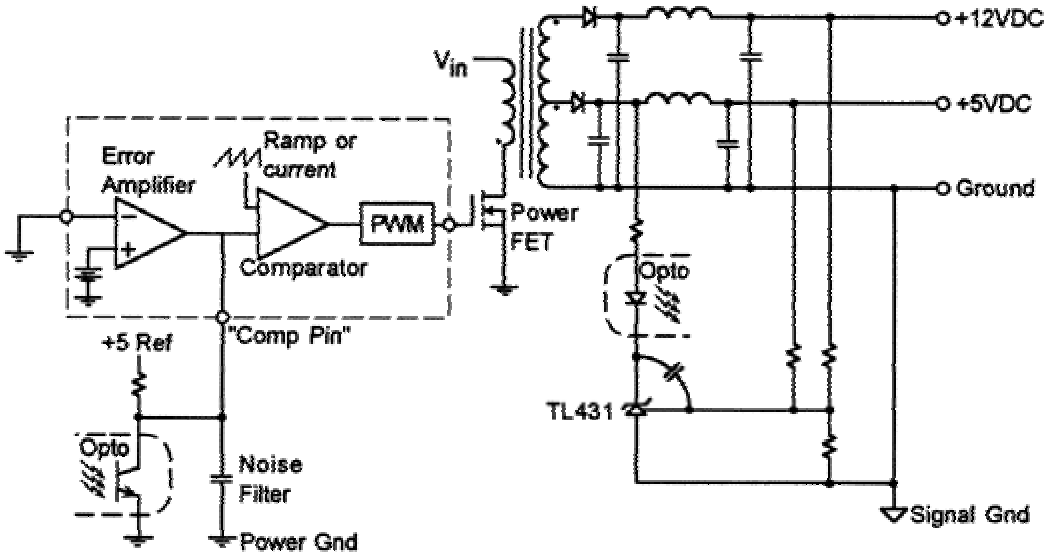

Figure 5. Signal injection in a complex power supply

There are three loops in the output. One is directly from the raw 5 volt line through a resistor and opto-coupler diode. Because the capacitor from cathode to gate of the TL431 holds the cathode at a relatively fixed voltage with respect to signal ground, an AC signal on the 5 volt output causes AC current in the opto-coupler diode without requiring any signal to pass through the TL431. At higher frequencies (above a few hundred Hz) this is the dominant signal path and the one which has most effect on loop stability. In order to avoid the phase shift of the second-stage L-C filter, the opto-coupler diode portion of the circuitry is commonly powered from before the filter.

The 2nd and 3rd feedback paths are the dividers from the 5 volt and 12 volt outputs respectively. To avoid having one output be closely regulated and wide voltage swings on the other, both outputs are used in the feedback. In this way, neither output is well-regulated but neither has extreme voltage fluctuations. Regulation is adequate for most applications.

These three signal paths are in parallel. Each can be measured, but none of them represents the entire loop. The signal after the opto-coupler transistor is confined to a single path but the impedance ratio is indeterminate since the input impedance of the compensation pin of the PWM chip is not specified. It is possible to measure the input impedance and compensate the measured gain using the formula above and proper transfer function math software. Actually, without the compensation technique just mentioned this topology is still untestable, but can be made testable with a few minor changes using the new signal injection technique.

New Signal Injection Technique

The new injection technique involves putting the injection signal in an op-amp feedback path rather than in series with the input or output. It was suggested to us by Randy Wagner of Autec. While it is frequently not possible to break the connection between the error amplifier and the comparator in a PWM chip, it is almost always possible to access this point, which is provided as a "compensation pin" to connect feedback from the op-amp output to it's inverting input. Figures 6 and 7 show the conventional and the new signal injection points.

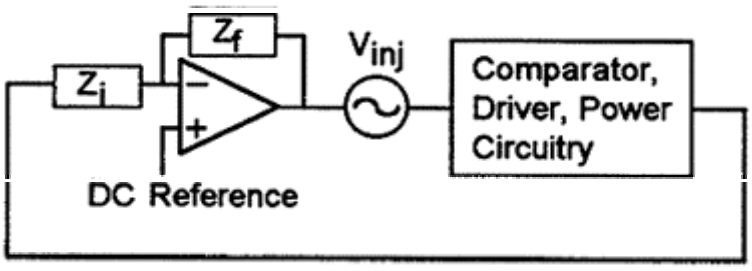

Figure 6. Conventional signal injection technique

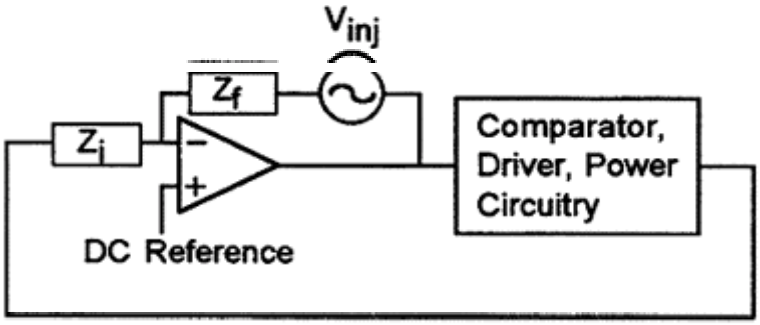

Figure 7. New signal injection technique

The gain of an op-amp is given by the ratio of feedback impedance to input impedance, Z_f / Z_i. If the feedback impedance is connected across the op-amp as in Figure 6, the output voltage of the op-amp is given by the ratio of the feedback impedance to the input impedance. The injection voltage is added in series after the op-amp. If, however, an injection voltage is connected in series with the feedback network as shown in Figure 7 then the output voltage of the op-amp will be the ratio of the two impedances plus the signal source voltage. This is exactly the condition when the signal source is connected in series with the output of the op-amp as it would be with conventional injection techniques (shown in Figure 6).

Needed Modifications to Existing Designs

In order to inject in the feedback network, the op-amp inside the PWM chip must be used. (It is now frequently bypassed.) For chips with both inverting and non-inverting inputs available, the chip can simply be wired as a unity gain buffer. For chips with an internal connection to the non-inverting input, the chip can be wired as an inverting buffer and the opto-coupler transistor can be reconnected from the reference voltage to the op-amp input rather than from the op-amp output to ground. Figures 8 and 9 show the new connections for each type of op-amp.

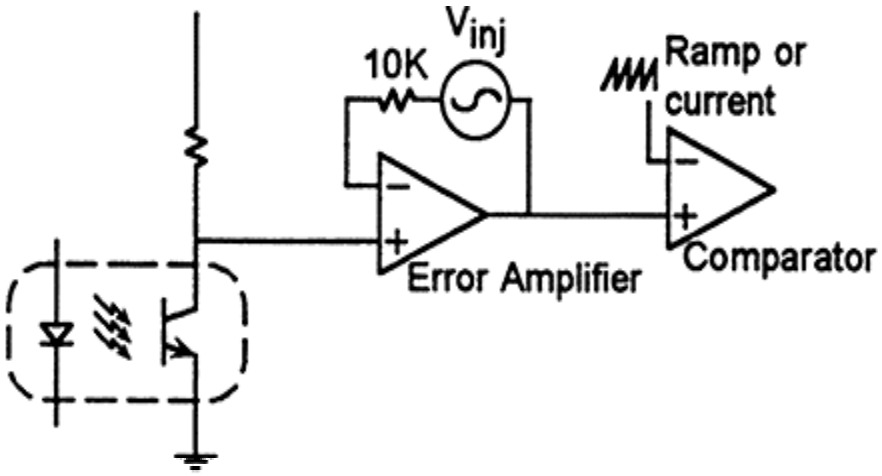

Figure 8. Both inputs available

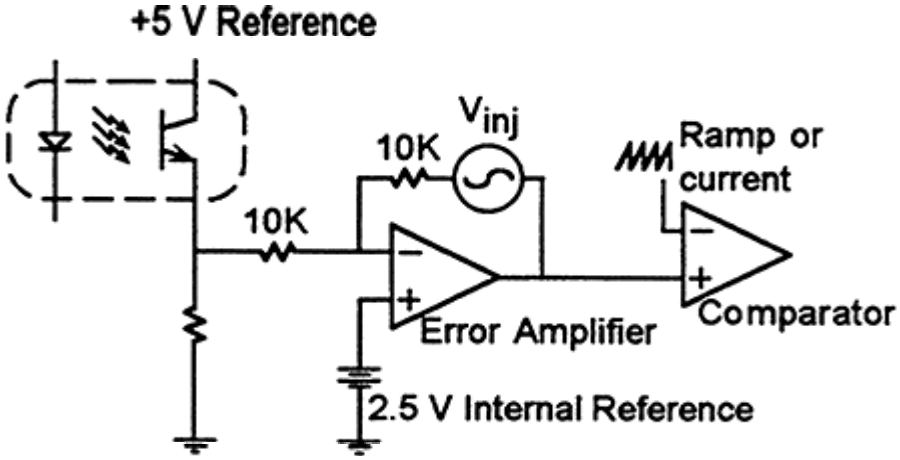

Figure 9. Inverting input available

Biasing For Desired Operating Point

In most cases, the circuit will work as a unity-gain inverting buffer with no additional biasing since the voltage range will be essentially 0 to 5 volts if the opto-coupler transistor is tied to the +5 volt chip reference voltage. If it were necessary to change the gain or the DC operating point of the source, it can be easily done by changing the ratio of the feedback resistor to the input resistor to some value other than one, and/or by adding bias resistors from the inverting input to either ground or the +5 volt reference.

Relating Feedback Loop Measurements (Bode Plots) to Transient Response

There is a direct correlation between frequency response and time response of a circuit. Power supply response time to a step load change is proportional to the reciprocal of the feedback loop bandwidth, and the amount of ringing is related to phase margin (*phi*$_m$). A phase margin of 72° gives no ringing or overshoot. A phase margin of 60° gives one overshoot but no undershoot or ringing. A phase margin of 45° gives a few cycles of ringing but has low settling time.

The total voltage excursion from a step load is given by

$$\Delta V = \frac{\Delta I}{C \times f}$$

Equation 2.

where

delta V = peak voltage excursion in volts
delta I = step load current in amps
C = output filter capacitance in farads and
f = bandwidth of the voltage feedback loop in Hertz

The time to recover is given by

$$t = \frac{1}{4 \times f \times \cos(\phi_m)}$$

Equation 3

where

t = time to recover in seconds
f = bandwidth of voltage feedback loop in Hertz
phi $_m$ = phase margin of voltage feecback loop in degrees

Conclusions

The new injection point in series with an op-amp feedback network is available on virtually every PWM chip, and solves the problem of how to inject a test signal when the signal path cannot be broken. It also solves the problem of how to test the frequency response of the feedback loop when the voltage sensing amplifier on the secondary side has no single feedback path. Bode plots are essential design tools which reveal problems such as conditional stability that step load testing does not reveal and as such should be used on all new designs. Frequency response analysis systems such as the Venable Model 102A can perform all the necessary tests, and in addition can measure conducted susceptibility, conducted emissions, filter response, power line harmonics, and component parasitics such as capacitor ESR and ESL.

This paper is the basis of an article which appeared in the September 1995 issue of PCIM magazine.