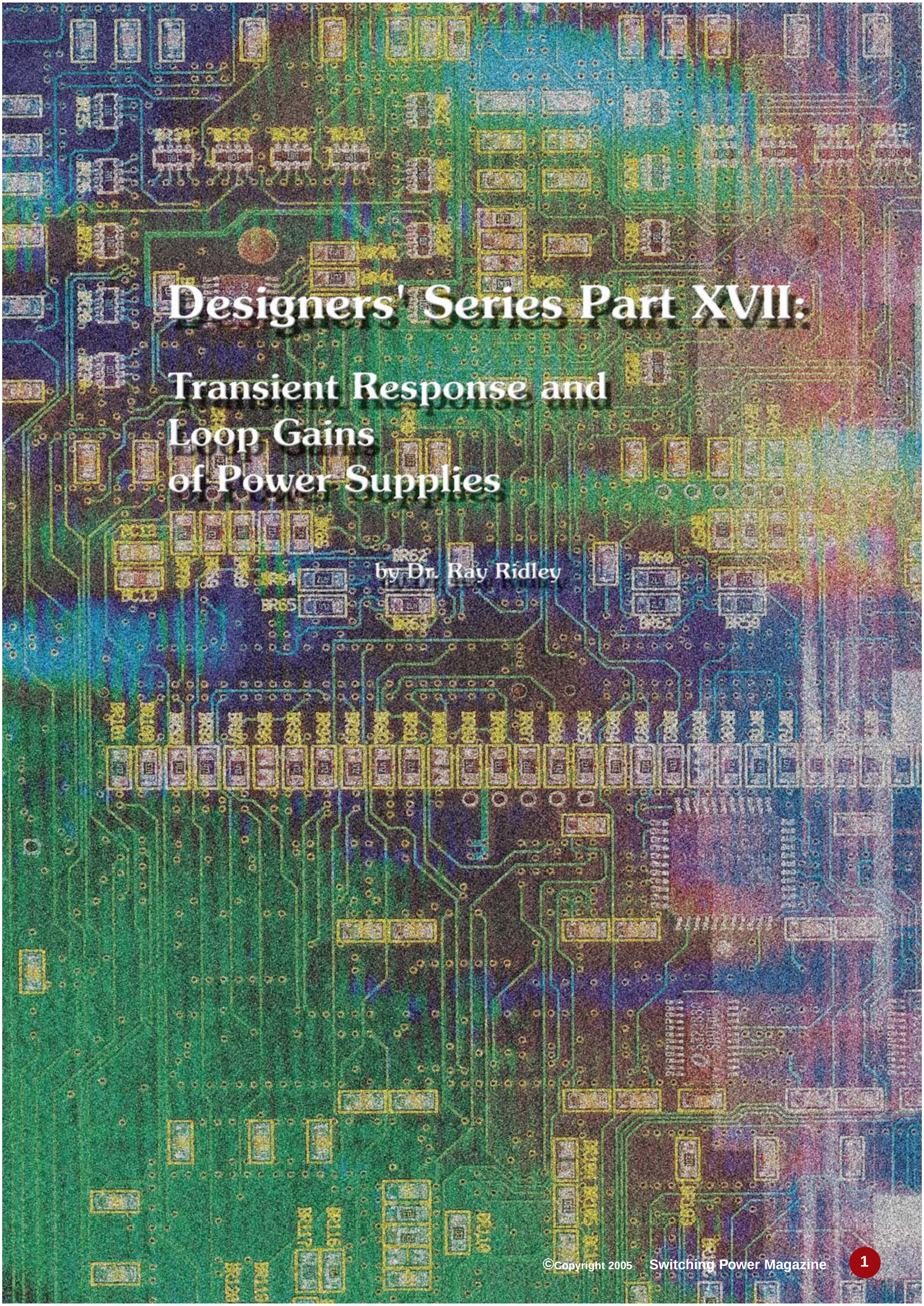

Designers' Series Part XVII:

Transient Response and Loop Gains of Power Supplies

by Dr. Ray Ridley

Proper design of a converter's feedback loop is a crucial step in making a rugged power supply. Yet it is still a fact that many power supply designers do not make proper loop gain measurements needed for fast and reliable designs. The reasons are varied-lack of time, knowledge, or budget to purchase the right kind of equipment.

Many old-timers in the industry claim that they can see all the characteristics necessary by just looking at the transient response, and that there is no need to make loop measurements at all. This misconception can often lead to expensive errors in design, long and expensive time delays in product development and instability in the field.

Because I hear this claim often, I decided to set up some test cases. Through these test cases, I will illustrate how much trouble it can cause.

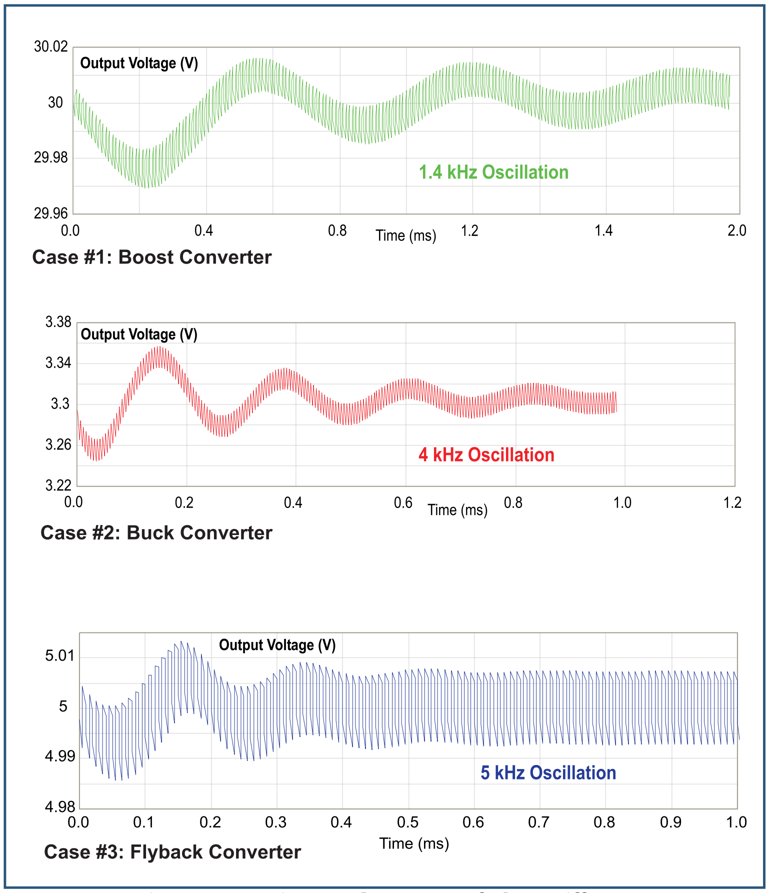

Figure 1: Transient Load Response of Three Different Converters

Power Supply Transient Response

If a feedback loop has inadequate phase margin, it will result in a system that has complex poles in its transfer functions. There are numerous text books you can read on this topic, relating phase margin of systems to pole locations, but I will not cover the math involved in this article. Instead, I'll focus on waveforms measured on converters, and how to stabilize the systems.

Figure 1 shows a step load transient response for three different power converters. There are numerous ways to apply step loads. The simplest is a switch in series with a resistor to turn incremental loading on and off. A standard mechanical switch, however, suffers from switch bounce. For this reason, a fast acting semiconductor (such as a FET in series with a resistor) is generally preferred to apply a step load. The FET is usually driven with a signal generator that allows flexibility of repetition rates for transient testing.

The waveforms of Figure 1 show different amplitude and frequency damped oscillations. The first converter, a boost supply with current-mode control, has a 1.4 kHz oscillation. The second, a buck converter with voltage-mode control, has a 4 kHz oscillatory response, and the third, a flyback with current-mode, a 5 kHz response.

As proponents of transient response will immediately tell you, each of these converters has inadequate phase margin. Transient responses can certainly predict this. At the crossover frequency of the loop, we can even extract the actual phase margin estimate from the duration of the ringing, or from its damping coefficient obtained by observing the waveforms.

So far, so good– but what next? Unfortunately, while the transient response gives us a single data point of the loop gain (the 0 dB, or crossover point) it does NOT tell us what to do next.

NOTES

Each of the oscillatory transient responses indicates a power supply that is nearing instability. But what should you do to fix it? (a) Decrease the Gain? (b) Increase the Gain? (c) Something Else? The answer is different for each case. Looking at the transient response tells you to do something, but offers no guidance as to what to do.

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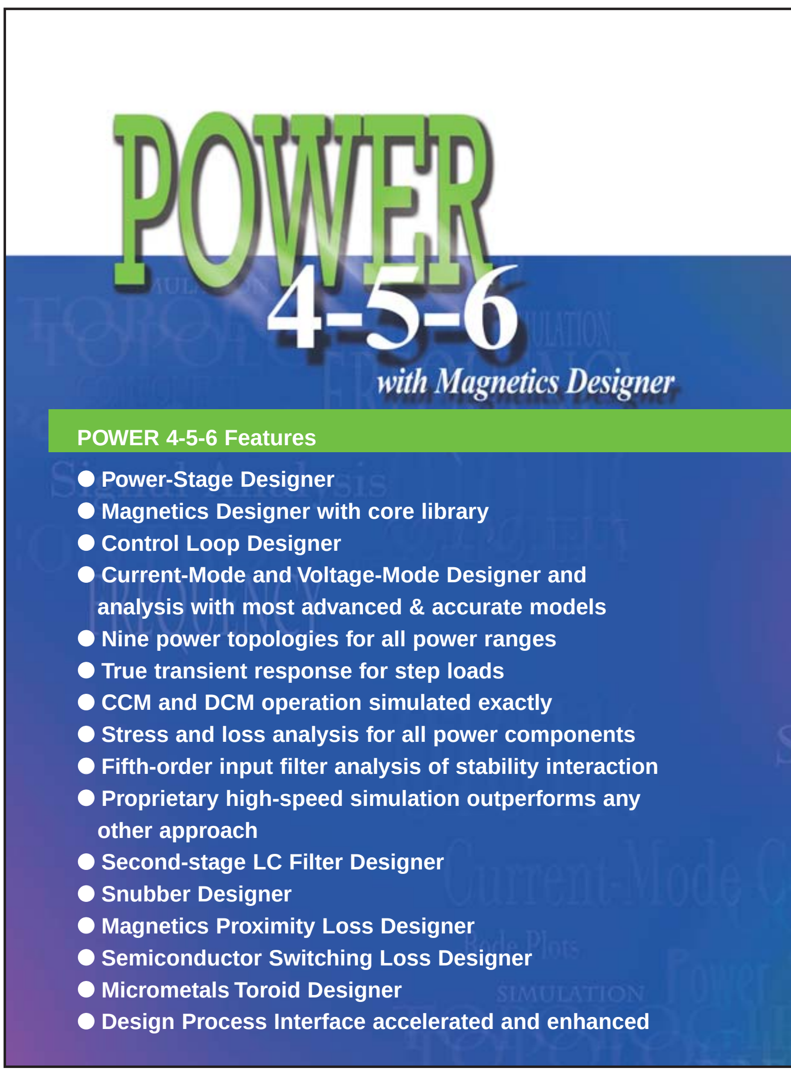

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For each of the first three examples, the solutions to make the loop stable differ. Although the three responses are similar, the strategy for redesigning the loops are different as well.

NOTES

There are many cases where the transient response does not even tell us the phase margin of the loop. A system can have a completely stable control loop, and still have an oscillatory transient response. For example, consider a power supply with extremely low output impedance, and a very stable loop. If an additional LC filter is added to the output of the power supply, and not properly damped, a step load will result in an oscillatory response.

Case #1 - Too Much Gain

The classic case where transient response testing might actually work well is when the converter loop gain is too high, and the phase margin is insufficient. Whenever we see oscillations, it is a common approach to reduce the gain of the loop to the point where the phase margin improves sufficiently to stabilize the system.

Figure 2a shows the initial transient response, with a 1.4 kHz oscillation. A reduction in gain of the loop by a factor of 2 results in the waveform of Figure 2b. The reduction in gain is sufficient to stabilize the system. Transient response testing in this case works ok, but how do we know that the system has been optimized? There is no way to assess this without looking at the loop gain directly.

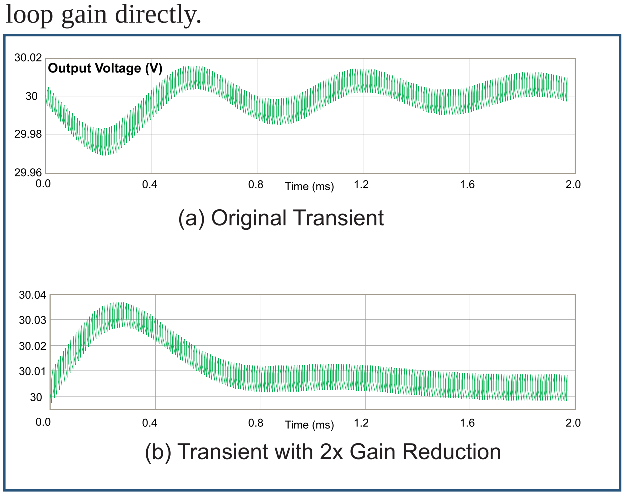

Figure 2: Transient Load Response of Boost Converter (a) Before and (b) After Gain Reduction.

The loop gains of Figure 3 gives us much more insight into this simple case. The green curve shows the original gain, the red curve the decreased gain. The phase margins at the crossover frequencies give us the characteristic transient response. For the final red curve, looking at both lower and higher frequencies, we can see that the loop is closer to optimum. The gain decreases uniformly with about a -20 dB slope after the crossover, and at the same time, the phase drops quickly. This is indicative of a system with a RHP zero, and there is little we can do to change the compensation for this system.

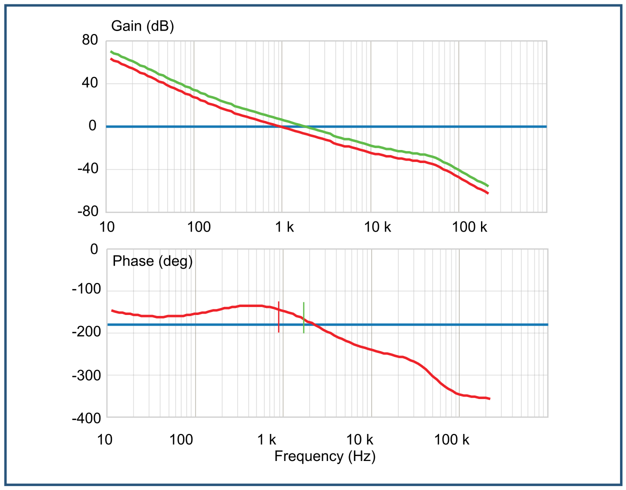

Figure 3: Loop Gain and Phase of the Boost Converter.

The value of looking at the loop gain directly is that we get full information at all frequencies, not just the crossover frequency. In this case, we see that the gain at frequencies below the crossover increase to a high level. This provides optimum noise rejection at these frequencies.

Case #2 - Too Little Gain

Figure 4 shows a case where reducing the gain does not help improve the stability. In fact, as can be seen from Figure 4b, the oscillations become worse as the loop gain is reduced. We could, of course, reduce the gain even further, but transient response information would show oscillations due to the LC filter of the converter ringing when the gain is very low. It would be impossible to continue to reduce the gain, and obtain good design information from the transient response alone.

Figure 4c shows the transient response when the gain is *increased*. While there is evidence of overshoot, the response does not show any ringing, indicating that the converter is stable at the selected crossover frequency. There is no indication from the transient response as to how we might eliminate the overshoot. Changes in gain alone cannot achieve this.

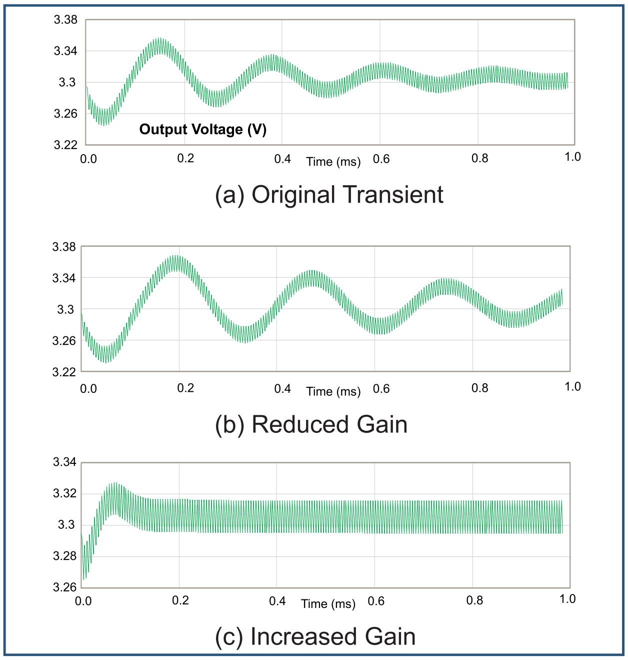

Figure 4: Transient Load Response of Buck Converter (a) Before and (b) After Gain Reduction.

Figure 5 shows the loop gain for this converter. The green curve shows the original gain and phase of the loop. The phase has a sharp dip at the resonant frequency of the converter, and if the gain is too low, the phase margin is insufficient. As the gain of the loop is increased, the phase margin actually improves. The blue curve shows the loop with increased gain. This is the opposite situation to Case #1 above.

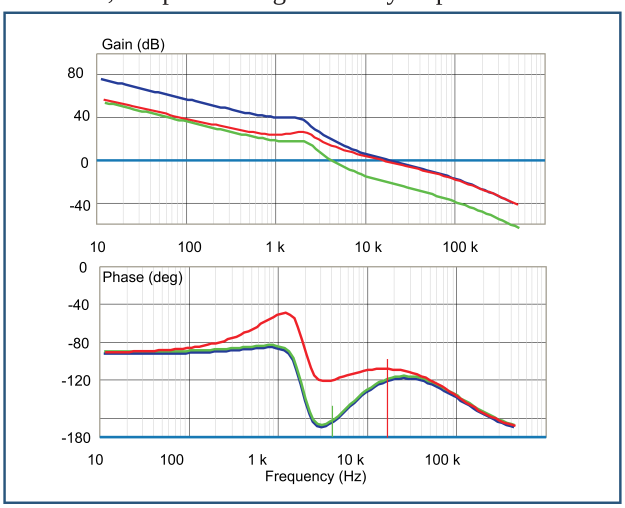

Figure 5: Loop Gain and Phase of the Buck Converter.

NOTES

Only a loop gain measurement gives full information at all frequencies. A transient test only provides indirect information about the phase of the loop at the crossover frequency.

We can see that the phase reaches a maximum value at around 30 kHz or so. Experience tells us that this is too high a frequency for crossover for a 100 kHz converter. In order to improve phase margin further, and eliminate the overshoot, it is necessary to reshape the loop gain characteristic, as shown by the red curve. In this case, the gain of the loop is lower at low frequencies, and equal to the blue curve at high frequencies. This has the effect of raising the phase response in the region where it is needed.

Figure 6 shows the transient response of the converter after the loop gain has been fully optimized. Overshoot is removed from the waveform. Even with 20 years experience in designing loops, I would never have been able to achieve this response just by looking at the transient data. But, with full loop gain information, I can recompensate within a few minutes.

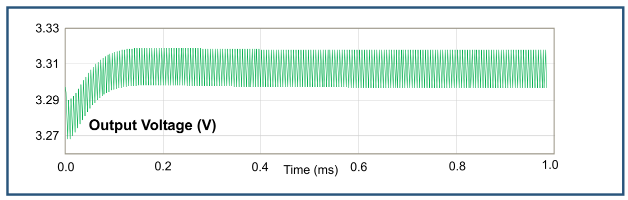

Figure 6: Transient Response of the Buck Converter with Optimized Loop Gain.

Case #3 - Incorrect Loop Shaping

Figure 7 shows a case where reducing the gain does not help improve the stability, and neither does increasing the gain.

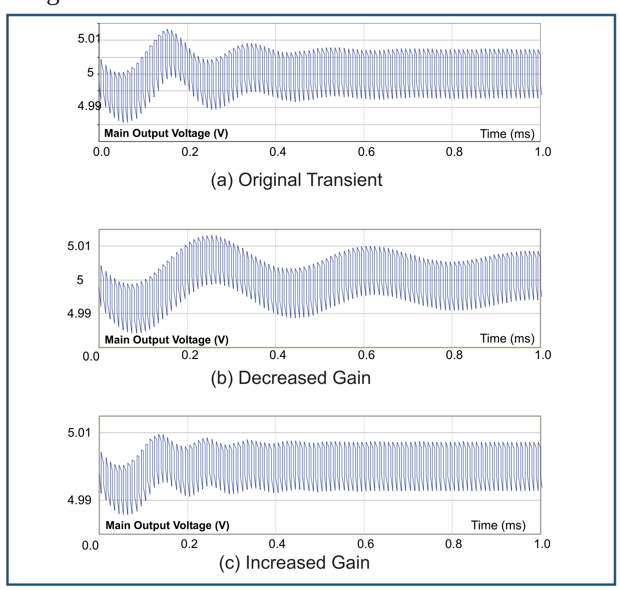

Figure 7: Transient Load Response of Flyback Converter (a) Original Gain (b) Decreased Gain (c) Increased Gain.

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As you can see from Figure 7b and 7c, merely changing the gain of the loop does not stop the converter from oscillating. The converter rings less at a higher gain, but it is still unacceptable. How can you use this information to shape the compensation properly? Well, you can't. There is not enough information to execute a proper design. An experienced designer may decide to move around compensation parts. With enough time and luck, this approach may achieve a stable response, as shown in Figure 8.

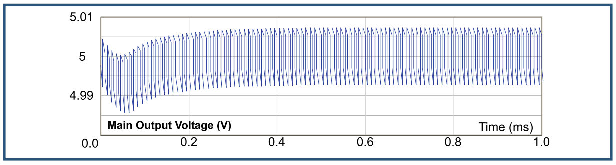

Figure 8: Transient Response of the Flyback Converter with an Apparently Optimized Loop Gain.

However, when we look at the loop gain response, it is clear what is going on with this system. The final design, shown in green, has an increased gain at high frequencies, and has been reshaped to improve the phase. The transient response suggests that the system is completely stable, and the design is finished.

Pending disaster can be seen in the loop gain plot in Figure 9. The gain flattens out just beyond the crossover

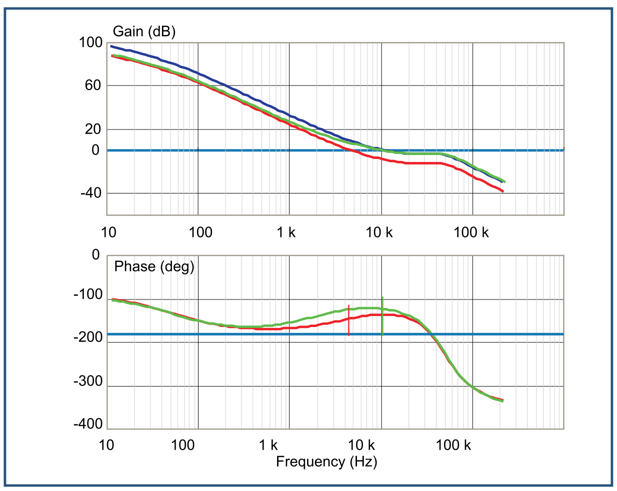

Figure 9: Loop Gain and Phase of the Flyback Converter.

NOTES

Trying to arrive at the optimized loop gain with only transient response data is not possible. You might be able to find a stable operating point, but never really know whether the system is performing as well as it could.

frequency, and a small change in control parameters, (component tolerance, optocoupler gain variation, etc.) can cause the gain to increase, and the phase margin to be quickly lost. Only the loop gain can give this information, and assure a properly stabilized system that will remain stable in production, and over its full lifetime. The final design for this system must reduce the green loop gain to achieve better gain margin.

How much does it cost to not have the right equipment for your power supply development? Take the projected peak production rate of a current project and calculate the amount of revenue generated at that rate for the amount of time your product development will be delayed due to the lack of equipment.

NOTES

In this article, I have presented very simple design examples. These examples illustrate that transient response is simply not adequate data for properly stabilizing control loops. And these are ideal cases. Changes in gain do not suddenly alter the phase response of the error amplifier, for example. Nor do they introduce noise that suddenly changes characteristics. These are events that are common in real life. You may have a power supply that requires increased gain for stability. But as soon as you change compensation components to increase the gain, the limits of an amplifier are reached, and the phase margin becomes worse. On the loop gain plot, this effect will be obvious. With a transient measurement only, all that will be evident is that the system is oscillatory before and after increasing the gain. It will not tell you why.

Loops are often far more complex that those described here. In our last issue of Switching Power Magazine, we showed how complex the very popular TL431 compensation scheme is. Simply increasing gain is a complex affair. Trying to change the compensation without measurements is a very risky thing to do.

The bottom line is, you cannot expect to properly compensate a power supply without frequency response measurements. If crude dc regulation is all you need, then guessing the compensation with transient measurements may suffice. I certainly see plenty of examples of application notes and designs with very poor responses.

If you are serious about a stable, rugged, and fast power supply, a frequency response analyzer is a necessity. If the objection is cost, consider the cost of product development delays due to instability-or worse-failure in the field after production.

An interesting book on the topic of product development delays is Accelerating Innovation: Improving the Process of Product Development1, by Marv Patterson. In this book, Mr. Patterson points out that a delay in product development costs a company an equal amount of time of peak revenue generation, and this number far exceeds the cost of engineering time. During a product design cycle, if done properly, the loop design process will take no more than a couple of days when you have the proper test equipment. Without the proper knowledge and equipment, it can take months - sometimes resulting in a cancelled project.

NOTES

Transient data can indicate a power supply is very stable when, in fact, a small change in parameter values can easily make it unstable. Only the loop gain can predict this type of event.

1. Accelerating Innovation: Improving the Process of Product Development, Marv Patterson, Published by John Wiley & Sons, 1997, ISBN: 0442020651. Available from Amazon.com
2. For information on frequency response measurements, please visit: http://www.ridleyengineering.com/analyzer.htm

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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
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