How to Measure the Loop Transfer Function of Power Supplies

Introduction

The regulation characteristics of most power management circuits are defined by the converter loop transfer function which can be plotted in a Bode plot. This representation of the gain of the loop as well as of the phase shift of the loop taken over frequency gives valuable information about the speed of the control loop and stability of the power supply. A Bode plot is ideally measured with a network analyzer but can also be obtained with very simple equipment available in most labs.

This tutorial will show how to measure the critical points of a bode plot with only an audio generator (or simple signal generator) and an oscilloscope. The method will be explained in an easy to follow step-by-step manner so that a power supply designer can start performing these measurements in a short amount of time.

Step 1: Setting up the Circuit

The first step is to break the loop of the power supply in order to have a point to inject a small signal and also to measure the signal going into the loop as well as coming out of the loop. Usually, the loop is broken at the low impedance output node above the high side feedback resistor in the feedback path. For a good injection point, one side of the node should be high impedance and one side should be low impedance. The injection point selected offers this combination. *Figure 1* shows a typical step down switch mode regulator schematic with the required measurement setup.
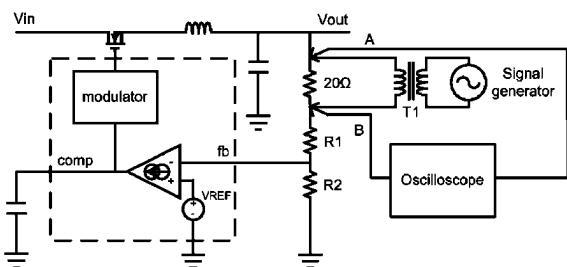
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FIGURE 1. Measurement Setup

To electrically separate the measurement points, A and B, a small resistance should be put in the feedback path. A good value is a 20Ω resistor. With such a resistor the adjusted output voltage will be negligibly influenced but the nodes to inject a small signal and measure the system are established.
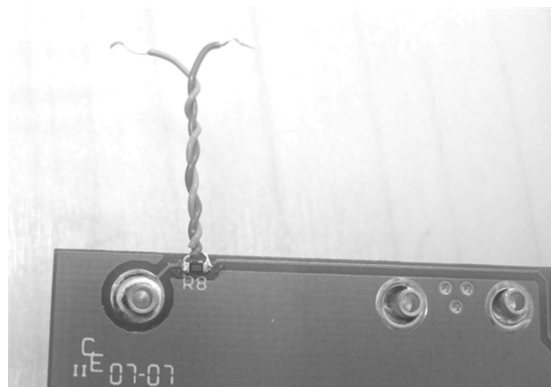
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**FIGURE 2. Suggested Preparation of the Board**

Any RC phase lead network which might exist in parallel with the R1 feedback resistor should stay in parallel with R1 and not be modified by the introduction of the 20Ω resistor.

A sound mechanical measurement structure is shown in *Figure 2*. The feedback path is broken on the PCB and a 20Ω resistor is soldered on the PCB. Some of evaluation boards may already have the spot for the stability measurement resistor prepared. On other boards it is relatively easy to cut the feedback trace on the PCB and reconnect it through a 20Ω resistor. For the connection of the two voltage probes as well as the signal injection cables a twisted cable as shown in *Figure 2* is very useful. Such a small twisted pair works very well for minimizing noise pickup which is critical for a good measurement. The tight connected twisted cable can be run for about two inches without a problem. Such a connection will help with the mechanical stress coming from the voltage probes as well as the signal injection connector while not influencing the measurement due to the tight twisting of the wires. The voltage probe ground connections should be connected at one ground connection on the power supply board. *Figure 3* shows the two scope probe connections to the board.

Step 2: The Injection Transformer

The injected signal has to be a small signal in relation to the output voltage. The injected signal should not be allowed to change the large signal behavior of the power supply, yet has to be large enough, so that it can be recognized once it travels around the loop. However it must not cause the loop to change its behavior. For example, some devices have output over voltage protection thresholds reflected at the feedback pin which should not be triggered due to the injected signal. A typical injected sine wave signal should be between 30mV and 100mV across the measurement resistor as described in step one. The exact value changes depending on the gain of the system and will vary with frequency. Start with a smaller signal first and then increase the signal if needed in order to see the injected signal. This will ensure that the signal is still considered a small signal in the application. The injection transformer is mostly used so that there is no DC connection from the tested power supply to the signal generator. There

are special transformers for such measurements available, which offer a very flat voltage transmission over a wide frequency band. When sweeping the frequency automatically such as with a network analyzer, the flat gain can be beneficial. For most applications and especially when the frequency of the injected signal is changed manually, the voltage transmission characteristic of the transformer can be balanced by changing the amplitude at the signal or audio generator. Then a transformer can be used which does not show a flat voltage transmission curve such as a very low cost standard transformer intended for a 110V to 12V off-line conversion. *Figure 3* shows such a transformer. In the schematic of *Figure 1*, *Figure 6* and *Figure 7* the transformer is labeled T1.
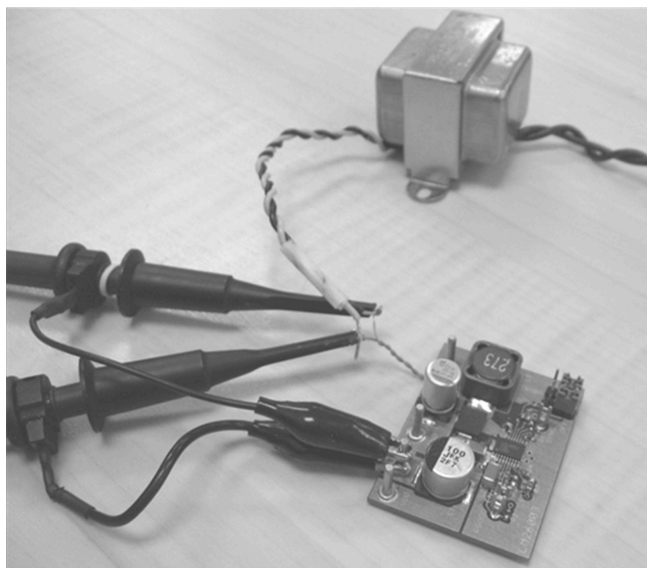
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FIGURE 3. Setup of Injection Transformer and Scope Probes on a Switch Mode Power Supply Circuit

Step 3: Preparing the Signal Generator

The signal generator should provide a sine wave signal and the output should be connected to the 110V input side of the injection transformer. Then the output voltage of the injection transformer should be adjusted with the amplitude setting on the signal generator. This should be tested at different frequencies so that the amplitude on the signal generator can be adjusted to not drive the power circuit into non-linear operation. The DC offset of the output signal of the signal generator should be set to 0V since only the AC is coupled through the injection transformer.

Step 4: Hooking up the Oscilloscope

The oscilloscope may be analog or digital. It is important to have two calibrated scope probes with the same attenuation to simplify the measurement. Adjust both channels to the highest resolution possible and set AC coupling.

In order to avoid switching noise filling the oscilloscope screen and to focus on the waveform of interest, set the scope to bandwidth limiting. To get a well triggered picture of the sine waves one can trigger off a third channel which is attached to the signal generator. Triggering directly on channel A or channel B might be difficult due to the high frequency switching

noise pickup. When triggering on the signal generator directly, such problems are avoided. Also, this way the trigger will not have to get readjusted with changing amplitudes of channel A and B.

Step 5: Preparing the Power Supply

The power supply has to be put in the condition in which the stability test should be performed. This means powering up the board and attaching a load to the output. *Figure 3* does not show these cable connections to keep the picture simple. It is always a good idea to perform a stability measurement with different load and line conditions. At low output loads most power supplies will go into discontinuous current conduction mode which exhibits different loop characteristics. Also in voltage mode converters without input voltage feed forward, the loop characteristics will change with input voltage. Before a measurement can be taken, make sure to attach the signal injection transformer across the frequency injection resistor of the power supply and to attach the two voltage probes of channel A and B. The ground of both scope probes should be attached to a common ground connection on the power supply under test.

Step 6: Taking the Measurement

After setting up the equipment and powering everything up, the scope will probably show one line on one channel and a sine wave on the other channel. If there is no sine wave visible, either the scope is not set to the highest amplitude resolution (typically 20 mV per division) or the amplitude of the signal generator is set too low. Once a sine wave is visible, changing the frequency of the signal generator will lead to a change in amplitude on channel A and channel B. There will be a certain frequency when the sine waves of channel A and channel B have the same amplitude. This is the point where the gain of the loop is 1. The amplitude of the signal injected into the system is the same as the amplitude of the signal after being fed through the loop. The frequency set by the signal generator at which this happens is the frequency of the 0dB crossover of the system.

Figure 4 shows channel A and channel B on the oscilloscope screen when both waveforms have the same amplitude. This is the 0dB frequency.

20µs/DIV
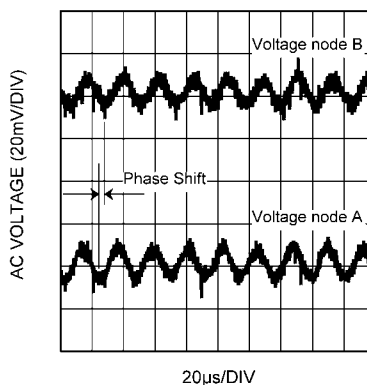
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FIGURE 4. Measurement Showing 0dB Crossover

Typically, the two sine waves are phase shifted to each other. The amount of phase difference of the two signals is the phase margin at the 0dB crossover frequency. Besides the 0dB crossover point, other measurement points at lower fre-

quencies may be taken. The amplitude difference between channel A and channel B gives the gain at the frequency the signal generator is set to. The table below helps with the voltage difference and the corresponding value in dB according to the formula: dB = 20log A/B.

TABLE 1. Commonly Used dB Values

dB level	Voltage ratio
-30dB	0.03162
-20dB	0.1
-10dB	0.3162
-3dB	0.7071
0dB	1
3dB	1.414
10dB	3.162
20dB	10
30dB	31.62

In order to take a full bode plot, the signal generator frequency is swept and at different points the gain as the amplitude relationship between the two channels and the phase shift are measured. Depending on the oscilloscope used for the measurement and the gain of the loop, it might be very difficult to see points of the bode plot with very large or very small gain. For 30dB for example, it is quite difficult to see a voltage relationship between channel A and B of a factor of about 32. For typical designs the most important points of a bode-plot such as the 0dB crossover point can easily and relatively accurately be measured. At high gain frequencies, it might be difficult to see the exact dB value, but a quantitative observation such as 'the gain is very high and probably above 30dB' can easily be made.

Loop measurements can only be taken successfully on a design which does not oscillate or is not in some sort of hysteretic over voltage protection mode. To achieve a stable design for measurements to be taken, one can use the following trick on current mode control designs. Place a large capacitance from the compensation pin to ground in designs where the error amplifier is a transconductance amplifier and from the compensation pin to the FB pin in designs were the error amplifier is a standard voltage to voltage error amplifier. A capacitor value of 1 µF will typically work well. It will set a pole at very low frequencies and force the gain to drop quickly so that the 0dB crossover is at a very low frequency as well. In current mode control designs, the phase margin at very low frequencies is usually enough to yield a stable design. This way plant gain measurements can be performed.

This measurement is only good for getting a compensation to output plot showing the power stage transfer function. This transfer function helps when selecting the right compensation components for the loop.

Step 7: Analyzing a Bode Plot

The most important measurement is the 0dB crossover of the gain. It provides information about the bandwidth of a power supply as well as the phase margin of a system.

System bandwidth can be considered as a combination of the level of DC gain as well as a the frequency of the 0dB crossover. When looking at the phase shift of channel A versus channel B at this frequency, one measures the phase margin of the system which is used as an indicator of the stability margin of a power supply. Depending on how conservative a design is, a minimum phase margin of 45 to 50

degrees is necessary. More is better. *Figure 5* shows a typical bode plot taken with a network analyzer. It is taken from a current mode step down switch-mode regulator.
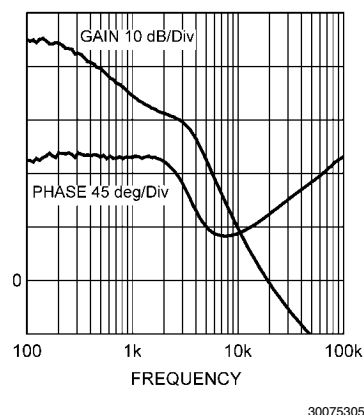

FIGURE 5. A Typical Bode Plot of a Step-Down Voltage Mode Switching Regulator

Also the frequencies of the plant poles and zeros can be found. This can help in selecting power stage components and compensation components.

Measuring the Plant Transfer Function

Besides the measurement setup of *Figure 1*, the channel which measures the injected signal going into the loop can also be attached to the compensation pin of a power supply design such as shown in *Figure 6*. In this setup the transfer function of the plant is measured without the influence of the compensation network attached to the compensation pin. This provides valuable information about the power stage. With this information it is easy to select optimized compensation components for a desired bandwidth and phase margin of a converter.
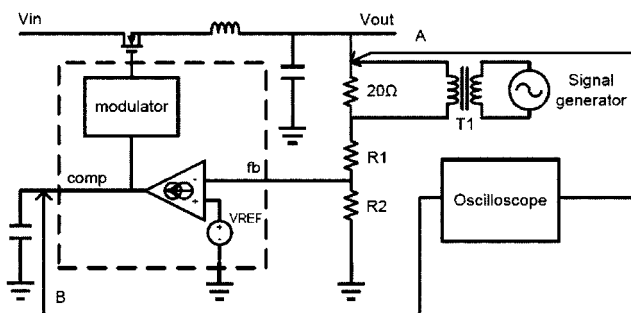
FIGURE 6. Setup to Measure the Plant of a Converter

Measuring in Cases with a Special Output Stage

As mentioned in step one of this document it is necessary to have an injection node in the loop which has a low impedance node on one side and a high impedance node on the other side for placing the injection resistor and attaching the voltage probes for the measurements. In typical fixed output voltage power supply designs, the best point to inject this signal is

between the output voltage and the high side feedback resistor. There are other designs where such a point is not available. One example is a fixed current source power supply to drive LEDs. The loop of interest is regulating a current through a string of LEDs. The current is measured with a high side current sense block which is sensing the LED current and is translating it into a voltage for the feedback node. To produce a place in the feedback path which has one side low-impedance and the other side high-impedance, the operational amplifier OP1 is added into the feedback loop as a buffer. If this amplifier is selected to be faster than half the switching frequency of the converter, the influence of this additional stage on the loop should be minimal. *Figure 7* shows such a loop stability measurement setup.

Summary

A real network analyzer which sweeps the frequency of an injected signal automatically and computes the phase difference and the gain between channel A and channel B on the fly is nice to have and very convenient. However, measuring the control loop of a power supply can be done with basic lab equipment such as an oscilloscope, a simple signal generator and a very inexpensive standard transformer. In addition to line and load transient evaluation of a power supply, very useful data can be taken when performing these measurements such as the phase margin of a power supply design. When taking multiple measurements at different frequencies, a basic bode plot can be drawn without the use of expensive equipment. At the very least some sense of the accuracy of gain calculations can be obtained.

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FIGURE 7. Setup with Artificially Generated Injection Node

Notes

Notes

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