SMPS Technology Knowledge Base

Power Supply Instability

Causes of power supply instability and methods to prevent it occurring in manufacturing and field use.

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Summary

Problem - Power supply becomes unstable during manufacturing or in the field.
Relevance - Applies to any circuit with a feedback loop.
Solvability - No complete solution, but the risk can be reduced greatly.
Solution - Planned strategy of analysis and test followed with a closed-loop oven screen.
Personal - A personal anecdote.
On the Web - Additional information on the Web.
References - One to a few key papers.

Problem

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One of the most embarrassing things that can happen to a power supply circuit designer is to have their "finished" design go unstable during manufacturing or after delivery to the customer. This happens quite often and it is not too surprising. Switching-mode power supplies are one of the toughest circuits most engineers will ever have to stabilize. The reasons are:

- The power supply can operate in different modes, such as the continuous and discontinuous current mode, presenting different control loop parameters in each mode.
- The input voltage can appear in the gain of the feedback loop, changing the gain characteristics as the input voltage swings over the wide operating range typical of many applications.
- Load variations affect the location of poles or zeroes associated with the output filter.
- The effective value of components contributing to poles and zeros, such as inductors and the load resistance, can vary as a function of line and load variations.
- The circuit can contain both real and complex right-half-plane zeroes that migrate as a function of line, load, and temperature.
- Many of the components affecting circuit poles and zeroes are nonlinear, such as swinging inductors.
- Many of the components affecting stability have large variations in tolerance as purchased and over operating temperatures and system life, such as electrolytic capacitors.
- Long power source leads or added system filters, such as EMI filters can have a dramatic effect on system stability criteria. See Input Filter Interaction.

- Added load capacitance, including high quality decoupling capacitors shorting the ESR of the power supply output capacitor, which may be contributing a stabilizing zero, can effect stability.
- Minor loops inside the power supply, like those causing emitter follower oscillations or power MOSFET drive resistance instabilities, may go unstable over the range of purchasing tolerance or variations caused by manufacturing, temperature, and age. These can go unstable with little noticeable effect on output observables (except perhaps radiated EMI in the Megahertz range), but can alter the feedback loop by causing saturation of components or DC level shifts in interior states and can greatly degrade field reliability.
- Things like the magnetizing current in the magnetics can affect stability.
- Switching noise can affect stability and stability measurement. One of the industries first challenges with switching-mode power supplies was trying to measure small gain and phase signals in a noise environment much larger than the signal. See personal anecdote below.
- Chaos can occur in these circuits. SeeChaos and personal anecdote below.

A common and totally inadequate defense against the above is often to analyze the circuit at nominal input voltages and load and verify the analysis with a measurement on the breadboard using a resistive load and laboratory bench supplies. No wonder switching-mode power supplies often break into oscillation during manufacturing or over the life of the product in the field.

Relevance

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Applies to any circuit with a feedback loop, but keeping switching-mode power supplies stable over the life of the product in all environments is far more difficult than most feedback loops.

Solvability

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No complete solution, but the risk can be reduced greatly. What is needed is a practical strategy of analysis, measurement, screening, and follow-up. There is a tradeoff between cost and risk in all of this. The elements of such a strategy are discussed under solutions.

Solution

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Planned strategy of analysis and test followed with a closed-loop oven screen and follow-up. The questions to answer are:

- At what operating points should analysis be performed and tests made?

- Is there a useful screen?
- Is this sufficient or is some follow-up necessary?

Analysis and Measurement

Nominal Measurements: You normally have to calculate one gain-phase plot and make one set of measurements so you can show your management or the customer that the system is stable with sufficient gain and phase margins, even though analysis and measurement at a single set of operating conditions is high risk. Typically the operating conditions are room temperature, nominal input and bias voltages, and either the expected or full load. This approach is at the lowest cost, highest risk extreme.

10% Increments: Another approach is measuring on a grid of intercepting operating points. This results in combination explosion. For example, using 10% increments with input voltage, one bias voltage, load current, and temperature, you would have to calculate 14,641 gain-phase plots and measure the same number. Even if you could or would want to do this, you probably are not going to have the patience to examine each one critically. This is the other extreme, maximum cost, but not necessarily the minimum risk, because no one is going to critically look at this many calculations and measurements. You increase the increments, say to 25%, but this is still 625 calculation/measurement pairs for the above example.

Coffin Corners: This approach, called the coffin corner approach here, is to calculate/measure at the worst case extremes only. For the above example this reduces the analysis/measurement pairs down to sixteen pairs for the above example. You've cut the cost, but you still have some uncomfortable risk, since you have not even measured at the nominal conditions that the power supply will most likely be used. To correct for this you add back in the min, nom, max load at nominal input, and the min, nom, max line at nominal load all measured at nominal bias and nominal temperature. This adds five more measurements for a total of 21 analysis/measurement pairs. This can be done, especially if you are using a computer controlled analysis/measurement system for this.

Coffin Corners Modified for Switching-Mode Power Supplies: The above may work for most feedback circuits, but for switching-mode power supplies you have a few more critical measurement points. The control loop characteristics change at the continuous/discontinuous current boundary. Typically a second order system in the continuous current mode reduces to a first-order system in discontinuous current, which is normally stabilizing. But other stability-related things happen near this boundary, for example see the Jang and Erickson paper in the discussion on Input Filter Interaction.

Finally, power supplies are often overloaded or shorted, and you don't want them to go unstable under these conditions. Hence more analysis/measurement pairs are called for and often you have to increase risk to get the number of pairs down to a reasonable number. Can you cut the pairs and do something else to reduce risk?

Oven Screen

The oven screen described below has proven extremely successful in finding operating conditions where stability margins in a switching-mode power supply deteriorate.

In essence, a square-wave voltage is applied across the reference and the output voltage response is observed as the load current is swept from no-load to full-load for various input voltages, biases, and temperatures.

Figure 1 shows some of the waveforms that can occur on the output.

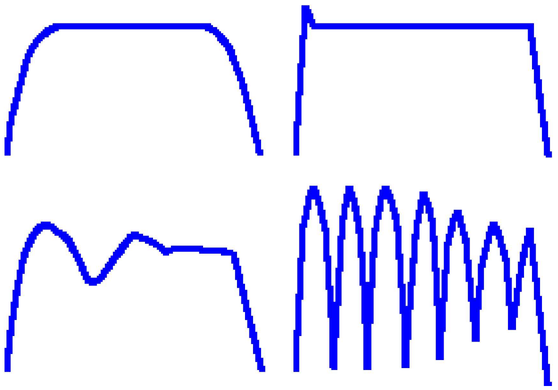

Figure 1: Oven-Screen Waveforms
Overdamped, ideal, underdamped, near oscillatory

The upper left waveform shows the overdamped response of a conservatively stabilized system where performance may be sacrificed for a robustly stable system.

The upper right waveform shows the ideal waveform. The output replicates the input waveform.

The lower left waveform shows the very beginning of ringing. Usually damping should occur within a cycle of the first overshoot/undershoot. Any less damping should be noted.

The lower right waveform shows a system about to go unstable.

The circuit is set up in an oven and for a given temperature, the load is swept for a fixed input voltage and bias voltage and any ringing or oscillations noted, along with frequency, on a plot of Vin vs. Iout as shown in Figure 2.

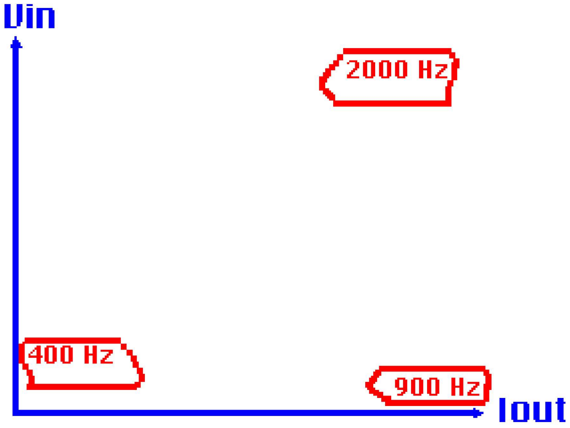

Figure 2: Oven Screen - Vin vs Io

A grid of input voltages for a fixed bias is set up and the load sweeps made. Then repeated for various biases, and then repeated for a grid of temperatures.

Collapsing all the graphs on a single graph, such as Figure 2, shows the line and load conditions that are problem areas over the temperature range.

Typically, it takes a half day to set up the circuit in oven, and a half day to make all the sweeps. Most of the time is waiting for the circuit to reach thermal equilibrium with the oven ambient.

The theoretical foundation of this approach assumes a system no higher than second order, which is rarely the case. However, since you try to make the circuit behave like a first or second order system, it seems to work in practice. I have known a lot of power supplies to develop oscillation in the factory or the field, but never one that has passed this screen.

Variations. Inject white noise across the reference at various injected levels of noise. Noise can induce subharmonics and chaos in susceptible circuit.

Practical Advice

The signal can be injected from a square-wave generator through a blocking capacitor if the reference internal impedance is sufficient to develop a clean square wave across it. If a noise filtering capacitor is across the reference, then it may have to be removed in order to get a clean square-wave signal. More sophisticated injection approaches can also be used. Make sure that if capacitance or resistance at the reference node is modified, the break-points are outside the frequency range of interest. Always monitor the injected signal, to make sure it does not distort, as well as the output signal.

Scope probes melt before 125C. Keep the probes outside the oven if the range will exceed the temperature rating of the probes, either hot or cold.

Make sure the circuit in the oven reaches thermal equilibrium with the oven ambient before you make the measurements. This will take most of the measurement time.

You can also make ripple, regulation, and other measurements of interest at various temperatures while you have the circuit in the oven.

Measuring your circuit alone is necessary but not sufficient to guarantee stability in the system. You need to include input filters, cable impedances, nonresistive and nonlinear load impedances, etc. in both your analysis and measurements.

Follow Up

Ultimately, your power supply must be stable in its operating environment over the life of the system. For that reason, an injection point and measurement point are often built into the power supply and brought out to board and system test connectors. You have to be very careful that the injection lines do not pick up noise and inject it into a critical point in your circuit. This approach lets you check your stability as the system builds and is deployed. An early version of this was the marginal test capability that was built into early computer power supplies that allowed the power supplies to be varied plus or minus some amount during maintenance tests in order to weed out weak integrated logic circuits. By observing the wave forms during this test, you could get a feel for the stability of the power supply.

One risk you will face is that some cost-reduction suggestion or "improved" part will be incorporated in your design during the manufacturing life. These often negate your hard work and make changes to your system that degrade it, including causing it to oscillate. You have to be continually vigilant.

Personal Anecdote

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I remember in the mid 1960's when I was first asked for a gain-phase plot of a switching-mode power supply I designed. Fortunately, at that time I believed in limiting the gain of my feedback loops to 40dB and using feedforward and other compensation to minimize the effect of line and load changes, so things were manageable. Still, breaking the loop was a challenge. I used batteries with potentiometers for a true open loop measurement, or large capacitors to open the loop to AC signals, and was finally able to make open-loop measurements. However, there was so much noise from the switching frequency that it was anyones guess what the amplitude and phase was near unity gain. For many years I had, and others had, gain-phase plots that they could show people, but anyone who had actually made a measurement didn't believe in them. It was then I developed the oven screen and learned to trust it.

R. David Middlebrook changed all this when he published a 1975 paper and expanded on it in a 1976 paper describing a measurement technique using a tuned voltmeter that eventually gave some credibility to gain-phase measurements of switching-mode power supplies.

When I and others started to use Middlebrook's techniques, it took about 40 hours, starting with a simple RC circuit and graduating to switching-mode power supplies, to learn how to make them with confidence -- and they were always tedious to make.

The next breakthrough came in the late 1970's and early 1980's when people started to successfully put together systems based on instruments from Hewlett Packard, Schlumberger, Nicolet, and Bafco. Some of these systems took man-years to put together and debug -- and then gave mixed results.

In 1980 Dean Venable experimented with various systems, published a paper and founded Venable Industries that provided turnkey systems, including accessories and documentation, for making these measurements. Venable Industries is still a leader in this field and Dean Venable has kept publishing papers on the subject (see references). Some of Venable Industries computer controlled systems have gotten quite sophisticated.

In the late 80's, some of the major measurement companies like Hewlett Packard, figured out how to do it and gave some seminars, but it still took some figuring out to use their equipment.

Lately, some other companies, such as Ridley Engineering, have entered the field with low cost approaches.

These developments have turned the once very difficult task of measuring the gain-phase of switching-mode power supplies into something manageable. But you still have to be careful. If the signal distorts on you, then things are no longer linear, and under these conditions even sophisticated equipment can give erroneous results. This is the most common mistake with the new equipment. I always monitor the input and output signals with an oscilloscope so I can either control distortion, or at least know not to trust the measurements when, as at some resonances, distortion is inevitable.

Finally, a comment on injecting white noise across the reference. I noticed the problem when one of my 25 KHz switching regulators developed a 12.5 KHz subharmonic ripple when in the system. When in the lab or on an extender board, there was no subharmonic. Thinking it might be related to noise, I injected white noise into the reference and other circuit nodes. When the white-noise generator hit a certain level, the subharmonic would appear. Increasing the level started what I now know as bifurcation to other harmonics, probably on the way to chaos, which at the time, I had never heard of.

On the Web

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Many of the pioneers and players in stabilizing switching-mode power supplies have websites.

Ardem Associates, R. David Middlebrook's website, describes a seminar that covers his techniques of loop analysis and measurement. The site includes Dr. Middlebrook's annotation of his papers covering his techniques of analysis and measurement with the pioneering papers on measurement of switching-mode power supplies at the end.

Venable Industries provides many uses of a network analyzer and a list of his papers, many with full text.

Ridley Engineering's pages provide additional information including his page on Design Tips which gives some solid information on closing the loop. It also has a list of his papers with some excellent annotations.

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References. A short bibliography of test paper abstracts related to stability testing.

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