Measuring power supply control loop stability.

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Introduction

There is an increasing demand for high performance power systems. They are found in applications ranging from high power, high efficiency aerospace and automotive systems to very low power battery efficient systems for consumer and medical applications. Because of this demand, it is important to optimize the design of power converters to meet performance and cost targets.

Central to the overall performance of the switching power supply is the feedback control system. The control system continuously adjusts the power conversion to maintain a constant output voltage as the demand for power changes depending on the load requirements.

Usually, switching power supplies will include energy storage and electric current routing devices such as inductors, capacitors, diodes, transformers and power switches (usually low loss MOSFETS). Many (if not all) of these components are included in the control loop. Additionally, the supply is switching at a high frequency with sharp rise and fall times. Because of the high frequencies, second order effects of the components may contribute to the overall efficiency and performance (or lack of) the power system. *Please see application notes AN-1 and AN-3 for a detailed discussion of some of these parasitic effects and how to measure them.*

There are many circuit simulation packages that demonstrate the general performance of switching power supply topologies. A common pitfall is for engineers to make the mistake of assuming that the supply will perform comparably to the simulation model. Many, unfortunately, discover that the "real" circuit performance is nowhere near that of the circuit model, despite having acceptable stability as the simulation indicated. PC board layout, component tolerance stack up and parasitic effects usually go unaccounted for in the simulation model. Additionally, variations in load, input voltage and temperature could push the supply to instability.

Improved efficiency and performance can be realized by MEASURING and optimizing the open-loop frequency response of the control system.

The open-loop transfer function is best measured with a network analyzer. A network analyzer is a narrow bandwidth detector that supplies it's own stimulus frequency to the device under test. The network analyzer detectors are synchronized to the stimulus test frequency. This "tuning," allows the analyzer to measure very small signal levels even in the presence of noise. This is advantageous especially in switching power supplies where high frequency noise, large signal levels and EMI are continuously present.

Basically, a stimulus signal is injected into the control loop of the power supply with an isolation transformer. The network analyzer inputs are connected at each injection point and the differential signal between them is measured at each test frequency over a specified frequency range. The result of the measurement is plotted in the form of a Bode diagram. The Bode diagram represents the open-loop frequency response of the system in two plots: a magnitude vs. frequency plot and a phase vs. frequency plot. The primary stability parameters of phase margin and gain margin are easily determined from the Bode diagram.

The open-loop transfer function

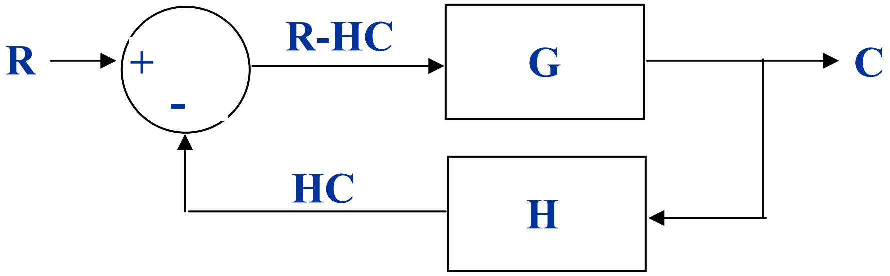


Figure 1. Classical closed-loop control block diagram.

Figure 1 depicts the textbook closed-loop control diagram. The definitions of the variables are as follows:

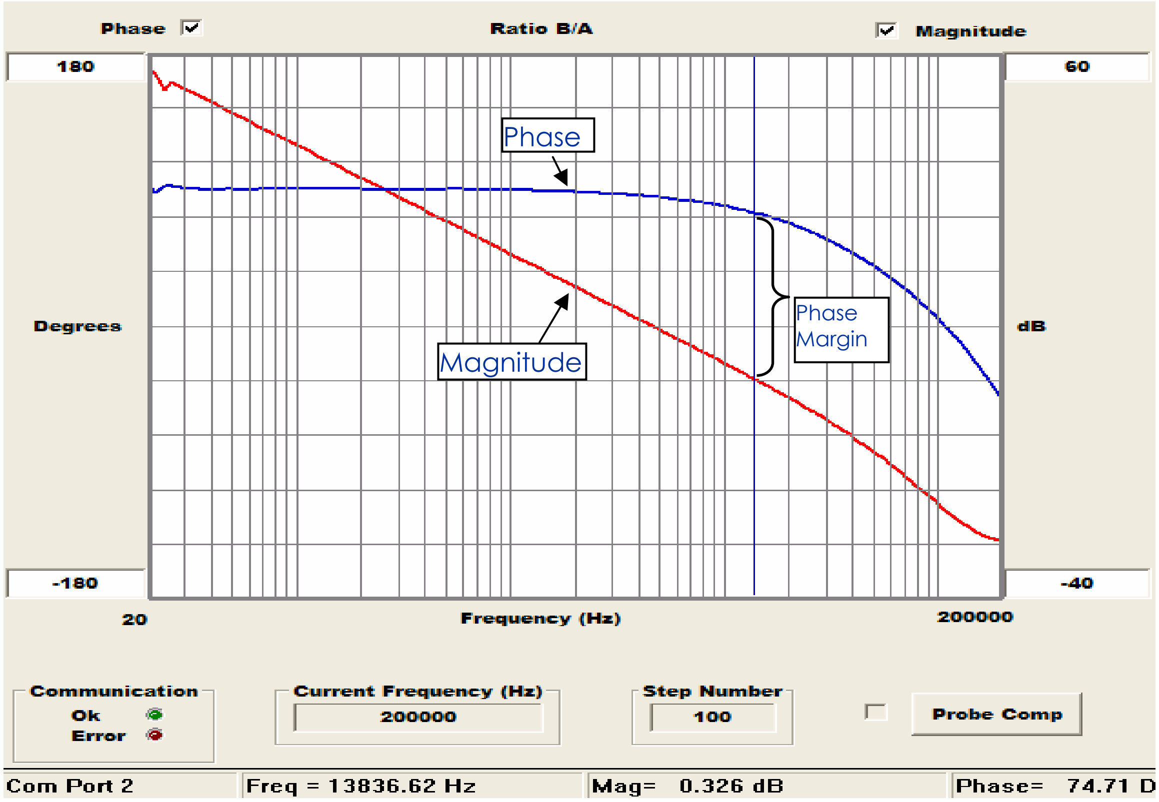
C = the controlled variable
R = the reference input or command signal
G = forward gain of the system
H = the feedback transfer function or feedback gain.

For a power supply, the controlled variable, C, is equivalent to the output voltage that is to be regulated. The feedback gain, H, is equivalent to a resistor divider or circuitry that provides a portion of the controlled variable to be fed to a summing junction. R is a reference voltage to which the quantity HC is continuously compared. G is the combined gain of all circuitry in the forward path of the system, which could consist of the pulse width modulator, power transformer, output filter and some feedback compensation components.

The open-loop gain (transfer function) is stated mathematically as:

$$OLG = G*H.$$

The open-loop gain is a vector quantity and is represented by magnitude and phase components vs. frequency.



Current Frequency (Hz) 200000

Step Number 100

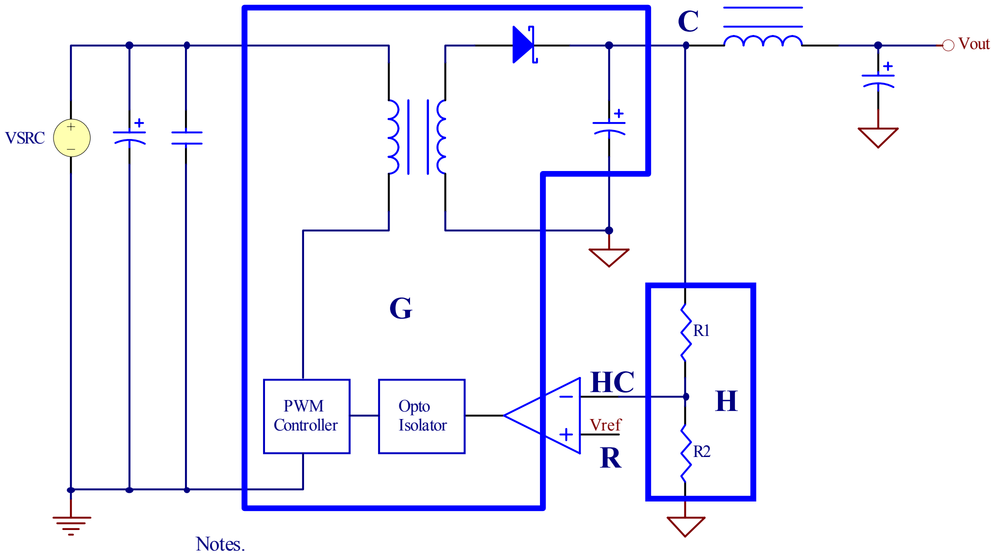
Com Port 2 | Freq = 13836.62 Hz | Mag= 0.326 dB | Phase= 74.71 D

Figure 2. Bode diagram of typical, single pole, open loop transfer function.

Figure 2 illustrates the Bode plot of a single pole, open-loop transfer function. The magnitude plot, in db, is shown in RED and the phase plot, in degrees, is shown in BLUE. The cursor (vertical blue) indicates that at close to unity gain (0 dB) the phase value is about 74 degrees. This corresponds to 74 degrees of phase margin. The low frequency response also indicates very tight regulation since the low frequency gain is very high at about 60 dB. Note that the 0 dB crossover frequency indicates the bandwidth of the system. This is similar to the gain-Bandwidth plot of an operational amplifier. The bandwidth of this system is about 13Khz as indicated on the Bode diagram. This bandwidth is an indication that the controlled output, C can respond very quickly to changes in the reference input, R.

Relating the control block diagram to the power supply and selecting a signal injection point

As an example, Figure 3 illustrates the topology of an isolated forward converter. The diagram is partitioned to show how the circuitry relates to the control system block diagram.



Notes.
G includes op-amp open loop gain, Ao.
R and HC are input to the op-amp summing junction.
R-HC, signal is embedded within op-amp.

Figure 3. Topology of an output isolated forward converter as related to a control block diagram.

A network analyzer allows measurement of the open-loop gain with the loop closed by injecting a signal into the feedback path and measuring the system's response to the stimulus signal.

At this point, a decision must be made as to where to inject the stimulus signal. This will vary depending on the topology of the power converter. Basically, the loop is opened and a low value resistor is inserted in series with the signal path at a point where the effect of the resistor is negligible. The test signal is developed across this resistor. The best location for the resistor is at a **low impedance point** in the signal path. In the example given, there are two possible locations for signal injection. The first point is between the output of the supply (**C**) and R1. The second location is between the output of the op-amp and the input of the opto-isolator. Figure 4 shows an example of signal injection using an isolation transformer and the points to be monitored (channels A and B) for measurement of the open-loop transfer function.

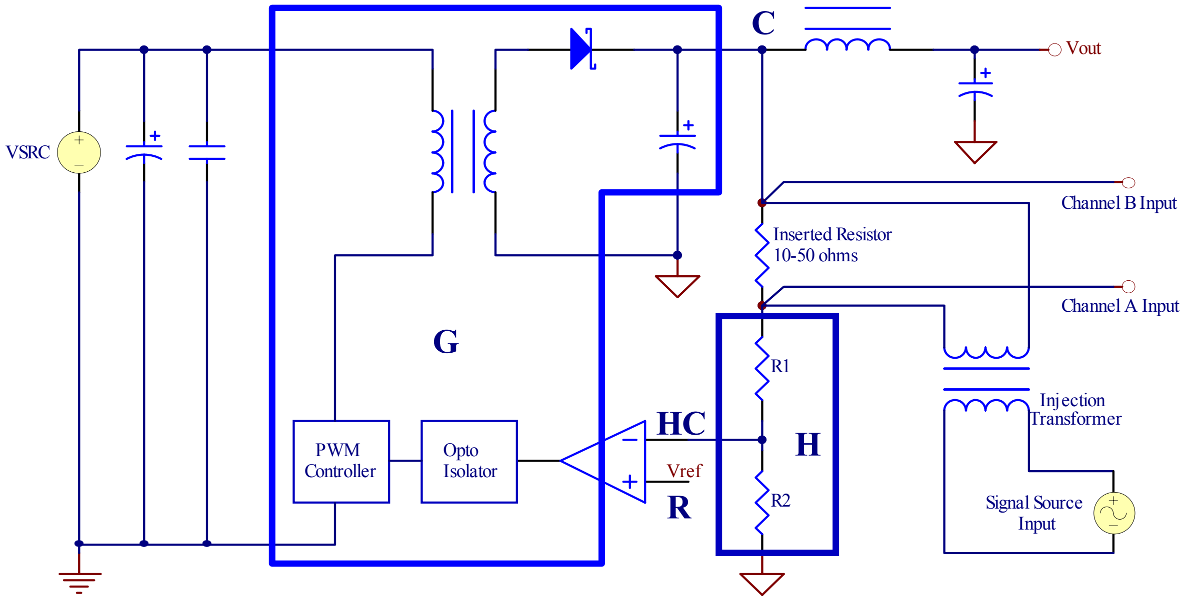


Figure 4. Example of signal injection using an injection transformer and the location of points to be monitored for measuring the open-loop transfer function.

Measuring the open-loop gain of the Texas Instruments TPS40071 Step Down Converter.

The availability of evaluation packages from several manufacturers nowadays, allows engineers to sample different systems, cost effectively, and choose the best solution.

This converter was chosen for this section of the application note because of the availability of the TPS40071EVM-001 evaluation module from Texas Instruments. It allows designers to have a point of reference when "practicing" making control loop measurements with a network analyzer. The power supply configuration is that of a buck regulator with feed forward control and output sourcing and sinking capability. The kit comes complete with a reference design on a PCB ready to test. There is also a "built-in" resistor ideal for making open-loop measurements. Control loop characteristic curves are also published in the users guide (Texas Instruments web site #SLUU180) as well as a full explanation of the circuit characteristics.

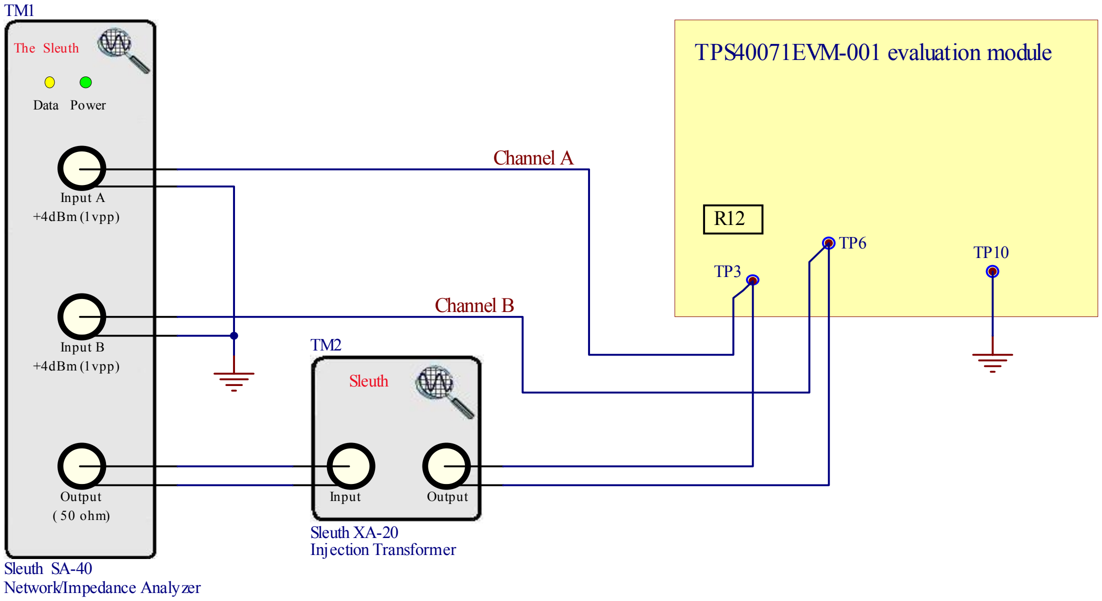
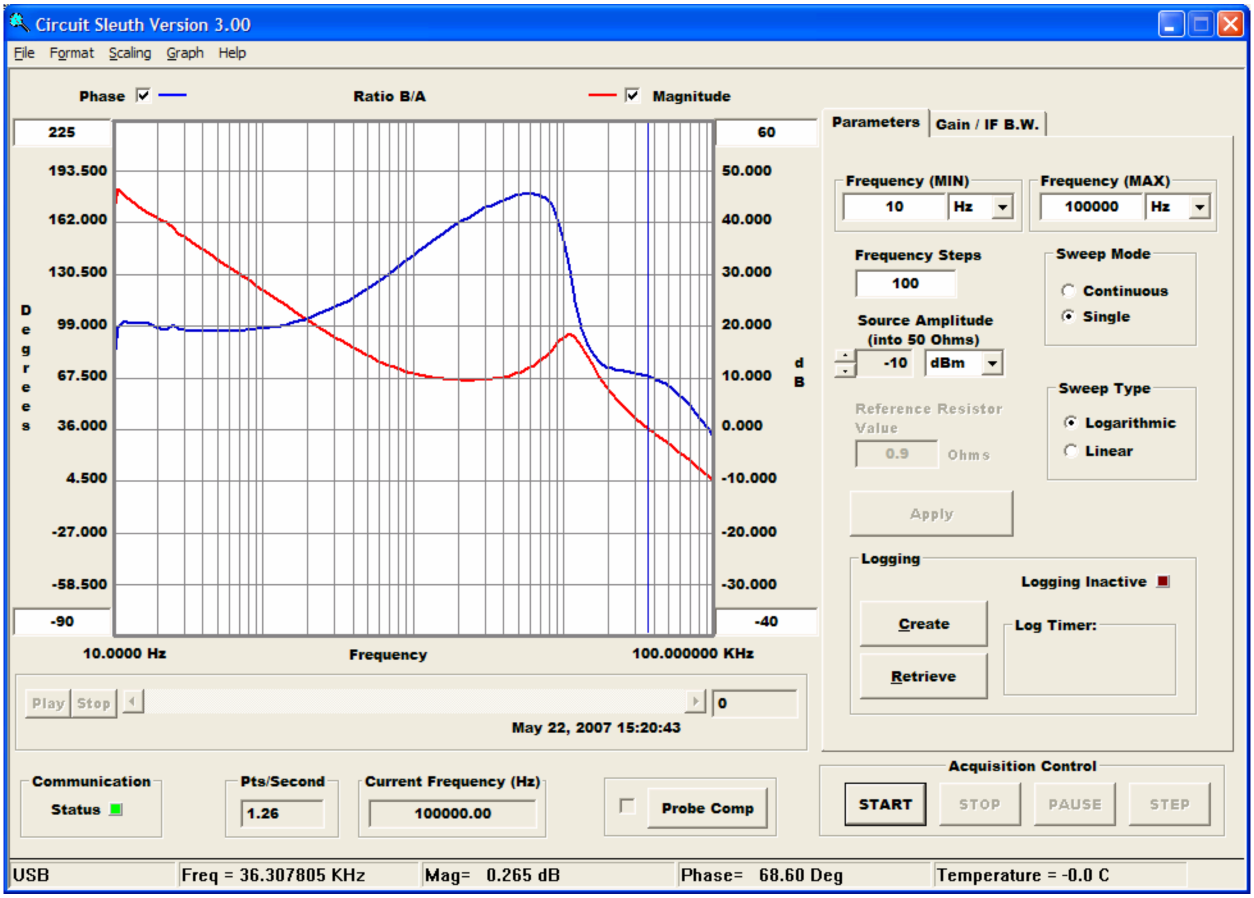


Figure 5. Connection of the Circuit Sleuth SA-40 to the TPS40071EVM with an injection transformer for open-loop gain measurement.

Figure 5 illustrates the connection of the SA-40 network analyzer to the Texas Instruments TPS40071EVM. Figure 6 illustrates the test parameters and results on the SA-40 virtual front panel.



0

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Frequency (MIN): 10 Hz

Frequency (MAX): 100000 Hz

Frequency Steps: 100

Source Amplitude (into 50 Ohms): -10 dBm

Reference Resistor Value: 0.9 Ohms

Sweep Mode: ○ Continuous ● Single

Sweep Type: ● Logarithmic ○ Linear

Logging Inactive 🟥

Pts/Second: 1.26

Current Frequency (Hz): 100000.00

☐ Probe Comp

USB | Freq = 36.307805 KHz | Mag= 0.265 dB | Phase= 68.60 Deg | Temperature = -0.0 C

Figure 6. Virtual front panel of the Circuit Sleuth SA-40 measuring the open-loop gain of the TI TPS40071EVM.

Figure 7 is a reproduction of the open-loop response of the TPS40071EVM from the users guide. Note that the plots agree near the endpoints and at the 0dB crossover. The manual cites a 50 degree phase margin at the crossover point of 45Khz. Our EVM measures a phase margin of about 68 degrees at the crossover frequency of 36Khz. Variations in manufacturing processes, test conditions and component tolerances may account for subtle differences between the data sheet and the actual unit under test. The laboratory power supply design would most likely be pushed to the limit of bandwidth, which reduces the phase margin. The production version of the unit would naturally be designed to be robust with a modest bandwidth slightly lower than the laboratory version but with more phase margin.

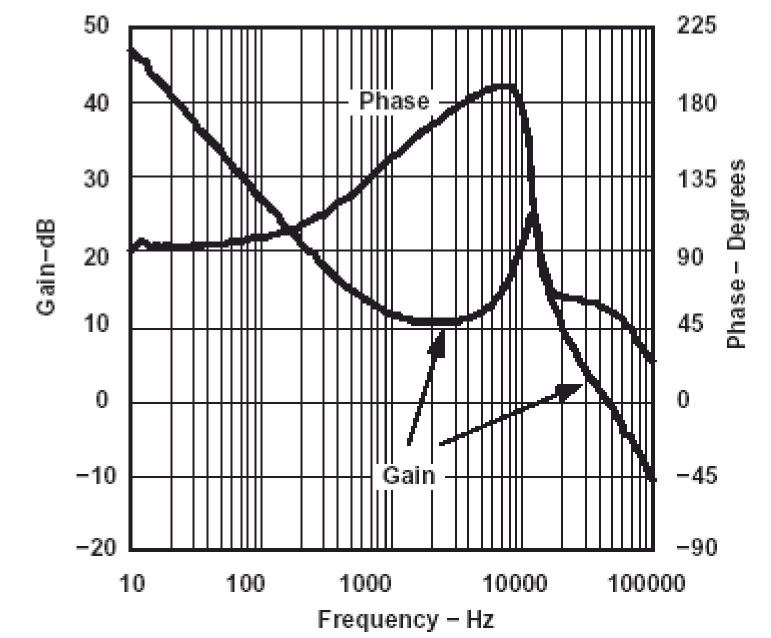

Figure 7. Open-loop gain and phase of the Texas Instruments TPS40071EVM.

Figure 7 is a reproduction of data as presented in the Texas Instruments TPS40071EVM User's Guide, "TPS40071 Step Down Converter Delivers 10A from 5-V to 12-V Bus voltages." Document number SLUU180. Copyright 2003, Texas Instruments Incorporated.

Summary

This application note describes a method to measure the open-loop frequency response (transfer function) of a switching power supply using the Circuit Sleuth SA-40 network analyzer and injection transformer.

A standard feedback control system block diagram was used to illustrate the mathematical nature of the open-loop response and an example schematic was partitioned off to show how the circuit configuration relates to the control block diagram. The schematic was also used to determine the best location in the circuit for the signal injection resistor.

Practical measurements were performed on a Texas Instruments TPS40071EVM power supply. The measurements were presented as shown on the Circuit

Sleuth SA-40 virtual front panel. The results were compared with the results of the TPS40071EVM as presented in the Texas Instruments user's guide for the module.

To meet the increasing demand for high efficiency, high performance power systems, engineers must optimize their designs to meet performance and cost targets. **MEASURING and optimizing the open-loop frequency response of the control system with a network analyzer can realize improved efficiency and performance.** A network analyzer is a narrow band detector with it's own signal source that has a high immunity to noise common in switching power supply designs. The loop is measured by injecting a test signal from the network analyzer signal source over a bandwidth of test frequencies. The loop response is measured and plotted for each test frequency and the result is a Bode diagram of the magnitude and phase response of the loop.