Venable Technical Paper # 11

Stability Testing of Multi-Loop Converters

Abstract:

Measurement of loop gain and loop phase shift versus frequency is generally possible with single output power supplies or multiple output supplies where each output is independently regulated. These measurements are necessary to determine the phase and gain margins and insure stability of the feedback loop. Measurement requires access to a point where the loop is confined to a single path. Such a point does not exist in many low-cost computer power supplies, and these supplies constitute the numerical majority of power supplies manufactured today. This paper presents techniques for overcoming this obstacle and obtaining loop data even where a single signal path is not accessible.

Introduction

Stability testing of any feedback control loop involves inserting a small known disturbance in series with the loop and then measuring the loop's response to this disturbance. This is done by measuring the amplitude and phase of the voltage on each side of the injection point as a function of frequency of the disturbing signal. This is a general technique applicable to any type of control system. A criteria for accuracy is that the disturbance be injected between a low-impedance point and a high-impedance point.

In power supplies, two such points normally exist. Figure 1 is a schematic diagram of a typical switching power supply. The two possible injection points can be seen in this diagram. One is the path between the output of the supply and the resistor divider string, which connects to the error amplifier input, between Vo and R1 in the diagram. The other is the path between the error amplifier output and the comparator input, the point labeled Vc in the diagram. Both of these points meet the impedance criteria for accuracy.

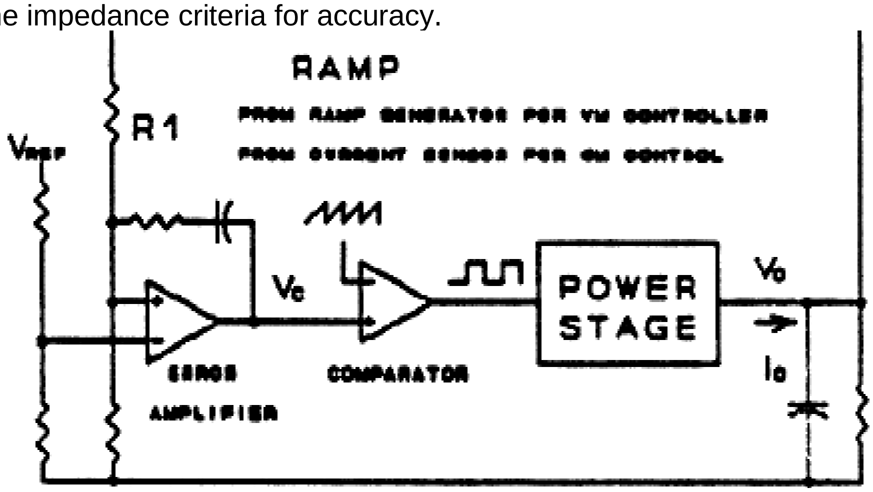

Figure 1. Typical Power Switching Supply

The problem comes when these injection points either do not exist or are inaccessible. There are many implementations and/or topologies that create this problem. The most common one is in low-cost computer supplies with two outputs, typically 5 volts and 12 volts. The 5 volt output is used for logic and the 12 volt output is used for disk drives. Neither voltage needs to be extremely well regulated, but neither voltage can be extremely poorly regulated either. Designers solve this dilemma by taking part of the feedback from each output, in effect having two R1s from two outputs driving the amplifier summing node. The paths from each output to each input resistor are valid
loops, but neither represents the overall loop.

The point between the error amplifier and the comparator is a valid injection point even in this case, but in low-cost supplies the control integrated circuit contains both the error amplifier and comparator. The connection between them is made inside the integrated circuit chip and cannot be broken, making this point inaccessible. Since the loop does not exist in a single path outside the chip and is inaccessible where it does exist inside the chip, this type of supply has been untestable. Many computer manufacturers, having witnessed vendor power supplies, which oscillate in their application, will attest to the danger of having an untestable design.

This example is not unique; many other topologies have the same problem. What makes this particular problem interesting is that this condition exists in numerically over half the power supplies manufactured today. This paper will discuss a new method for testing these untestable supplies, one, which can be, applied to a wide variety of similar difficult measurement conditions.

Stability Testing of Single Loop Converters

Before discussing the problems and solutions of multiple loop converters, it is useful to understand the principles of testing single loop converters. Figure 2 shows a measurement technique for testing the frequency response of a loop and also the major parts of the loop at the same time. It requires a three-channel frequency response analyzer such as the Venable Model 350 system.

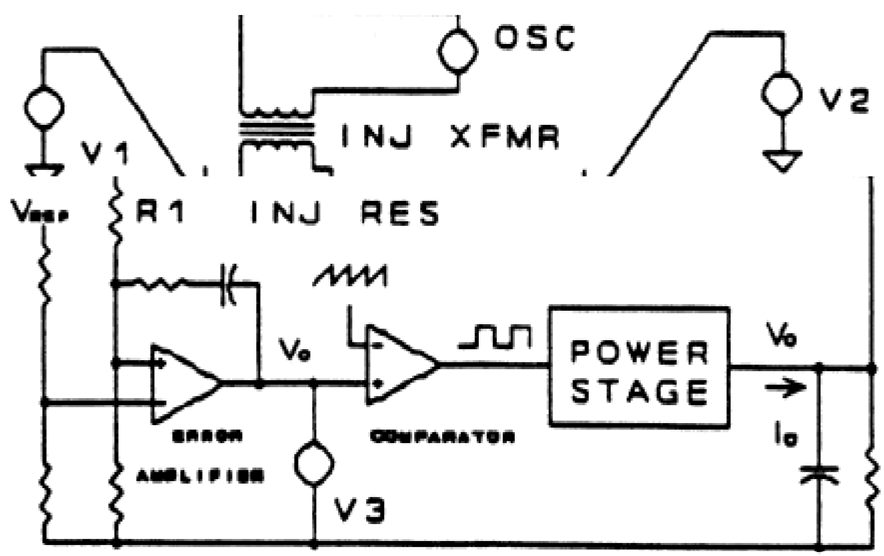

Figure 2. Typical Power Switching Supply

An OSCILLATOR, typically part of the frequency response analyzer, puts out a sinusoidal voltage. This voltage is passed through an INJECTION TRANSFORMER to allow it to float and to minimize the capacitance from the oscillator to the circuit under test. The output of the injection transformer is connected across an INJECTION RESISTOR, a resistor added in series with the loop between the output and the top of the amplifier input resistor divider string. The combination of these creates a FLOATING SINUSOIDAL ERROR VOLTAGE IN SERIES WITH THE FEEDBACK LOOP. This voltage then creates a disturbance in the operating point of the loop, creating voltages around the loop that can be measured with respect to signal ground. The voltmeter labeled V1 reads the voltage, which is the input to the loop. The voltmeter is frequency selective; it reads the amplitude of the voltage at the frequency of the oscillator and rejects all other frequencies. The voltmeter labeled V2 is also frequency selective and reads the voltage at the output of the loop, which is the input voltage multiplied by the loop gain. Dividing V2 by V1 yields the open loop gain measured while the circuit is operating closed loop. The third voltmeter, V3, available on three channel analyzers like the Venable Model 350 System, is also frequency selective and is connected to the point between the error amplifier and the comparator. While this path is internal to the chip and cannot be broken, it is accessible for measurement since it is brought out as the "compensation pin" for the amplifier on the chip. The transfer function from V1 to V3 is the error amplifier transfer function, from V3 to V2 is the power processing transfer function ("plant" to servo engineers), and from V1 to V2 is the overall loop. Figure 3 shows a typical transfer function from control to output, what we above called the "power processing" or "plant" transfer function. This transfer function may be inverting or non-inverting at low frequency, and whichever it is it requires the opposite kind of error amplifier. This plot shows a non-inverting control to output transfer function typical of current mode control. The scales are log gain and linear phase versus log frequency.

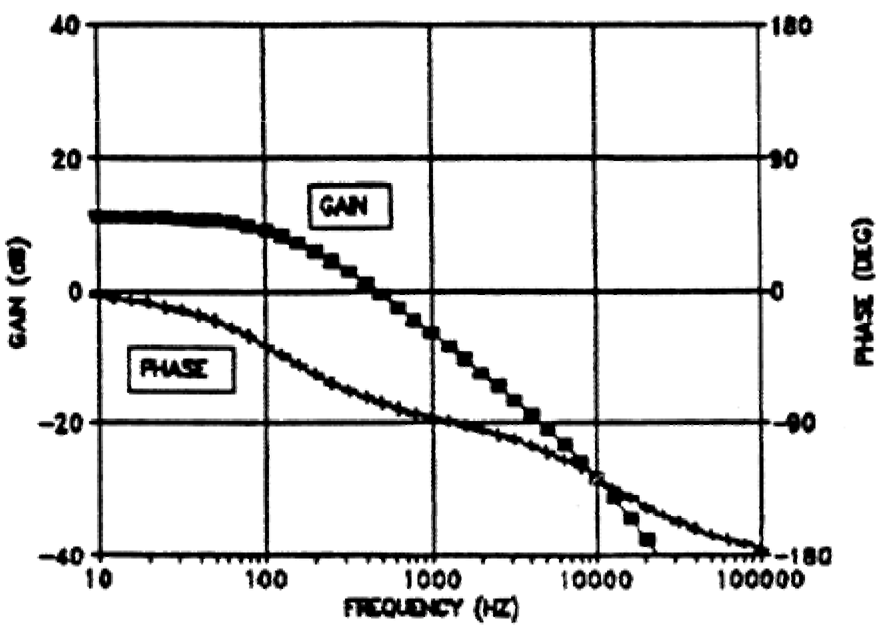

Figure 3. Control-to-Output Transfer Function

Figure 4 shows a typical error amplifier transfer function. This is the gain from output to control. There is a region of flat gain slope, which causes a corresponding reduction in phase lag. Note that the phase axis is 360°, indicating that the error amplifier output lags the input by 180° to 270°.

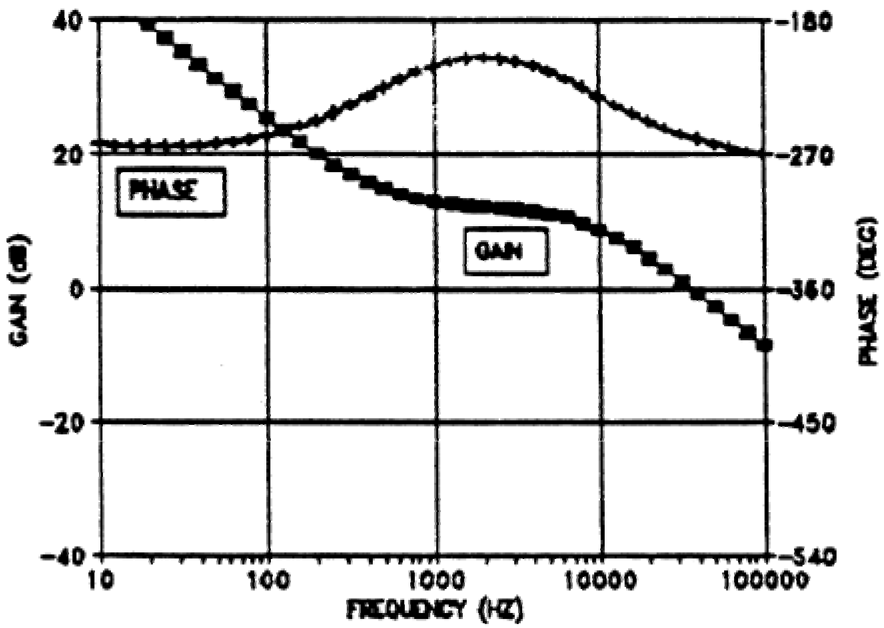

Figure 4. Typical Error Amplifier Transfer Function

The gain around the loop is the product of the two gains, control to output and error amplifier. The gains are vectors with both magnitude and phase components. Multiplication of vectors is accomplished by multiplying the magnitudes (gain) and adding the phase angles. Since the gain is already expressed logarithmically (in dB), multiplying is accomplished by adding. The overall loop plot is then the sum of the gain (in dB) and the phase (in degrees) of the two components of the loop. Figure 5 shows the overall loop transfer function as would be measured from V1 to V2.

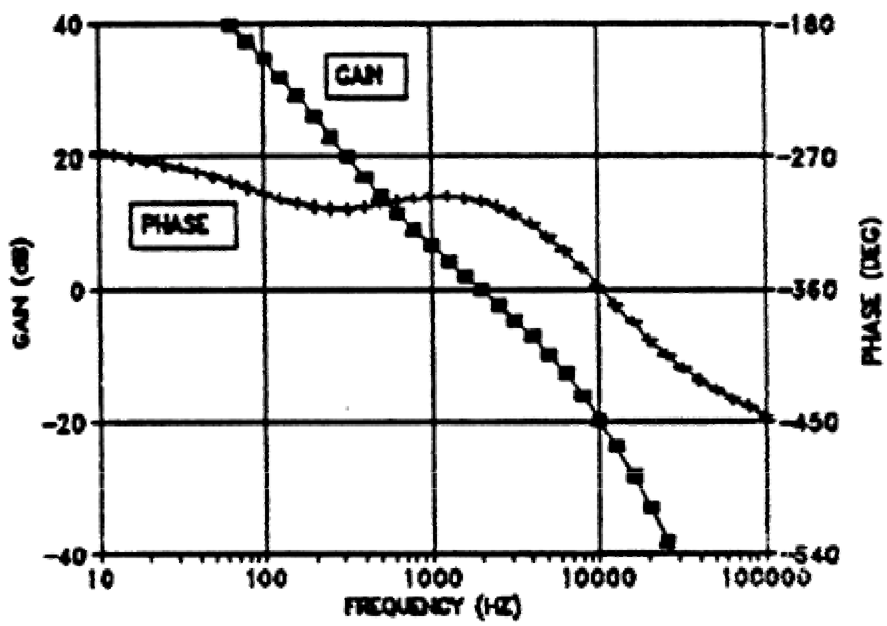

Figure 5. Loop Transfer Function

Note that the "boost" or reduction in phase lag through the error amplifier was designed to peak at the unity gain frequency of the overall loop. This maximizes the phase margin of the loop and optimizes performance.

Examples of Circuits with Multiple Loops

The example given in the introduction about split feedback from two outputs is just one example of many where multiple feedback paths exist. The phenomenon of multiple loop feedback often exists in such a surreptitious fashion that it goes undetected. Here are some obvious and not-so-obvious examples of multiple loop feedback.

A common problem comes from control circuits powered from the output they are controlling. The most frequent occurrence is when a TL431 "programmable zener" is used as an op-amp to sense and control the output. Figure 6 shows a typical circuit.

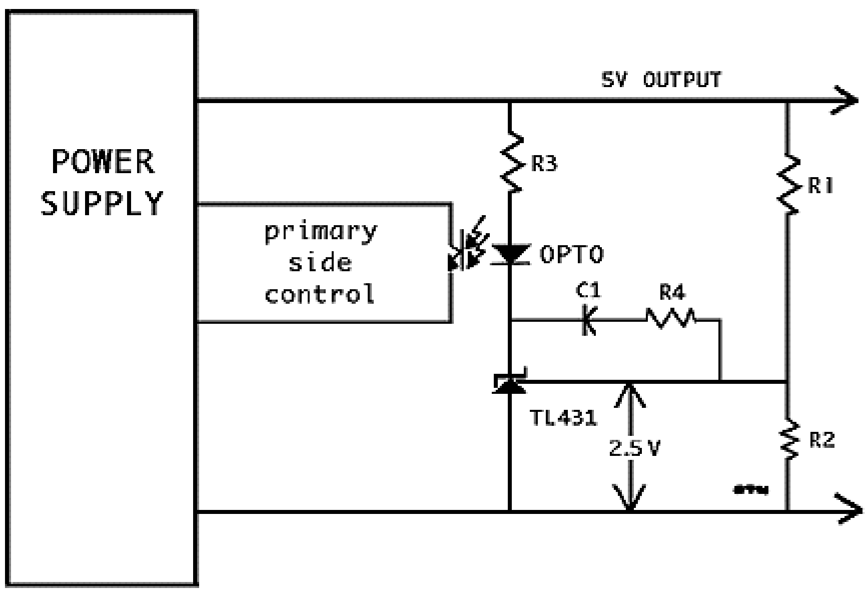

Figure 6. Supply with Two Feedback Paths

The obvious feedback path is through R1 into the summing node (control pin) of the TL431. Another (more important) feedback loop exists because C1 tends to hold the cathode of the TL431 at AC ground. At medium and high frequencies, this causes the current in the opto diode to be determined by R3 and the AC voltage on the 5 volt output rather than by the current through R1.

A similar problem occurs when the control op-amp drives the base of a PNP transistor whose emitter is connected to the output being controlled. AC voltage on the emitter often causes larger current in the transistor than the signal on the base. Solutions to these measurement problems are presented later.

Another well-known and often-used circuit with multiple loops is current mode control. Note in Figure 1 that in current mode control the ramp is generated by the output current, not by a fixed ramp generator as in voltage mode control. The feedback from output current to the comparator input makes an internal loop. The voltage loop is wrapped around this inner loop, and is measured and stabilized the same way regardless of whether the supply is operating in current mode or voltage mode. If the stability of the current loop is in question, it can be measured by measuring the closed loop transfer function of the current loop (from Vc to Io, using a current probe to measure Io) and then using mathematical post-processing of the data to calculate the open loop transfer function.

Stability Testing of Multi-Loop Converters

Stability of multi-loop converters can be measured using a combination of testing and mathematical manipulation of the test data. The Venable Model 350 System was used to prepare the examples for this paper, because both the testing and mathematical manipulation functions of this hardware/software package are standard features, which are easily accessed and used.

The general problem of multiple paths in the feedback loop as it relates to power supplies is shown in Figure 7.

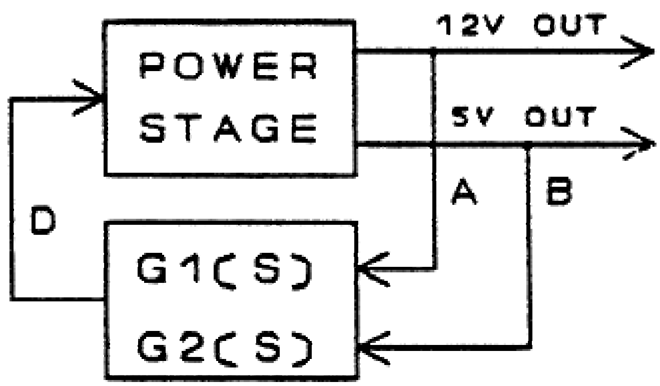

Figure 7. Two Controlled Voltages

If one measures loop gain by breaking the feedback path and inserting a disturbing signal, the requirements for good measurement insist that:

The loop signal flow must be confined to one path. The ratio of load impedance to source impedance at the point of breaking the loop must be very high.

These requirements are often difficult to satisfy in a multi-loop converter because much of the loop is confined inaccessibly inside an integrated circuit. This paper will provide three accurate techniques for measuring these circuits:

Impedance matching
Superposition
Mathematical combination of feedback paths

Circuits Powered from the Output They are Controlling

One of the places where converters with two feedback paths are often mis-measured is the circuit of Figure 8.

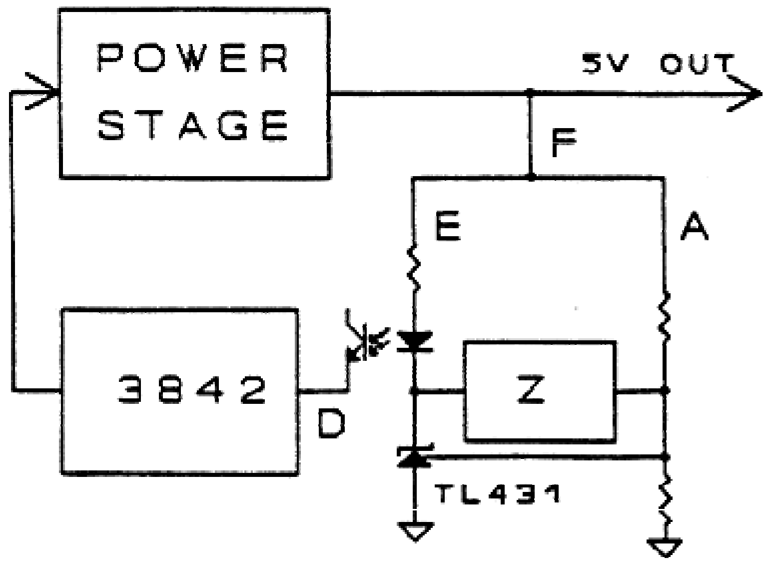

Figure 8. Single Output Supply with Two Paths

This is a commonly used circuit where the designer employs an optical isolator to pass the feedback signal across the primary-secondary isolation barrier. In this case, the TL431 programmable reference s used as an op-amp to drive the opto diode. The problem is that the loop on the secondary side is split into two paths, and measuring only one of these paths (violating the single path criterion) will give incorrect results. Breaking the loop at "D" or "F" accommodates the single path requirement, but path "D" requires some additional attention.

Insertion point "D" is typically a high impedance node. Injecting at this point will usually violate the impedance ratio requirement for accurate measurements. The circuit of Figure 9 will allow correct measurement at this point.

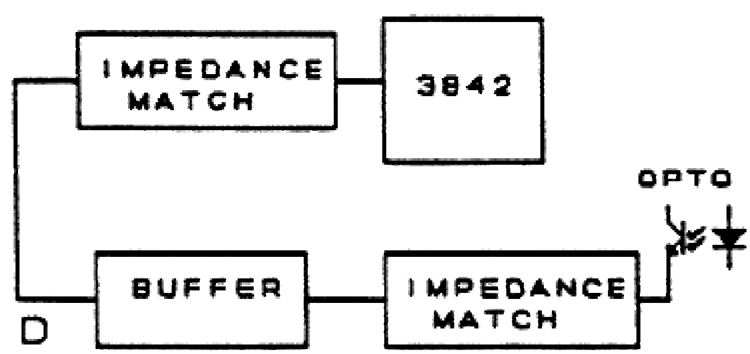

Figure 9. Typical Power Switching Supply

It provides a low impedance buffer to do the injection and the proper impedance matches to allow the opto-coupler to operate with the same gain as the undisturbed loop. Figure 10 shows the gain and phase of a typical circuit measured at point "D" of Figure 9. Point "F" in Figure 8 measures virtually identical gain and phase as point "D" in Figure 9. The response measured at these two points will be referred to as "THE" loop gain of the circuit. This technique unfortunately cannot be easily applied to every circuit because the buffer circuit must be tailored for each operating condition.

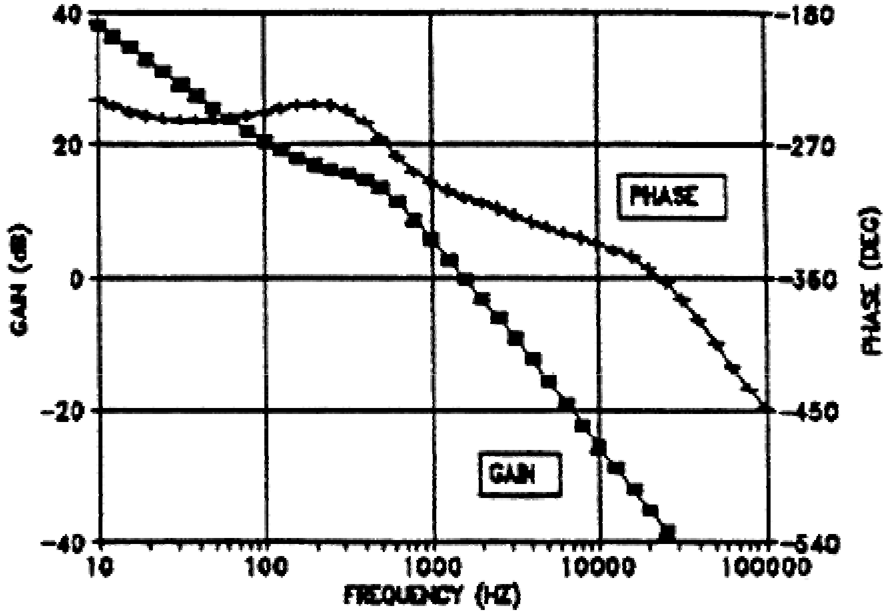

Figure 10. Typical Power Switching Supply

Another point, which is often considered the correct injection location, is "A" in Figure 8. This path is the one, which includes the feedback components "Z." If the path is broken at "A" and a conventional Bode plot is taken, the measurement is not the same as "THE" loop gain. Figure 11 shows a plot of a circuit measured this way. Figure 12 shows the loop gain of the same circuit measured at location "F" with both paths active.

The reason that injection point "A" fails is the second path through "E" in Figure 8. This path works as follows: The feedback components around the TL431 cause the output impedance of the device to become highly capacitive (low impedance) at mid-band frequencies. Injecting at point "A" causes signal on the 5 volt output. This signal appears across the opto diode and its resistor, causing modulation of the opto diode current independent of the path through "A." This represents a parallel signal path, which violates the current independent of the path through "A." This represents a signal path, which violates the signal path criterion.

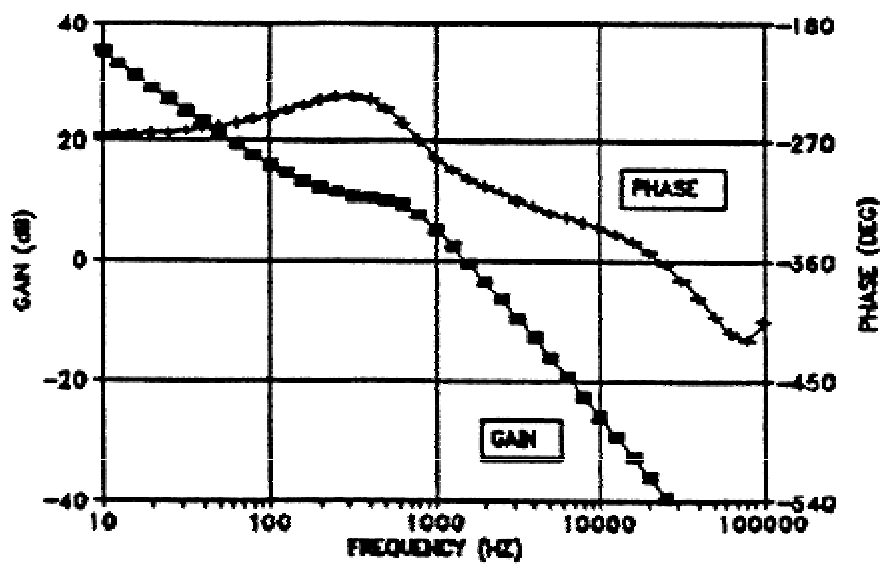

Figure 11. Two Path Circuit Measured at "A"

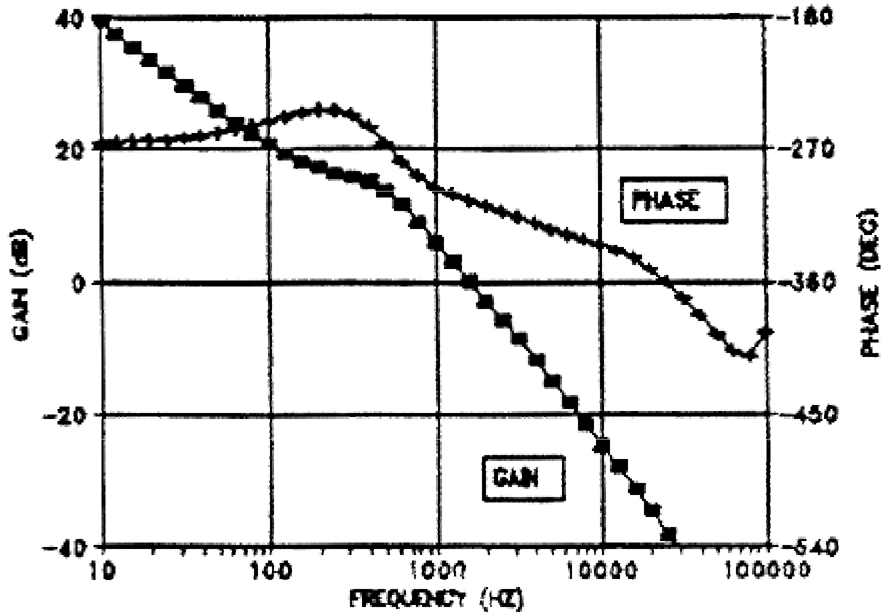

Figure 12. Two Path Circuit Measured at "F"

Feedback from Multiple Outputs

Another example of multiple feedback paths is the circuit of Figure 13. This circuit uses feedback from both the 5 volt and the 12 volt outputs to minimize effects of cross regulation. In this case, the measurement is not as easy as the previous example because path "F" no longer comprises the whole loop. One may be able to break the loop at "D" and use the circuit previously described to make the measurement, but if this point is not accessible, or the injection circuit is not available, testing was formerly not possible.

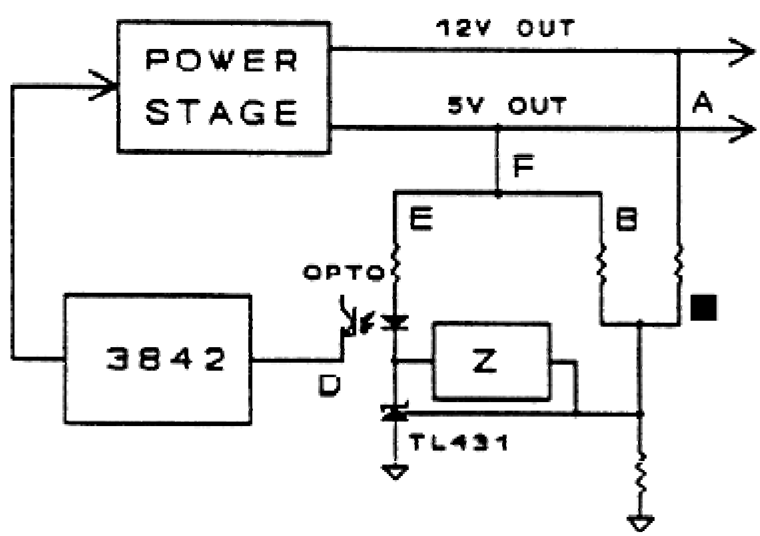

Figure 13. Dual Path Implementation with TL431

A New Method for Testing Stability

A new method presented here for testing the stability of the true loop of power supplies with feedback from multiple outputs.

This new method involves using a frequency response analysis system with both test and math capabilities to apply the principle of superposition to combine data from several paths to calculate the gain of "THE" loop.

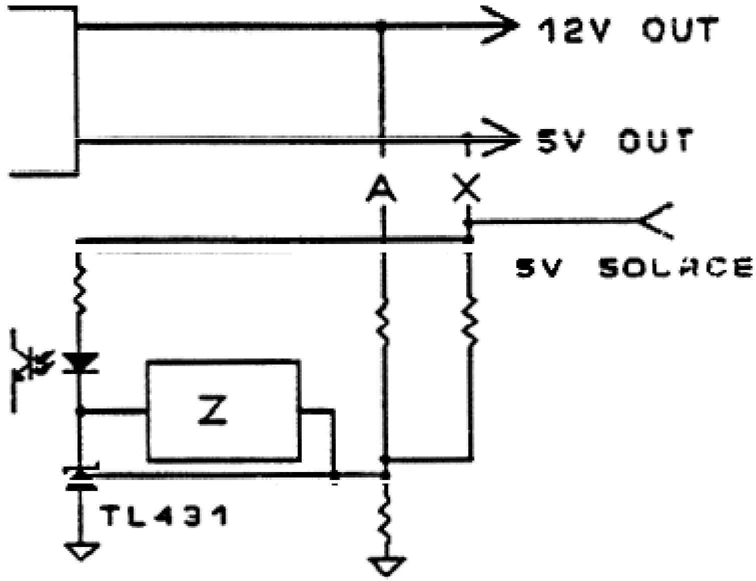

Figure 14. Loop Broken to Measure Path "A"

Figures 14 and 15 show how to break both loops and inject the measurement signal. First inject at "A" with path "B" replaced by a 5 volt source as shown in Figure 14 and measure the response. Then inject at "B" with path "A" replaced by a 12 volt source as shown in Figure 15 and measure the response.

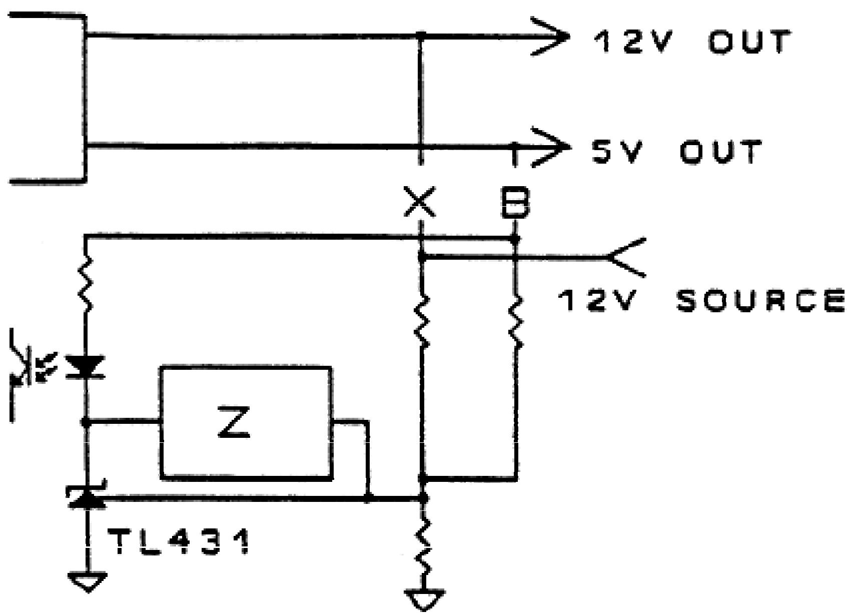

Figure 15. Loop Broken to Measure Path "B"

Next we mathematically calculate a new transfer function called TOTAL by adding the measured data point-by-point in a vector sense. Figures 16 and 17 show Bode plots taken at points "A" and "B," and Figure 18 shows the Bode plot of the mathematical sum called TOTAL. For proof of the technique, the loop was also measured at the opto-coupler (point "D"), and the data were indistinguishable from the TOTAL plot shown in Figure 18.

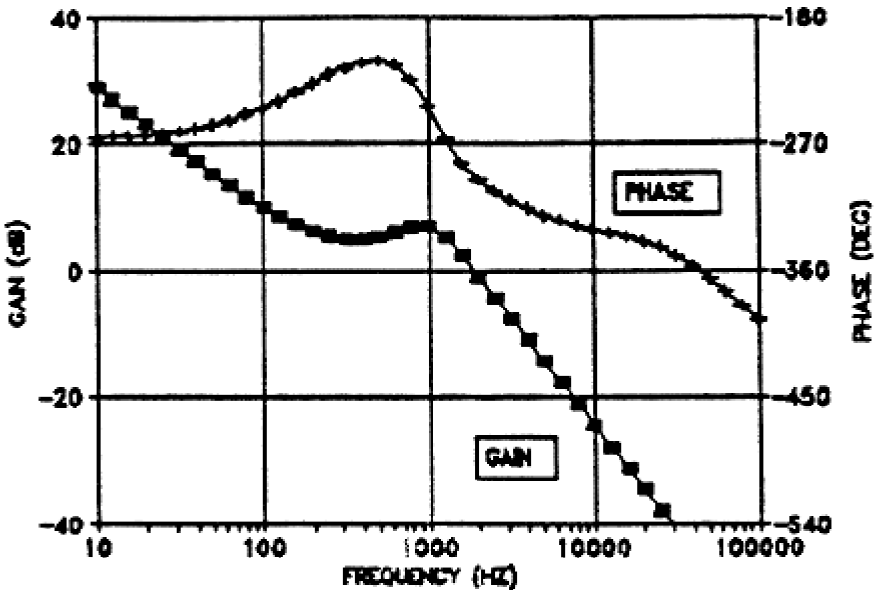

Figure 16. Bode Plot Measured at Point "A"

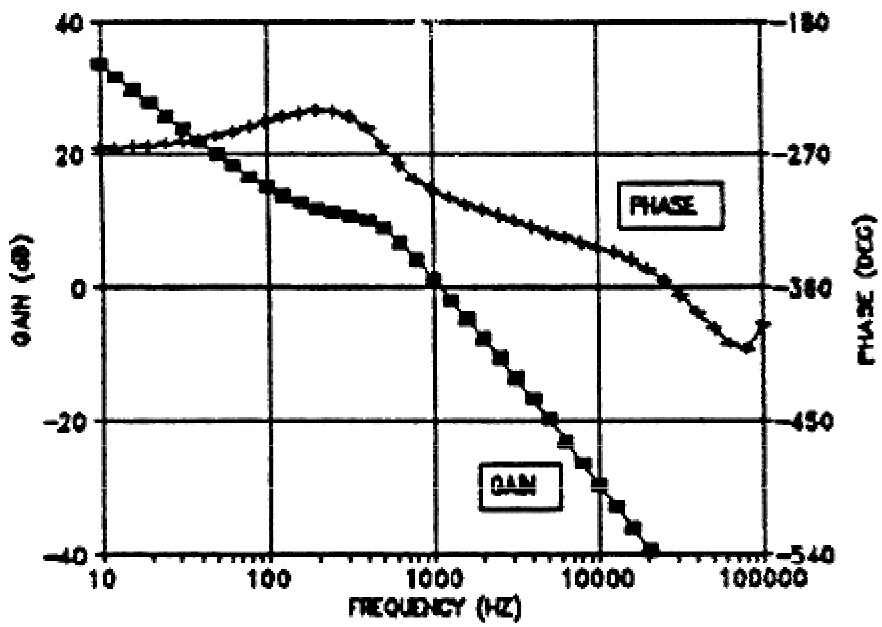

Figure 17. Bode Plot Measured at Point "B"

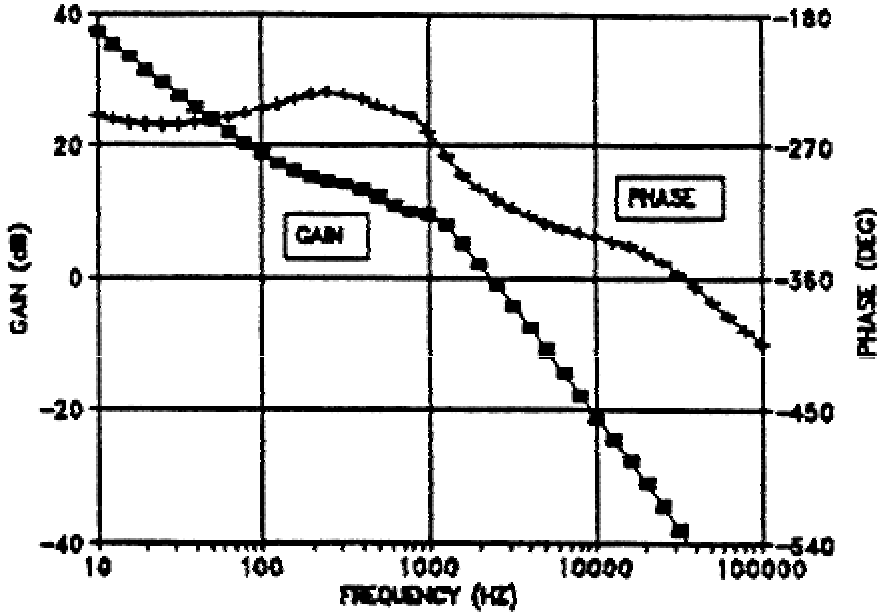

Figure 18. TOTAL, the Sum of Path "A" and "B"

Yet Another New Method for Testing Stability

Another new technique using more elaborate math can be used when the individual paths cannot be disabled. Each path is measured individually as before, but without disabling the other path. If the transfer function of one path is called GAIN1 and the transfer function of the other path is called GAIN2, "THE" loop gain can be calculated by the formula:

$$\text{LoopGain} = \frac{\text{GAIN1} + \text{GAIN2} - 2 * \text{GAIN1} * \text{GAIN2}}{1 - \text{GAIN1} * \text{GAIN2}}$$

These calculations are made as vector arithmetic on a point-by-point basis over the entire frequency range of the measurement.

Conclusion

In conclusion, problems encountered when more than one feedback path is operating at the same time were discussed, and solutions to overcoming heretofore difficult or impossible measurement problems were presented. Two new techniques using the principle of superposition have been shown to be completely valid for the calculation of loop responses in case the gain cannot be measured directly. In addition to these new techniques, several practical examples of test techniques, which may not be widely known, were presented. The possibility of multiple paths must be considered for all optical coupler and multiple output configurations.