

Loop Gain Measurement

with Current Injection

by Dr. Ray Ridley

In this article, we'll briefly review voltage loop injection, and the conditions under which it is valid. Then we'll show the dual solution— current loop injection. This is very useful for power supplies where access to a good voltage injection point is not available.

Voltage Injection

In SPM's Issue 3 in 2002, we talked about issues that can cause the appearance of instability, but which are not classic loop problems. As we mentioned at the time, when called in to help with stability problems on a power supply, much of the time can be spent troubleshooting these noise issues before moving on to the control issues.

The next phase of the stability measurement is to find somewhere in the loop to inject a signal. This is a critical choice, as the resulting measurements must be both accurate and useful to the designer.

Figure 1 shows the standard feedback system used for many power supplies. The output of the converter is fed into an operational amplifier network, the output of

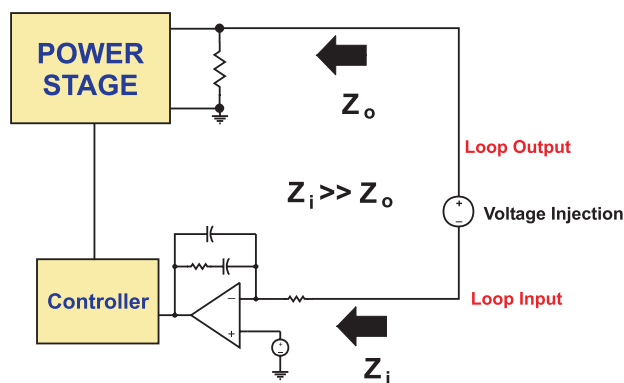


Figure 1: Power supply with conventional feedback and voltage injection

which is used by the PWM controller. In this case, the control loop is broken at the output of the power supply by injecting a voltage source in series with the loop.

This is an accurate and effective method as long as the proper guidelines at this injection point are valid. The rules for doing this are as follows: The impedance looking back before the injection point, Z_o , must be much lower than the impedance looking forward, Z_i . If this is violated, the loop gain becomes inaccurate.

Details of this measurement theory can be found in Bob Erickson's book "The Fundamentals of Power Electronics", or in Dr. Middlebrook's original papers "Measurement of Loop Gain in Feedback Systems", International Journal of Electronics, Vol. 38, No. 4, 1975 and "Design-Oriented Analysis of Feedback Systems", Proceedings National Electronics Conference, Vol. XX, October 1964.

The open loop output impedance of a power supply is typically less than 1 ohm, while the impedance looking into an error amplifier feedback network is normally at least 2 orders of magnitude larger than this. Hence the criteria $Z_i \gg Z_o$ is satisfied.

The practical circuit for voltage injection is shown in Figure 2. The injection voltage source is implemented with a wideband isolation device together with a resistor with a value of about 10-50 ohms. Voltage probes are used to measure the loop input and output signals, with respect to ground, on either side of the injection point.

This voltage injection technique has worked successfully at Ridley Engineering for over 20 years. In recent years, the semiconductor companies have created new controller solutions that do not lend themselves easily to voltage injection.

Current Injection

The TOPSwitch™ from Power Integrations is a product intended for low cost power supplies, integrating the power switch, bias supply, and feedback control all in one package. It has been very successful in the high-volume marketplace, leading to over \$100M in sales for the company for this and similar products.

Although the chip itself is simple, the control system formed when connected in the circuit can be quite complex. We could spend an entire issue on the complexities of modeling this type of controller, but we

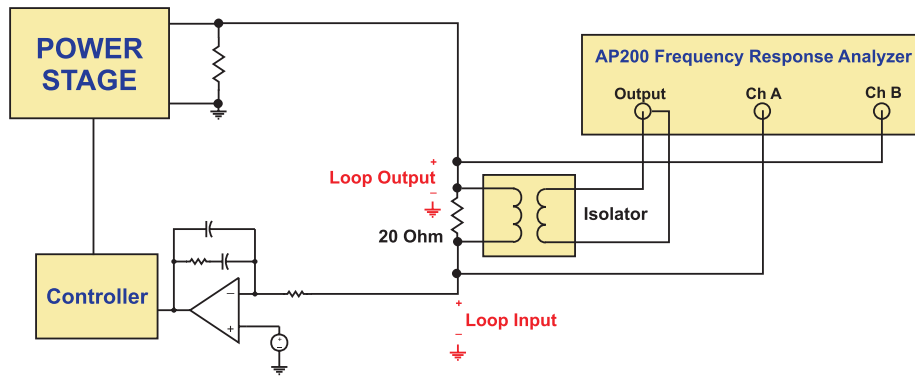


Figure 2: Practical implementation of voltage injection and measurement

will save this for a future issue. Let's just say for now that the control compensation circuit formed most certainly warrants confirmation through a loop gain measurement.

Figure 3 shows the feedback circuit recommended for use with the TOPSwitch™ controller from Power Integrations. The output is fed back and compensated through a TL431 controller, which drives the diode of an optocoupler. A two-stage filter is used on the output (you can always omit the output inductor if you choose not to use a second stage, but it is recommended for low-noise outputs.) The voltage at the load is used for the feedback path denoted *b*, which is the normal measuring point for the loop.

However, an additional feedback path *a* is also created to the anode of the optocoupler from the first stage of the output filter. In some designs, this feedback path is not significant, and the loop can be measured in the normal manner at point *b*.

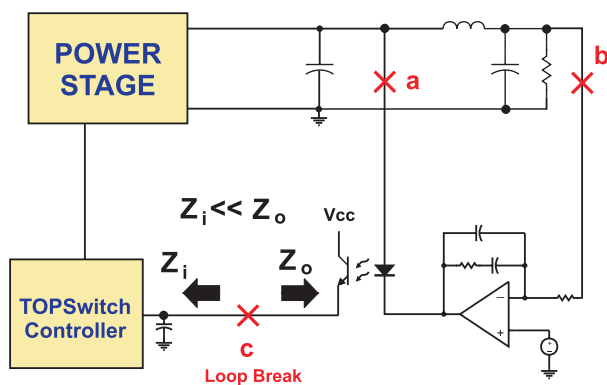


Figure 3: Feedback paths with TOPSwitch controller from Power Integrations

However, if the gain of the TL431 network approaches unity, the feedback path at point *a* becomes significant. In this situation, which is the norm, the feedback cannot be measured effectively at either point *a* or point *b*. according to feedback theory, you can certainly measure gain and phase at those points which

will tell you whether or not the system is stable. But it is very difficult to use these measurements for design since a second closed loop is embedded in the measurement.

More complications arise on the other side of the optocoupler. The secondary transistor of the optocoupler goes directly into the control pin of the controller, bypassed by a fairly large capacitor. The capacitor is needed since the control pin also provides the bias supply to the chip.

To properly understand the circuit, you need to look at the internal function of the TOPSwitch™ controller. A shunt regulator controls the input voltage to the control pin, and a series impedance, Z_c , sets the input impedance of the control pin. This is a value in the 10-20 ohm range. The value varies, but it is certainly much lower impedance than the output impedance of the optocoupler circuit which resembles a current source.

This circuit provides a single loop injection point *c* which brings together both feedback loops *a* and *b*, but unfortunately the rules for voltage injection are violated at all frequencies, and we cannot inject in the normal way.

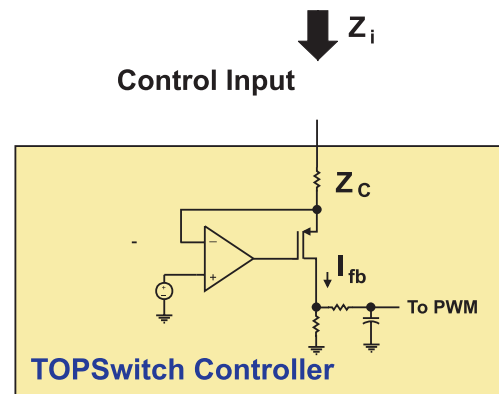


Figure 4: Control pin input impedance for the TOPSwitch controller

Frequency Response Measurement



USB port compatibility.

Designed specifically for switching power supplies, the AP200 makes swept frequency response measurements that give magnitude and phase data plotted versus frequency.

Features

Control Loops

- Avoid expensive product instability
- Control loops change with line, load, and temperature
- Optimize control loops to reduce cost and size

Magnetics

- Design and specify more reliable magnetics
- Measure critical parasitic components
- Detect winding and material changes
- Characterize component resonances up to 15 MHz

Power Line Harmonics

- Check IEC compliance for AC input systems
- Measure line harmonics to 10 kHz
- Avoid expensive redesign, and minimize test facility time

Capacitors

- Measure essential data not provided by manufacturers
- Select optimum cost, size, shape, and performance

Filters

- Characterize power systems filter building blocks
- Optimize performance at line and control frequencies
- 15 MHz range shows filter effectiveness for EMI performance

Pricing & Services

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Overseas Orders	\$13,100
Differential Isolation Probes	\$650/pair
5 Hz to 15 MHz Injection Isolator	\$595
Power 4-5-6	\$995*
*discounted price available only when purchasing the AP200	

Services:

Rental Units	\$1600/month
Consulting	\$250/hr + travel expense for On-Site \$200/hr Off-Site

Frequency Range	0.01 Hz to 15 MHz
Selectivity Bandwidth	1 Hz to 1 kHz
Output Injection Isolator	5 Hz to 15 MHz 3:1 Step Down
Input Isolation	Optional 1,000 V
Averaging Method	Sweep by Sweep
PC Data Transfer	Automatic

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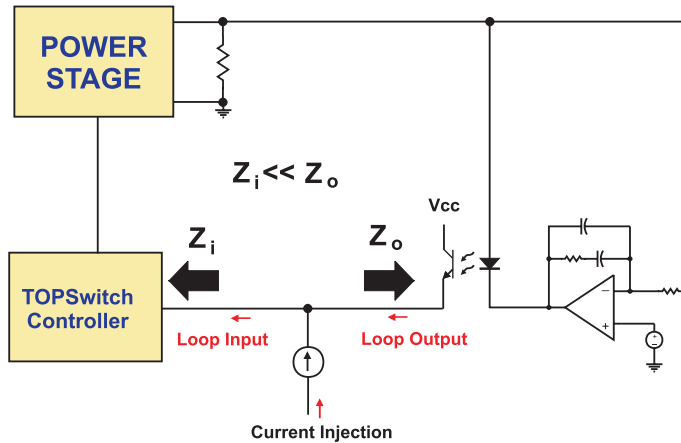


Figure 5: Current injection concept suitable for this type of control system

Fortunately, this scenario was anticipated in the early work by Dr. Middlebrook on loop injection. Rather than breaking the loop with a voltage source and measuring the ratio of two voltages, we inject a current source into the loop, and measure the ratio of two currents. This concept is shown in Figure 5.

When we inject this way, the criteria for proper measurements is the opposite: $Z_i \ll Z_o$. With the shunt voltage regulator on the input of the controller, and the emitter output of the optocoupler, this works well for this system.

Frequency response analyzers don't come with current source outputs, but it's certainly easy to make one. Just connect a resistor in series with the output voltage source as shown in Figure 6. A dc-blocking capacitor is also used to prevent disturbance of the operating point of the converter.

The loop input and output currents can be measured with the AP200 analyzer as shown with a pair of 10 Ohm resistors, and differential voltage probes. The guidelines for signal injection size are the same as for voltage injection-the injected current signal should be small relative to the dc operating point of the feedback currents to keep the converter in small-signal operation.

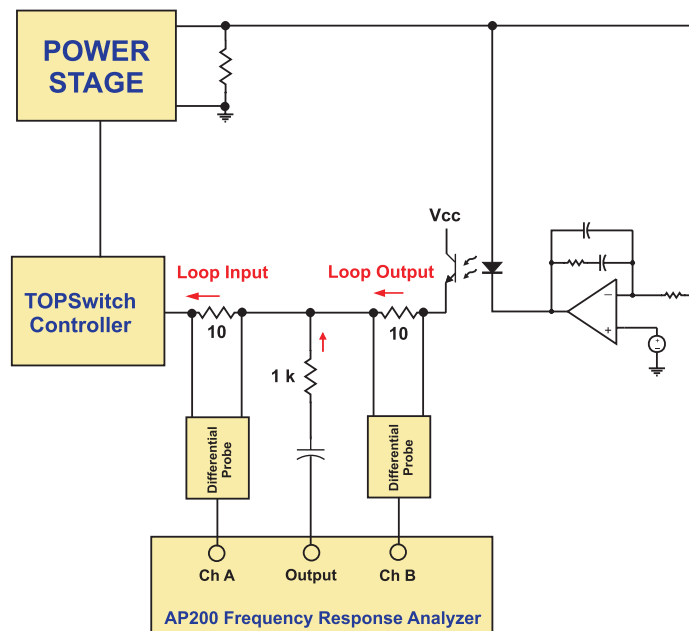


Figure 6: Practical implementation of current injection with AP200 frequency response analyzer

This method of loop injection makes the task of measurement much more versatile, and applicable to a much wider class of circuits and controllers. Many of the integrated power supply chips have followed the lead of Power Integrations is using a current-driven control input with low impedance, and we can now easily measure these converters.

As we mentioned earlier, the TOPSwitch™ is a convenient component that requires only a handful of parts around it to complete a power supply, but it creates a complex feedback system. In addition to the complications of the two-stage output and the two feedback paths around the TL431, further frequency dependent terms are created by the bypass capacitor across the control input of the TOPSwitch™, the shunt regulator dynamics, and the internal lowpass filter shown in Fig. 4. All of these contribute to the loop gain and phase, making measurement essential for a stable system.

Acknowledgements

We'd like to thank Roland St. Pierre, Field Applications Engineer for Power Integrations, for bringing this issue to our attention, and showing us how he implemented current injection for the TOPSwitch™.

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Day 1

Morning Theory

- Converter Topologies
- Inductor Design
- Transformer Design
- Leakage Inductance
- Design with Power 4-5-6

Afternoon Lab

- Design and Build Flyback Transformer
- Design and Build Forward Transformer
- Design and Build Forward Inductor
- Magnetics Characterization
- Snubber Design
- Flyback and Forward Circuit Testing

Day 2

Morning Theory

- Small Signal Analysis of Power Stages
- CCM and DCM Operation
- Converter Characteristics
- Voltage-Mode Control
- Closed-Loop Design with Power 4-5-6

Afternoon Lab

- Measuring Power Stage Transfer Functions
- Compensation Design
- Loop Gain Measurement
- Closed Loop Performance

Day 3

Morning Theory

- Current-Mode Control
- Circuit Implementation
- Modeling of Current Mode
- Problems with Current Mode
- Closed-Loop Design for Current Mode w/Power 4-5-6

Afternoon Lab

- Closing the Current Loop
- New Power Stage Transfer Functions
- Closing the Voltage Compensation Loop
- Loop Gain Design and Measurement

Day 4

Morning Theory

- Multiple Output Converters
- Magnetics Proximity Loss
- Magnetics Winding Layout
- Second Stage Filter Design

Afternoon Lab

- Design and Build Multiple Output Flyback Transformers
- Testing of Cross Regulation for Different Transformers
- Second Stage Filter Design and Measurement
- Loop Gain with Multiple Outputs and Second Stage Filters

Only 24 reservations are accepted. \$2495 tuition includes POWER 4-5-6 Full Version, lab manuals, breakfast and lunch daily. Payment is due 30 days prior to workshop to maintain reservation.

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