Frequency Response Measurements for Switching Power Supplies

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ABSTRACT

Frequency response papers typically focus theoretical and mathematical aspects of modeling. Rarely mentioned is the essential need to make measurements of the resulting system to ensure stability. In the real world of design and product development, measurement of frequency response is far more important than theoretical modeling. When designing a product for modern quality standards, careful measurement of control loop stability is required to minimize risk.

I. INTRODUCTION

Most papers on frequency response concentrate on theory and modeling. This has the unfortunate result of leading engineers to think that modeling is the most important step in designing a control loop, and that the hardware will work reliably as predicted if the modeling is done.

The reality is that modeling is a useful and valid step, but it is also vitally necessary to measure control loop stability with a frequency response analyzer. Why? There are several reasons:

1. *Modeling has limitations in predicting hardware response – the models are often wrong!*
2. *Measurements almost always differ from predictions.*
3. *Risk is high in shipping a product without loop stability measurements.*

It's not that the theory of modeling is necessarily incorrect. But component values are often inaccurate and incomplete. PCB layout, temperature effects, and component parasitics, which appear minor, can have a major impact on control loop stability.

One way to think of it is this - measuring the stability of the power supply control is as important as using your oscilloscope to measure peak voltages and currents on critical semiconductors. No experienced designer would depend upon the results of simulation to fully predict critical circuit waveforms. The same philosophy should apply to control loop stability.

II. CIRCUIT MODELING

Modeling of power converter circuits started in earnest in the late 1960s at Caltech [1]. Why? Because observations on the hardware showed phenomena that were unexpected, and which caused hardware failure. This led to the development of the theory of state-space averaging, which quickly became the standard way to analyze power conversion circuits.

In the 1980s, simpler methods replaced state-space averaging in the form of the PWM switch model [2]. Different versions were created for the proliferation of new circuits and technologies that came along in the 1980s and 1990s [3], (PWM, resonant, soft-switched, quasi-resonant, etc.).

The PWM switch model works better than state-space averaging and is much easier to apply. Fig. 1 shows a typical equivalent circuit that results from this kind of analysis. This circuit diagram can be used with a circuit analysis package such as PSpice to generate the transfer functions that can be measured on the ideal equivalent PWM converter circuit, in this case a flyback converter.

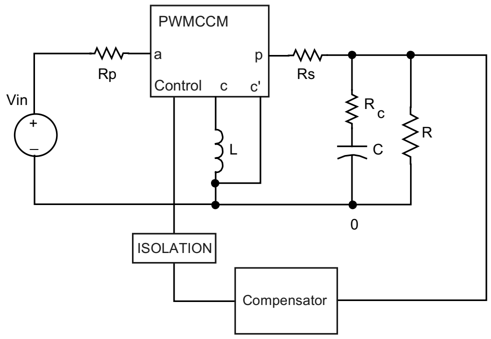


Figure 1. PWM switch model in flyback circuit. Simple linear circuits replace the switching action of the real circuit.

These models have their strengths and uses, and help designers in their work. And, in almost all of the papers that derive models, measurements are used to confirm the validity of the work [1-4]. This leads naturally to a conclusion for the reader– modeling is accurate and sufficient.

What the modeling papers don't tell you is the amount of effort that goes into the test circuits to make sure that measurements and predictions agree closely. For example, the converter is always operated in the center of its range, and noise is completely eliminated from the system. This often requires converter grounding setups and instrumentation that may be completely unrealistic in practical production power supplies. When you measure a real production supply, it is often extremely difficult to get it to conform closely to the published theory.

III. MODEL BREAKDOWN

There are two main reasons why modeling frequently fails for a circuit:

1. *The model is not detailed enough to account for the circuit operation.*

2. *The circuit elements of the model are not accurately known or modeled.*

Examples of circuit operation that can cause the model to fail are:

1. *Discontinuous conduction mode operation (and associated ringing waveforms after diode shuts off).*

2. *Snubber operation, especially lossless snubbers.*

3. *Light load operation, especially for current-mode control.*

4. *High-ripple circuits such as flyback converters.*

5. *Control system noise and ripple.*

6. *Propagation delays.*

7. *Semiconductor nonlinearities – diode offsets, junction drops, etc.*

8. *Multiple output converters.*

9. *High and low temperature operation.*

If you look through this list, and your circuit has none of these issues, the models can be very accurate, assuming you meet the second criteria of using the correct component parasitics. Unfortunately, almost every real converter built for production has at least one of these characteristics. Which gets back to the main point of this paper – measure your power supply control loop stability!

IV. FREQUENCY RESPONSE ANALYZER FUNCTIONS

So what is required to measure the control loop of a power system? Basically you need an oscillator to inject into the circuit, and two test channels to measure the response. There are several functions needed to do the job properly:

A. *A sinusoidal oscillator output signal of adjustable size that is swept over several decades automatically.*

B. *An accurate measurement algorithm that compares the signals for gain and phase information – accurate to 0.1dB for gain, and 2 degrees for phase.*

C. *A narrowband noise measurement system that will reject all the switching, line frequency, and other noise in the test signals.*

D. *Dynamic range of at least 80dB to accommodate the range of signal sizes and gains that will be encountered.*

A. Swept-Sine Output

A switching converter needs to be measured from low frequencies of interest up to high enough frequencies to show the major system dynamics.

This is typically below 50Hz at the low end, (less than this for motor control circuits and PFC circuits) up to the switching frequency. (Half the switching frequency is theoretically more than sufficient, but there are often practical benefits in seeing the higher frequency data.)

A typical switching power supply operating at 100kHz will be measured from 10Hz to 100kHz, and will have a crossover frequency of 2kHz - 10kHz. Across this range, you want a piece of equipment that can output a test sine wave, and automatically step it in logarithmic increments. For each test frequency, the instrument needs to measure two signals at the test frequency, and compare their magnitudes and phase.

B. Noise rejection

Fig. 2 shows a typical power supply loop gain measured with a frequency response analyzer.

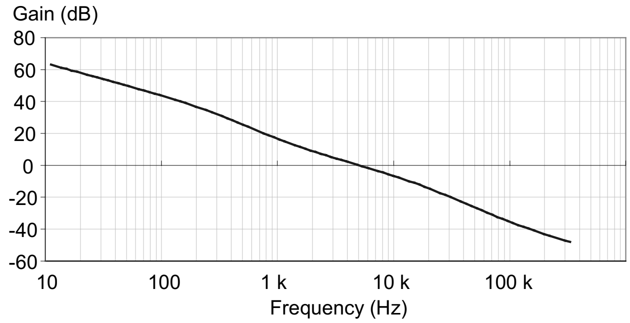
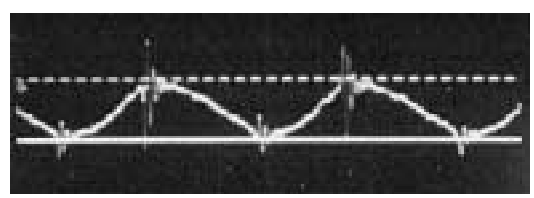


Figure 2. Typical loop gain showing high gain at low frequency, and 5kHz crossover frequency.

At the low frequency end of a power supply loop measurement, the gain of the system will be very high– in excess of 60dB, and sometimes as high as 80dB. Consider the size of the signals needed to make this measurement. You must ensure that you are measuring “small-signal” with a small ac perturbation on top of the dc operating point. For this, the output signal will typically be 100mV or less.

The input signal to the loop, for a 100mV output, will be 0.1mV for a gain of 60dB, and 10μV for a gain of 80dB. It is common, however, to have up to a few hundred mV of noise in the signals. It is impossible to measure the test signal in so much noise without a specialized instrument. That is the second main function of the frequency response analyzer – to extract the test frequency only, with a very narrow bandwidth, so system noise does not interfere with the measurements.



100mV/div

Figure 3. Typical test signal to be measured, with switching spikes and other noise. Less than 0.1mV test signal must be accurately measured in the presence of over 200mV noise.

A **Frequency Response Analyzer,** also referred to as a **Network Analyzer**, is specifically designed to provide these functions. Until recently, it was necessary to spend $30k or more to get an instrument suitable for the task of measuring switching power supplies and their components. Today, this type of instrument can be purchased for under $10k, making it both affordable and indispensable for all power engineering companies [5].

V. LOOP GAIN MEASUREMENTS

Power supplies are extremely high dc-gain systems. They use integrators to maximize the dc gain, and ensure that the output voltage dc regulation is tight. The power supply and control circuits cannot, therefore, be run with the loop open. It’s simply not possible to hold the dc operating point steady with an open loop system.

Fortunately, there are established and documented techniques for measuring the open loop gain of a system while the loop is kept physically closed. The only invasion into the circuit is through the insertion of a test resistor. The technique is very accurate as it does indeed measure the true open loop gain of the system, not a gain modified by the injection technique itself.

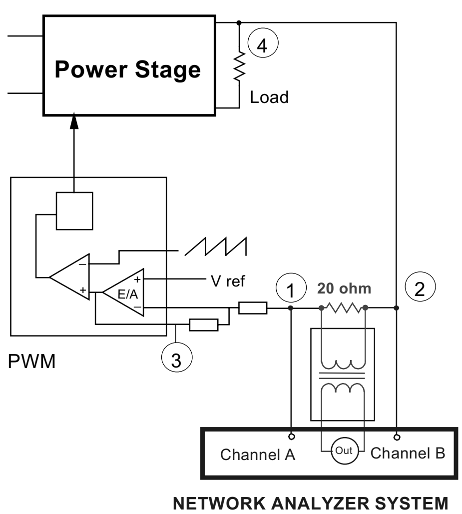


Figure 4. Feedback loop system showing frequency response analyzer connection and injection resistor.

This is shown in Fig. 4. The only complication with this technique is that the signal injected into the circuit must be injected differentially across the resistor, not with respect to ground. This is typically done with a signal injection transformer. The output signal from the network analyzer is coupled through an isolation transformer.

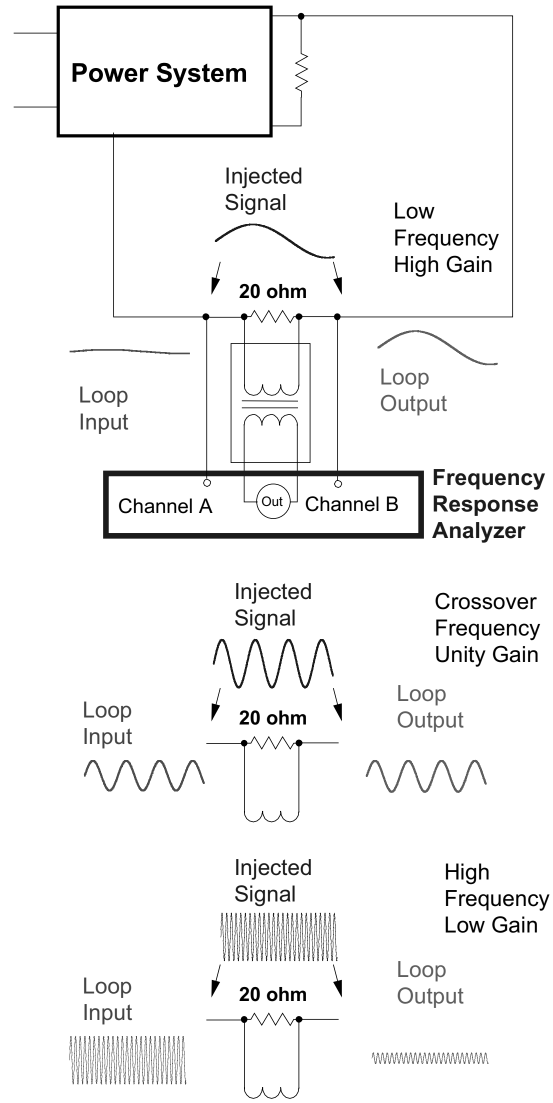


Figure 5. Signal distributions at different loop gains– high gain, crossover, and low gain. The injected signal size stays constant across the whole frequency range, and gets distributed between the input and output of the loop, depending on the loop gain.

It's a little unusual how this works– the signal size across the resistor is constant. The vector sum of the injected signal and return signal are exactly equal to this injected signal. The power supply feedback system will adjust the signal sizes according to the gain needed. For example, if the gain of the system is 60dB, and the injected signal is 100mV, almost the entire injected signal appears across the output and only 0.1mV across the input.

At the crossover frequency, the injected signal is distributed equally between input and output signals. And, when the gain of the system is very low, beyond the crossover frequency, most of the signal is applied to the loop input, and only a small fraction to the loop output.

An animated example of this process can be seen at the Ridley Engineering web site [5], showing graphically how the injected signal is divided between loop input and output.

In order not to disturb the operating point of the system, the injection resistor is kept small relative to other components in the circuit. Typically, a 20Ω or 50Ω resistor is used in series with several kΩ already in the circuit.

During measurement, it is usually advisable to monitor critical waveforms of the control system to make sure that they remain in the small-signal region. An oscilloscope probe on the output of the error amplifier, and output of the power supply is usually sufficient. As the gain of the loop changes, it is customary to adjust the size of the signal injection to keep the signals large enough to be measured, but small enough keep the system linear.

Other concerns and techniques for measuring loop gains properly are given in [5].

VI. CASE STUDY NO. 1

A printer power supply company was ready to release a design to manufacturing. A substantial amount of modeling and prediction ensured system stability. The power supply was considered ready for production with quantities exceeding 10,000 units per month.

The company had a frequency response analyzer in house, ready for evaluation. But, like most of us, the engineer was too wrapped up in the production details to take loop gain measurements.

Finally he was persuaded to do a quick test with the analyzer on this latest product. Reluctantly, he did, taking a couple of hours out of his schedule.

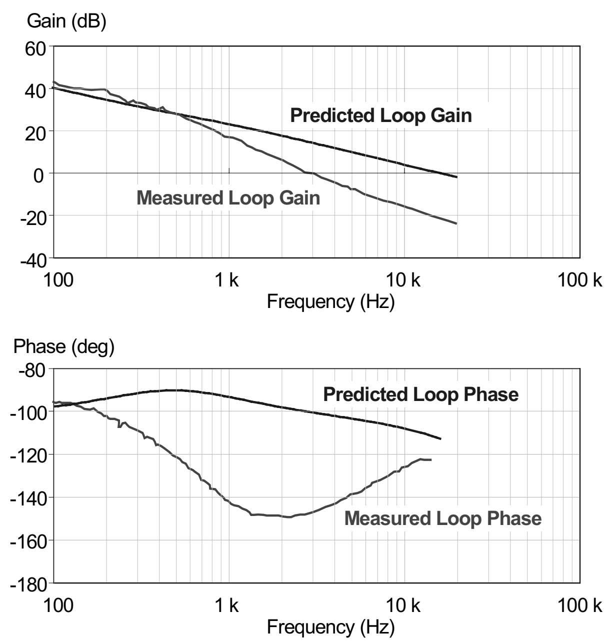


Figure 6. Predicted and measured power supply loop gains using manufacturer's data for capacitor esr. Over 50 degrees phase error!

To his amazement, the power supply was almost unstable, with only 35 degrees of phase margin at the selected nominal operating point – 50 degrees lower than expected. The production release was delayed for a day to figure out the problem, and fix it quickly.

The model the engineer was using was fine, and that all the values corresponded to the manufacturer's data for the passive components. And that's where the problem lay– the wrong value of ESR for the output capacitor was being used. It was correct according to the data sheets, which called out a maximum value of 7.5Ω for a tantalum capacitor. The real value of the ESR was only 0.25Ω– a factor of 30 lower than the published maximum! This corresponded to a change in gain of 30dB at higher frequency. And, since we often cross a control loop over in the region where the output capacitors are resistive, the whole loop gain was depending on this value.

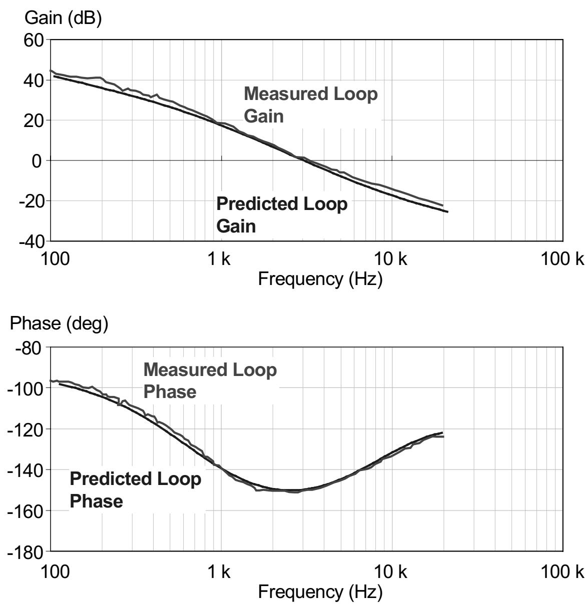


Figure. 7. Same measured loop gain as Fig. 6, but predicted loop gain using measured values of capacitor esr (30 times lower!).

A refinement to the model values confirmed the measured loop gain, and the need to add a couple of additional compensation components to the board.

Cost to the program was only a few hours engineering time, and the changes were incorporated in the final production board run the next day. The savings in potential product recall and re-engineering were substantial.

VII. CASE STUDY NO. 2

Researchers in the academic community who spend all their time on theory and modeling often advise engineers that they should be very concerned about stability. The fact is that most designers have so many other issues on their plate during development, this is just one more item on the list, and it's frequently overlooked

It's often inconvenient to stop and think about control systems. When deeply involved in the development of power supplies– including all the details of design, layout, parts selection, testing, etc. it's easy to neglect control. At the end of the project, when final testing is almost complete, we all find it tempting to assume the fact the converter works assures us that everything is OK in the loop without needing to measure it directly. Even the most experienced of us make wrong assumptions, and forget the importance of this step.

This example is of an off-line flyback converter with dual outputs. The simplified schematic is shown in Fig. 8. One of the outputs is used to power an electronic load, and has a large amount of storage capacitance. This output is isolated from the mains input. The second output is referenced to the primary side, and used to power the control IC. This second output is also used for feedback regulation, since it does not need isolation in the feedback path.

Like the previous example, the power supply was built, tested, and ready for prototype manufacturing. And, like many engineers, it was assumed that a simple DCM flyback circuit like this would behave as predicted by small-signal circuit models.

The small-signal model initially used for the design is shown in Fig. 9. This makes the assumption that the outputs of the converter track each other well, and all the output capacitances can be reflected to a single output. The converter model then reduces to just a single-output flyback (i.e. the model format that appears in almost all theoretical papers– there is little published on how to handle multiple outputs properly.)

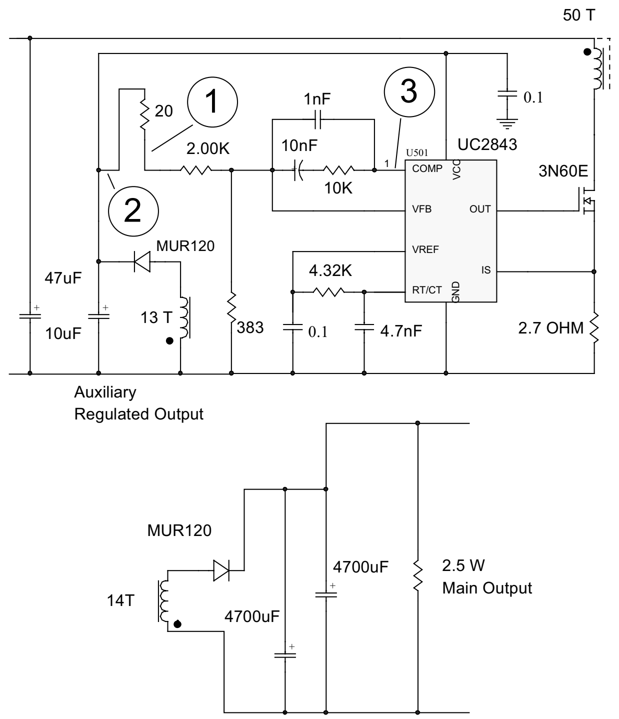


Figure 8. Simplified schematic of flyback power supply with auxiliary regulation. Main output has a large storage capacitance. Auxiliary output is used for feedback regulation, and to power the controller. The 20Ω resistor in between points (1) and (2) is used for experimental signal injection.

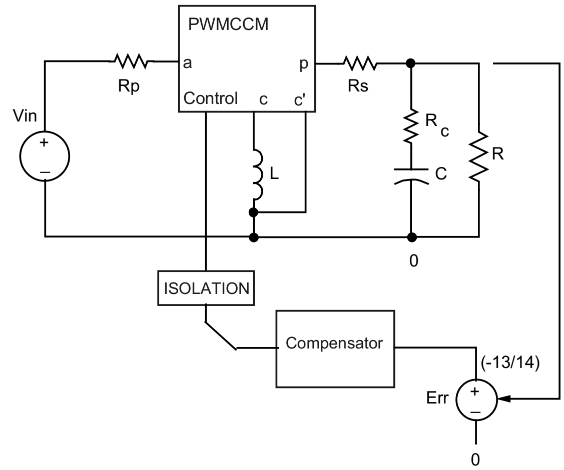


Figure 9. Small-signal circuit model. (Simplest assumption – the two outputs track each other according to the turns ratios).

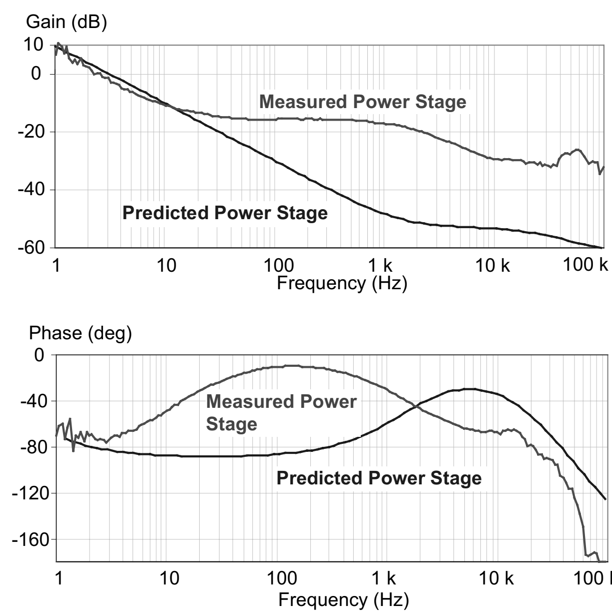


Figure 10. Measured and predicted loop gains.

Figure 10. shows an extreme when things go awry. The gain is dramatically off in the critical crossover frequency region, and the two phase curves have almost no resemblance to each other!

This is a more subtle problem than simply using the wrong component values. First, a more complex model is needed to predict the multiple output converter response. Fig. 11 shows the equivalent circuit model that separates the output capacitors, and allows for winding resistances of the individual outputs.

Inserting the winding resistances still produces large errors. The gain is much too high in measurement versus prediction. More detailed analysis shows the problem to be the equivalent series resistance of the diode! This is a parasitic that is often overlooked in modeling. Very few of the papers on modeling highlight the diode esr as being an issue– it's always assumed to be very low, and therefore somewhat irrelevant.

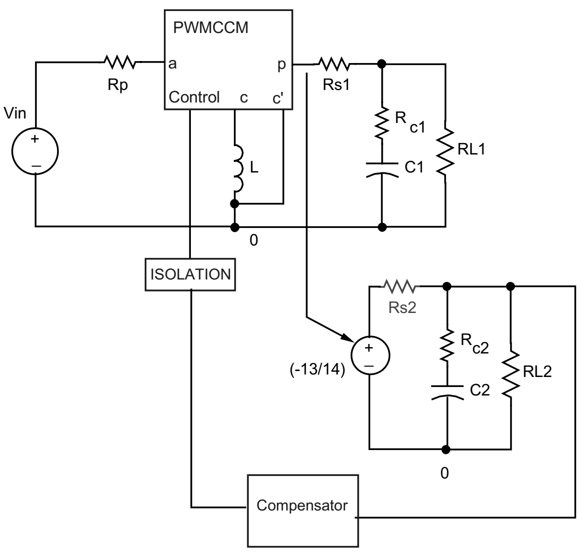


Figure 11. Two-output flyback converter with more accurate modeling of output circuits. Diode esr, included in Rs2, is the critical parasitic causing errors.

What's different here? The second diode, on the auxiliary output, is used at very low current. And, as semiconductor experts are well aware, the incremental series resistance of a diode at low currents is very high– in this case, about 1Ω. This resistance is high enough to decouple the large storage capacitor on the main output from the feedback output, substantially increasing the converter gain.

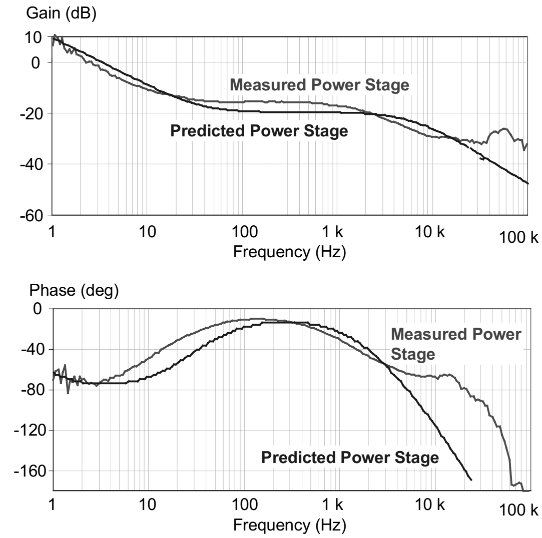


Figure 12. Loop gain measurement and predictions with proper diode esr value in the model.

For both of these design examples, further deviations from predicted results can be expected as the power supplies are operated at the corners of the electrical specifications, and at temperature extremes. You should always measure your systems across the full range of operation to minimize risk of subsequent problems and failure.

VIII. COMPONENT MEASUREMENTS

Both case studies uncovered an important aspect of switching power supply design. Parasitics of components in a power converter can have dramatic effects on the overall system operation, especially on stability. It is, therefore, crucial to understand which elements are important in the design (that's part of the role of good modeling) and to know how to get their values.

Many manufacturers of power components do not give adequate data for their parts for proper converter design. For example, capacitor manufacturers may specify an esr at 120Hz, a relic of the days when all power was processed at line frequency. The esr at 100kHz will typically be substantially different and often lower. It is up to the design engineer to determine which value to use in modeling and control design.

Similarly, the parasitics of magnetics parts are critical to good design. Changing leakage inductance, for example, can make or break (literally!) a power supply design. Prototypes and manufacturing units of transformers must be properly characterized, specified, and controlled in volume production to ensure system reliability.

If you have a frequency response analyzer on your bench for loop gain measurements, you also have a very powerful tool for characterizing the impedances of components, and finding the critical parasitic values.

A frequency response analyzer is designed to measure transfer functions of a circuit, in the presence of substantial noise. However, it can also be used as a very effective engineering tool for impedance characterization of components. This is a very important function of such an instrument, since a dedicated RLC meter, capable of operating over the range of interest of power conversion components, can be very costly.

While a frequency response analyzer does not have the same resolution capabilities of a true RLC meter, its ability to measure impedance continuously over a wide frequency range makes it very applicable to power components. Parasitics of magnetics, capacitors, and other components are often a function of frequency. Most RLC meters do not provide this continuous data. And it can be very misleading if the component manufacturers do not have the proper test frequency for measurements.

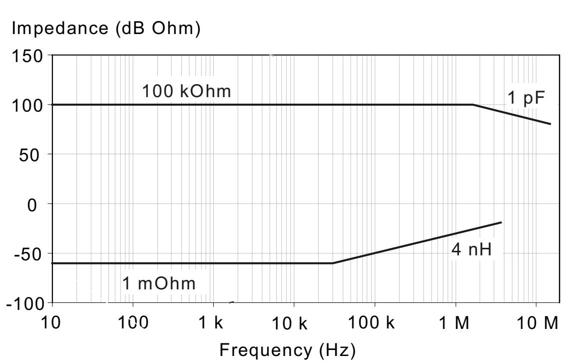


Figure 13. Range of impedance measurements for the frequency response analyzer using simple measurement setup circuits.

It is not necessary to have sophisticated setups for measuring impedance to the degree of accuracy needed for power components. Some very simple circuits can provide a wide dynamic range of measurement, as shown in Fig. 13. Careful selection of test circuits allows the measurement of high impedances up to 100kΩ, and of capacitors as small as 1 pF. This allows characterization of almost any power transformer at its resonant frequency.

At the low impedance range, 4-terminal Kelvin measurements allow a frequency response analyzer to effectively measure down to 1mΩ and 4nH of lead inductance. Impedances below this range require expensive calibrated setups used on high-end RLC meters to measure anything other than dc resistance. (DC resistance can also easily be measured in the μΩ range with very simple lab instrumentation – an accurate voltmeter and current source.)

IX. TRANSFORMER IMPEDANCE MEASUREMENTS

One powerful use of a frequency response analyzer is the measurement of impedances of transformers and inductors. Extended impedance versus frequency plots provide significant design and performance data.

As in classical line-frequency transformer design, the proper way to characterize a power transformer for high-frequency applications is with priamry-side impedance measurements with the secondaries (i) open-circuited and (ii) short-circuited. This provides a wealth of design information, and should be measured and archived for every design that is done, and for each step of the transfer of the design into manufacturing.

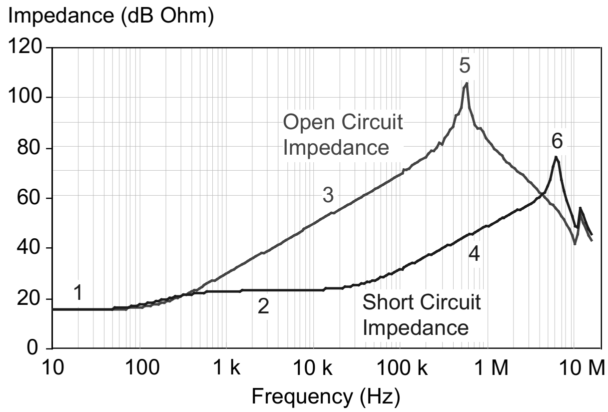


Figure 14. Transformer impedance measurements. Open circuit and short circuit measurements provide a wealth of design information.

Fig. 14 shows some example plots of power transformer impedance, measured from the primary, with the secondaries first open, then short-circuited. Several asymptotes on the curves of Fig. 14 are numbered, corresponding to the regions used for measurement of critical transformer parameters:

1. *Primary winding resistance*
2. *Primary + reflected secondary winding resistance*
3. *Magnetizing inductance*
4. *Leakage inductance*
5. *Open-circuit resonance (and equivalent winding capacitance)*
6. *Short circuit resonance (and its' equivalent capacitance)*

Don't underestimate the value to the design and manufacturing process of measuring these curves early in the product cycle. Magnetizing inductance is seen as the dominant component in the open circuit measurement from 1kHz to 100kHz. In manufacturing tests, it should be measured in this range. (Typical testing is done at 1kHz).

The leakage inductance impedance is only dominant in the short circuit measurements from 50kHz to 3MHz, and it should be measured in this range by the manufacturer. **Specifying and measuring the leakage at 1kHz will lead to unacceptable accuracy, and poor quality control**.

In some designs, it will become apparent that the leakage inductance asymptote is not a straight 20dB/decade slope. Instead, the leakage will decrease with frequency, due to proximity effects in the windings. If this effect is pronounced, great care must be taken in choosing the test frequency to avoid errors.

Fig. 15 shows an example of open-circuit impedance measurements on a production power supply. Curve number 2 is the impedance of a transformer built in the engineering lab. Curve number 1 was a pre-production prototype. The open circuit resonance of the engineering part was at 550kHz, and of the pre-production prototype, 340kHz. Both frequencies were high enough not to cause initial concern, with a switching frequency of 70kHz. The engineering prototype worked, however, and the manufacturing part did not. The power supply failed to start.

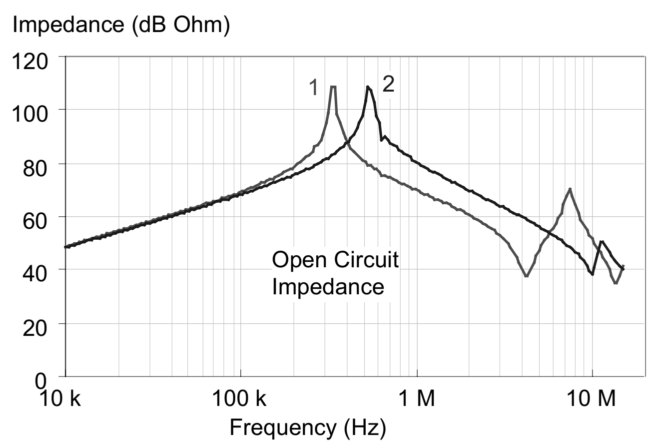


Figure 15. Transformer production problem– all parameters of the transformer are the same except the resonant frequency– the manufacturer omitted a single layer of tape, and the power supply no longer worked!

The change in resonant frequency actually corresponded to a change of winding capacitance from 16pF to 52pF. This was due to the manufacturer omitting a layer of tape in the windings! There were no safety issues in this case and the output was line-side referenced. The increased capacitance caused a current spike in the control circuit, which prematurely tripped the PWM controller, and prevented proper circuit operation.

Sometimes, even in the best designs, (scary though this is to management and purchasing departments!) a layer of tape is all that stands between success and failure of a product. Frequency response measurements during the development process are a tremendous help in detecting understanding, and solving subtle but potentially expensive problems like this.

There are many more details, of course, to frequency response testing and assessment of magnetics. These are covered in considerable practical detail in Ridley Engineering's design courses [6].

X. CAPACITOR MEASUREMENTS

In the loop gain design example earlier in this paper, a wrong capacitor esr value almost caused a very expensive problem in a power supply design. This was despite the fact that conventional wisdom would define the capacitor as "better" than its specification. The loop gain measurement was far from prediction, and the capacitor esr was found to be 30 times lower than the specified maximum from the data sheets.

Surprisingly, this is not an uncommon experience. Manufacturers often do not have the time, equipment, or incentive to properly characterize and document their components for the design engineer. It is good engineering practice to measure every capacitor destined for your power supply, and make sure the acceptable range of the parasitic components are well defined. And you should do this across the entire temperature range the components will operate in.

Fig. 16 shows a set of capacitor measurements useful for power supply design. The tantalum capacitor is the type used in the example of loop gain earlier in the paper. The measured esr is about -20dBΩ (0.1Ω), compared with the data sheet which specifies a maximum impedance at 100kHz of 7.5Ω.

Also plotted in the figure is the impedance of a 22μF electrolytic capacitor. The tantalum and electrolytic have the same impedances up to a few kHz. The esr of this particular electrolytic was 0dBΩ, or 1Ω. Clearly, the tantalum capacitor will do a better job of filtering higher frequency noise.

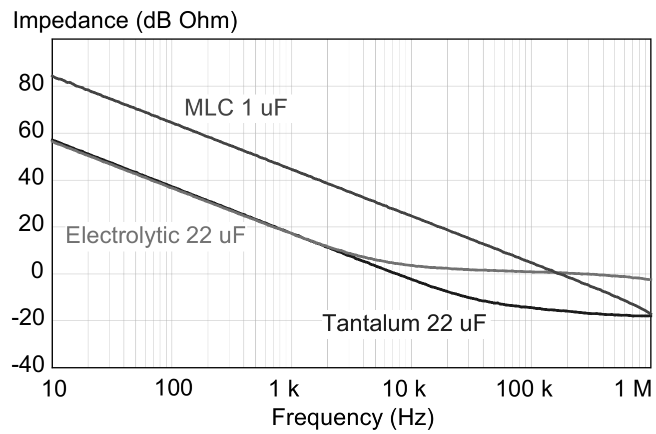


Figure 16. Impedances of different types of capacitors.

The final curve is the impedance of a multilayer ceramic capacitor. Notice that above 200kHz, the MLC, with a value of only 1μF, has a lower impedance than the 22μF electrolytic capacitor. For equivalent values, 22 of the 1μF MLC caps would give vastly superior performance. One reason we don't use this type of capacitor extensively in power supplies is the cost.

XI. SUMMARY

In today's marketplace, you cannot risk product failure. Modeling alone does not guarantee control loop stability. Measurement of control loops and components with a frequency response analyzer is an essential design step.

- *The critical factors to remember in all your designs are:*

- *You* ***must*** *measure power supply control loop stability for reliable design. This should be done at every stage of development and prototyping. In some instances, it makes sense to incorporate loop measurement as part of manufacturing, especially for low volume production, and high reliability supplies.*

- *Modeling is almost always inaccurate the first time. Simplified models often fail to account for the parasitics and circuit events that you may see in your design. The first control loop stability measurement will usually surprise you.*

- *Frequency response analyzers are now affordable. There's no reason for any company developing power supplies to be without one – you simply cannot afford the risk of shipping a product with an unknown stability margin.*

- *Component impedance measurement is a valuable capability of frequency response analyzers. Measurement of power components gives you critical design data that is often unavailable from manufacturers.*

Ray Ridley has specialized in the modeling, design, analysis, and measurement of switching power supplies for over 20 years. He has designed many power converters that have been placed in successful commercial production. In addition he has consulted both on the design of power converters and on the engineering processes required for successful power converter designs.

Ridley Engineering, Inc. is a recognized industry leader in switching power supply design, and is the only company today offering a combination of the most advanced application theory, design software, design hardware, training courses, and in-depth modeling of power systems.

XII. REFERENCES

R.D. Middlebrook, S. Cuk, *"A General Unified Approach to Modeling Switching Converter Power Stages,"* IEEE Power Electronics Specialists Conference, 1984 Record, pp. 18-34.

V. Vorpérian, *"Simplified Analysis of PWM Converters Using the Model of the PWM Switch: Parts I and II",* IEEE Transactions on Aerospace and Electronic Systems, March 1990, Vol. 26, No. 2, pp. 490-505.

V. Vorpérian, R. Tymerski, K.H. Liu, F.C. Lee, *"Generalized Resonant Switches Part 2: Analysis and Circuit Models,"* VPEC Power Electronics Seminar Proceedings, Virginia Polytechnic Institute and State University, Blacksburg, VA, pp. 124-131, 1986.

R.B. Ridley, *"A New Small-Signal Model for Current-Mode Control"*, PhD Dissertation, Virginia Polytechnic Institute and State University, November, 1990. See web site to order.

Switching power supply design information, design tips, frequency response analyzers, and educational material for power supplies can be found at the web site located at: **http://www.ridleyengineering.com**

Ridley Engineering, Inc. *"High-Frequency Magnetics Design"* professional engineering seminar taught semi-annually. See [5].

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