

Can ESR Be Too Low?

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Abstract

Tantalum and aluminum polymer capacitors with 7343 EIA footprint can now be manufactured with ESR below 5mΩ. Their small footprint, low profile, and low ESR make these capacitors popular for microprocessor decoupling and power supply filtering applications in notebook computers. In response to positive customer demand, manufacturers are aggressively pursuing even lower ESR to satisfy high-performance applications. But customers occasionally complain that some capacitors have ESR that is so low that it causes their circuits to become unstable.

It is well documented that the output ripple of switching power supplies generally improves as the output filter capacitor's ESR falls, but less has been written about the consequences of ESR that is too low. Some power supply circuits will become unstable if capacitor ESR is too low. In such circuits there is a limited range of permissible ESR that provides acceptable output ripple while avoiding circuit instability. In some cases, simple modifications of the circuit can move the ESR threshold of instability lower so that very low ESR capacitors can be employed while maintaining acceptable circuit stability.

This paper briefly discusses control theory as it relates to switching power supply stability. Also discussed is the role played by the ESR of the output filter capacitor. Data collected from a small, fully-integrated switching power supply chip demonstrate circuit instability caused by very low filter capacitor ESR. Simple circuit modifications are made that reestablish circuit stability. The improved stability is shown to correlate with improved "phase margin," a common criterion of circuit stability from control theory. Thus it is shown that such instability can be anticipated, understood, and avoided and is not the fault of a defective filter capacitor.

Introduction

In general, reducing the ESR of tantalum capacitors is a good thing. In switching power supplies, a direct correlation can generally be drawn between output ripple and the ESR of the output filter capacitor – lower ESR provides lower ripple^{1,2}. But occasionally customers complain that they have trouble with instability or oscillation of their power supplies if the ESR of the output filter capacitor is too low. The purpose of this paper is to briefly explain how this instability occurs, how it can be predicted, and what is required to control it.

No adequate discussion of this problem can be undertaken without reference to basic control theory of closed-loop systems. Rigorous mathematical treatment of the subject appears in engineering textbooks³, but is well outside the scope of this paper. Instead, a qualitative description of the applicable theory is given here and data collected from a troublesome real circuit are used to demonstrate the theory in action.

Closed-Loop Control Systems

Closed-loop control systems are commonly used in applications where it is necessary to regulate some output measure in the face of variation of system operating conditions.

A good example is a power supply where you want the output voltage to stay reasonably constant in spite of significant load changes. In the absence of some kind of control system, it is likely that the power supply's voltage will drop significantly under heavy load and rise under light load.

But in controlled power supplies, the effects of loading are largely mitigated by circuitry that compares the output voltage to an internal reference signal (via feedback) and either applies more or less power to the load automatically to keep the output voltage substantially constant. The concept of monitoring the output and comparing it to a fixed reference to decide how much power should be delivered to the load is illustrated in Figure 1 which is a generic diagram of a closed-loop control system.

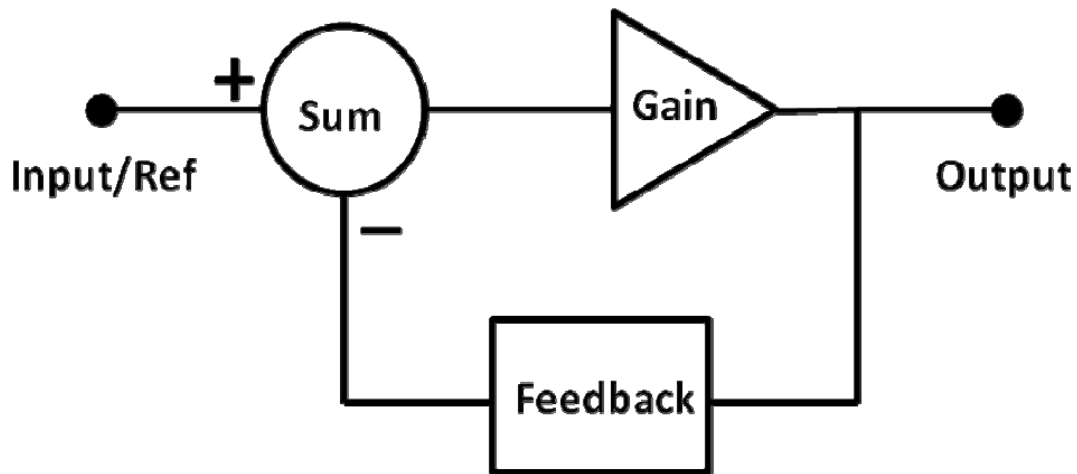


Figure 1. Generic Diagram of a Feedback Control System Such As Might Be Employed in a Power Supply, Amplifier, or Oscillator.

This diagram is called generic because it applies to a wide variety of electronic systems, including amplifiers, power supplies, and oscillators. In an even wider sense, the diagram of Figure 1 also applies to mechanical systems such as rocket motor pointing systems, biological systems such as heart and respiration rate control, and even global climate systems. The common thread is the concept of feedback that allows comparison of the system output to a reference, so that the difference between the output and the reference (an error signal) determines how strongly the system is driven to maintain the desired stable output.

So what adjustments to the diagram of Figure 1 would better distinguish among a power supply, an amplifier, and an oscillator? In a power supply, the input or reference is set to a constant voltage and the difference between the appropriately-scaled feedback signal and the reference signal is used to drive the output. If the output becomes too high, the difference between the feedback signal and the reference signal becomes smaller, or even negative, and the drive signal is reduced until the circuit reaches equilibrium. If the voltage drops under heavy load, the difference between the reference and feedback signals becomes more positive and the drive signal is increased until the circuit again reaches equilibrium (hopefully close enough to the target voltage to meet specifications).

In any event there must be some difference between the reference and feedback signals to generate some drive signal to the system. Thus the output never really reaches exactly the desired level, just close. To make this error very small, control systems typically employ high gain. In power supplies, this amplification or gain may be higher than 100 at low frequencies to achieve regulation better than 1%. This high gain can lead to instability and oscillation problems under certain circumstances as will be discussed later.

If the circuit were an amplifier instead of a power supply, the only difference is that you would feed a time varying input signal into the input/reference port and the output should faithfully follow the input signal up and down in time. The gain of the amplifier is established by how much attenuation occurs in the feedback

circuit. If the output signal is divided by 10 in the feedback circuit, the gain of the amplifier is 10 because a signal 10 times as large as the input/reference signal is needed to be almost equal to the input signal after it is divided by 10 in the feedback circuit.

Things are a little different in an oscillator. In this case the input/reference is set to zero and the feedback circuit is configured to not invert the output so that it provides *positive* feedback instead of negative feedback. In this case the objective is to provide just enough positive feedback to keep the oscillator “chasing its own tail.” Of course you want the oscillator to oscillate at the right frequency, so the feedback circuit is configured to provide these “just right” oscillating conditions at only one frequency.

Stability Criterion

A common joke in the engineering community is “oscillators won’t and amplifiers will.” This means that it is not uncommon for amplifiers to oscillate (like feedback in a PA system) and for oscillators to not oscillate when they should.

Control theory provides the ideal conditions for each of these systems. Power supplies and amplifiers should ideally have an exactly negative or minus 180 degree feedback with respect to the phase of the output signal, and lots of gain. Oscillators should have exactly positive or 0 degrees feedback with gain only a little higher than 1 (just enough to make up for system losses).

Unfortunately, real circuits cannot maintain these ideal conditions over all frequencies and in the face of other changing conditions such as temperature or electrically noisy operating conditions. So practical guidelines are employed to help the engineer know when the operating conditions have changed so much that he cannot be sure of proper operation.

For power supplies and amplifiers, the phase angle of the feedback signal must stay negative by at least roughly 30 degrees at all frequencies when the gain is greater than one⁴. Otherwise there is the chance that oscillation will start in the presence of electrical noise. This criterion is known as the *phase margin*. The phase margin is the difference between the system’s actual phase at gain equals one and an oscillator’s ideal operating conditions of 0 degrees phase with gain a little more than one.

For good designs, many engineers want the phase margin to be at least 45 degrees, since any lower phase margin causes slow recovery from transient events as the damping ratio (and overshoot percentage) rises and stability falls⁵. But if the engineer wants the system to perform well at high frequencies (to have high “bandwidth”), he may be willing to settle for a little less phase margin than 45 degrees since it is difficult to accomplish both high bandwidth and high phase margin simultaneously⁴.

How Phase Margin Degrades

All electronic systems either deliberately employ capacitors and inductors (certainly true for power supplies), or have parasitic capacitance and inductance in their circuitry (true for amplifiers). A consequence of the presence of capacitance and inductance is that signal phase changes as the signal propagates through the circuit. Ideal resistors do not introduce phase shift, but real resistors contribute some phase shift because of parasitic capacitance and/or inductance.

Any single capacitor or inductor cannot create a phase shift greater than 90 degrees all by itself. But the combined effect of many sources of capacitance and inductance in a circuit can lead to phase shifts of 180 degrees or more over the useful frequency range of a circuit. This is enough phase shift to cause trouble in power supplies and amplifiers if the gain remains above one at frequencies where the total phase shift approaches 180 degrees.

In power supplies, one significant source of phase-margin-robbing phase shift is the output filter capacitor. If this capacitor has very low ESR, it tends to contribute a little more phase shift at a given frequency than

if it has higher ESR. This is true because a low-ESR capacitor continues to look more like a perfect capacitor as frequency increases than a high-ESR capacitor does.

Filter capacitor ESR also influences phase margin in another way. No energy is lost in a perfect capacitor, but significant energy is consumed by high ESR capacitors. This results in reduced gain in circuits that have higher-ESR capacitors. The reduced gain of higher-ESR capacitors indirectly helps improve phase margin because the system loop gain falls to 1 at lower frequencies.

Especially troublesome is the combination of an inductor and a capacitor in the output stage of many switching power supplies such as the one discussed later. Just these two components (L&C) used in combination can lead to resonance at a predictable frequency that can produce almost 180 degrees of phase shift while simultaneously enhancing the gain of the circuit⁶. Unless steps are taken to shore up stability, such circuits are almost guaranteed to be unstable.

Of course there are negative consequences associated with using high-ESR capacitors such as heat generation, lower efficiency, and generally higher ripple voltage. So it's not usually desirable to achieve good phase margin by using high-ESR capacitors unless performance requirements are not demanding.

Compensating for Phase Shift

Phase shift versus frequency is virtually unavoidable in real circuits. However, the clever engineer can turn the enemy's strength into a weakness. It is possible to add circuits to a power supply or amplifier to introduce desired *compensating* phase shift versus frequency. Several strategies and corresponding circuits are in wide use, alone or in combination, to introduce desired compensating phase shift to partially offset the original unavoidable phase shift.

The details of such circuits are beyond the scope of this paper, but they generally consist of combinations of capacitors and resistors placed at strategic locations in the circuit to improve phase margin. The most common compensation circuits are called Type 1, Type 2, and Type 3 compensation circuits^{7,8}. The type number is associated with the complexity of the circuit, the shape of its phase compensation versus frequency curve, and whether the circuit affects a feedback path, feed-forward path, or both.

Virtually all power supply control circuits employ some kind of compensation to improve phase margin. But a recent trend is to integrate a predesigned compensation circuit into a single power supply controller chip⁷. This greatly simplifies the customer's design process, but at the same time limits his compensation options. A consequence is that the "standard" compensation circuit might not work effectively for all customers, especially if they try to use output filter capacitors whose ESR is too low.

For instance, if the customer chooses a low-ESR capacitor to improve output ripple, but the controller chip designer intended the chip to be used in low-cost systems with high-ESR filter capacitors, there might not be enough phase margin and the circuit might not be stable. Exactly this situation is present in the circuit that is investigated in this paper.

A Troublesome Power Supply Circuit

A customer provided us with a small evaluation circuit that he obtained from a power supply controller chip manufacturer (who shall remain unnamed). This circuit was originally designed for use with low-cost aluminum electrolytic capacitors. Our customer wanted to save space and improve performance by substituting a polymer tantalum capacitor for the original, larger wet aluminum capacitor. But to his dismay, the circuit was unstable and demonstrated a mild, but unacceptable oscillation.

But if he placed a 1 Ω resistor in series with the capacitor, the oscillation disappeared. Our customer wanted to know what was wrong with our low-ESR capacitor.

Our explanation was that the compensation circuit built into the controller chip was designed to work with high-ESR filter capacitors and does not adequately compensate for phase shift when low-ESR capacitors are employed. While this is indeed true, we wondered if it might still be possible to apply some external compensation to the circuit to allow stable operation with the low-ESR capacitor. We were successful in this effort and in the process collected the data that are presented in the next section.

Experimental Gain and Phase Data

There are several purposes served by collecting and presenting the following gain and phase data for the troublesome switching power supply circuit. First, these results demonstrate the unavoidable phase shift versus frequency that occurs in closed-loop control systems. Second, the data demonstrate that filter capacitor ESR affects phase margin. Finally, even though the primary compensation circuit may be hardwired into an integrated circuit chip, it may still be possible to achieve acceptable phase margin and circuit stability when using very low ESR filter capacitors.

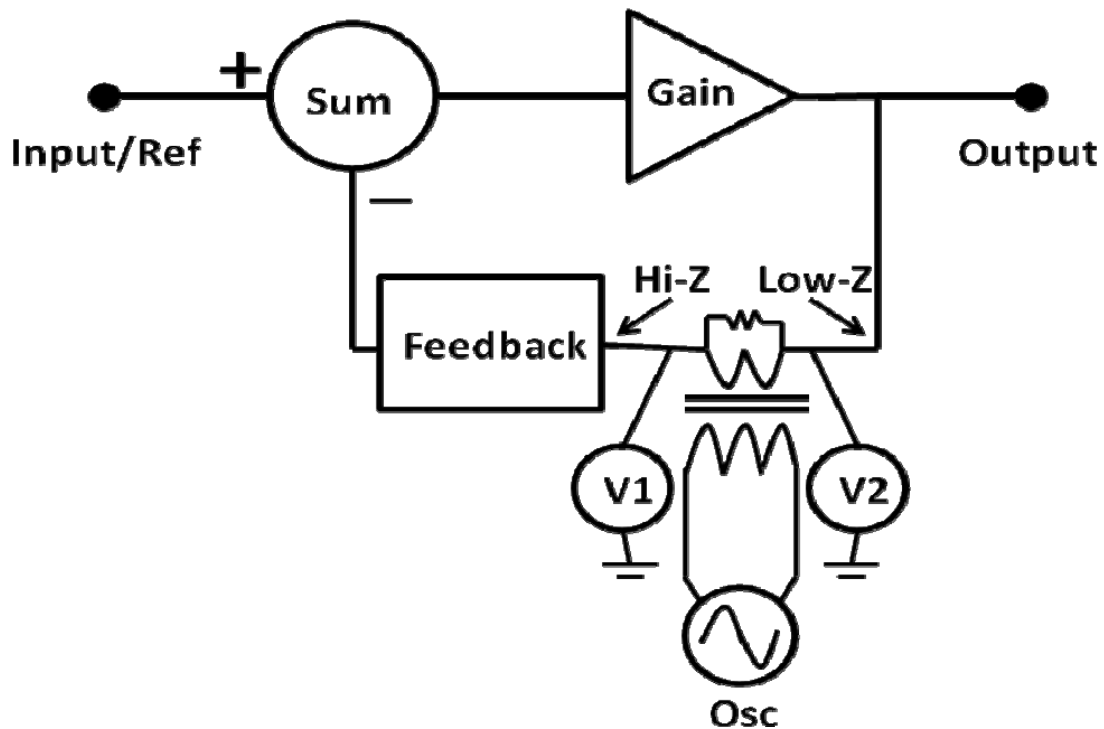


Figure 2. Injecting an AC Test Signal into the Control Loop of a Closed-Loop Control System

We started the investigation by measuring the frequency response of the gain and phase of the closed-loop power supply circuit with the output connected to a load of roughly 80% of the supply's rating. The strategy for injecting a stimulus signal and collecting stimulus and response measurement data is illustrated in Figure 2 and is described in various publications^{9,10}.

The challenge is to introduce an isolated stimulus signal into the control loop and collect vector response data (gain and phase) without significantly altering the loop characteristics or introducing significant external noise. The insertion point must be somewhere where the impedance looking into the loop in one direction is very low while looking into the loop in the other direction the impedance is very much higher. When these conditions are true, virtually all the stimulus signal appears at V1 in Figure 2 while essentially only the response signal appears at V2.

For this paper, V1 and V2 were measured with a high-speed, dual-channel digital oscilloscope and the stimulus signal was generated with an arbitrary waveform generator set to produce a sinewave. The time-domain waveforms from the oscilloscope were post-processed with Fast Fourier Transform to remove much of the uncertainty of visual interpretation of the somewhat distorted and noisy AC signals. The result is gain and phase data at discrete frequencies between 1 kHz and 100 kHz. The nominal switching frequency of the power supply circuit is roughly 300 kHz.

Three test conditions were investigated. The gain and phase data for these test conditions appear in Figure 3. First the circuit was measured with only the low-ESR polymer tantalum capacitor installed. This capacitor has ESR of $15 \pm 1 \text{ m}\Omega$ from roughly 5 to 100 kHz, rising to $27 \text{ m}\Omega$ at 1 kHz.

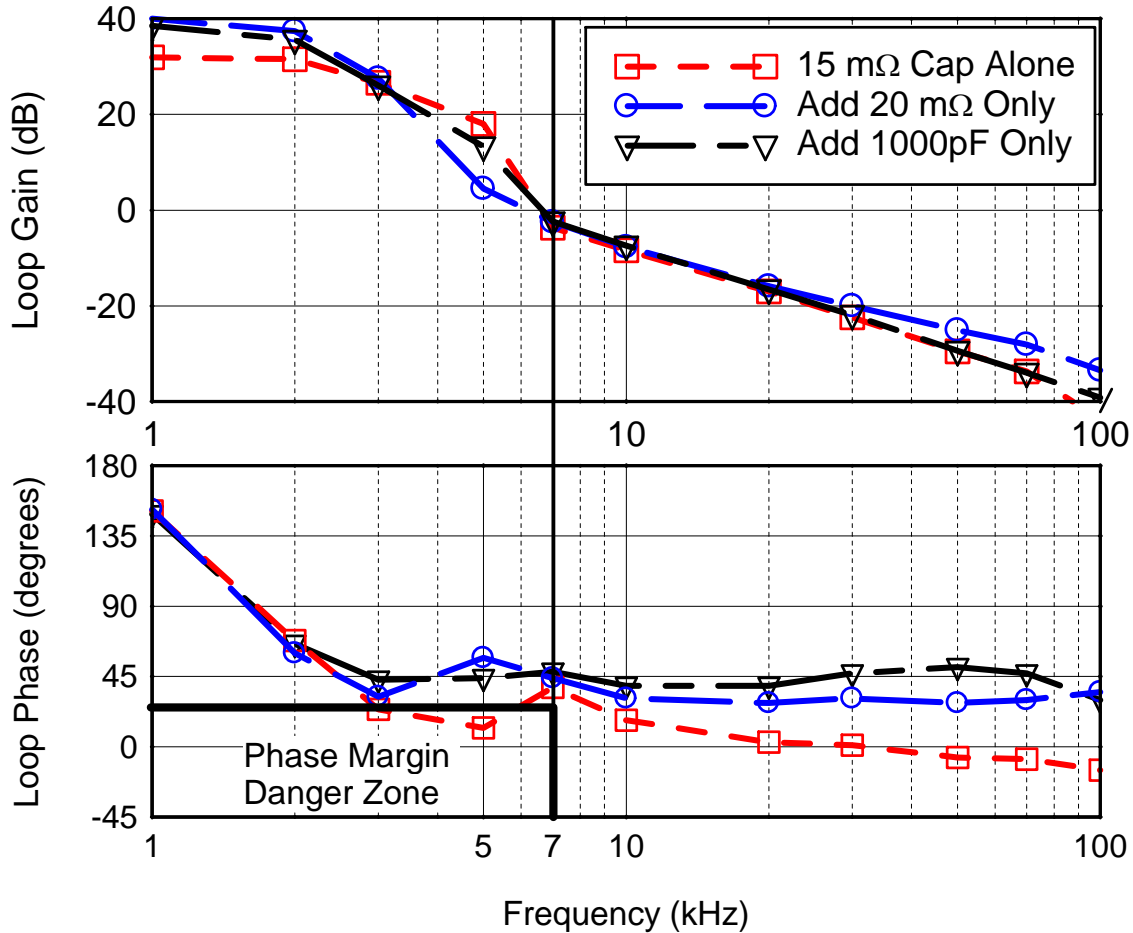


Figure 3. Closed-Loop Gain and Phase Data for Single-Chip-Controller Power Supply Circuit in Various Configurations.

In the second measurement configuration, a $20 \text{ m}\Omega$ resistor was added in series with the capacitor, raising its ESR to a total of roughly $35 \text{ m}\Omega$. This was done to observe changes to phase margin caused by adding ESR to the filter capacitor.

Finally, the additional $20 \text{ m}\Omega$ resistor was removed, and a 1000 pF external compensation capacitor was added to the feedback voltage divider circuit to improve the phase margin. This step demonstrates that it is possible to stabilize the circuit with minimal additional cost if the benefits of employing the higher-performance low-ESR capacitor are desired.

Observe that for all configurations, the gain falls below 1 (0 dB) at 7kHz from a much higher gain of about 50 to 100 (35-40 dB) at 1 kHz. So the “danger zone” for instability is the region of the phase plots in Figure 3 where the phase falls below about 30 degrees at frequencies below 7 kHz where gain remains above one.

For the case of the 15 mΩ capacitor alone, the phase margin falls to about 12 degrees at 5 kHz. This is a very small phase margin and it is not surprising that the circuit is unstable and demonstrates a low level of oscillation. This oscillation can be seen in Figure 4 where the output waveforms of the power supply circuit appear for the various configurations.

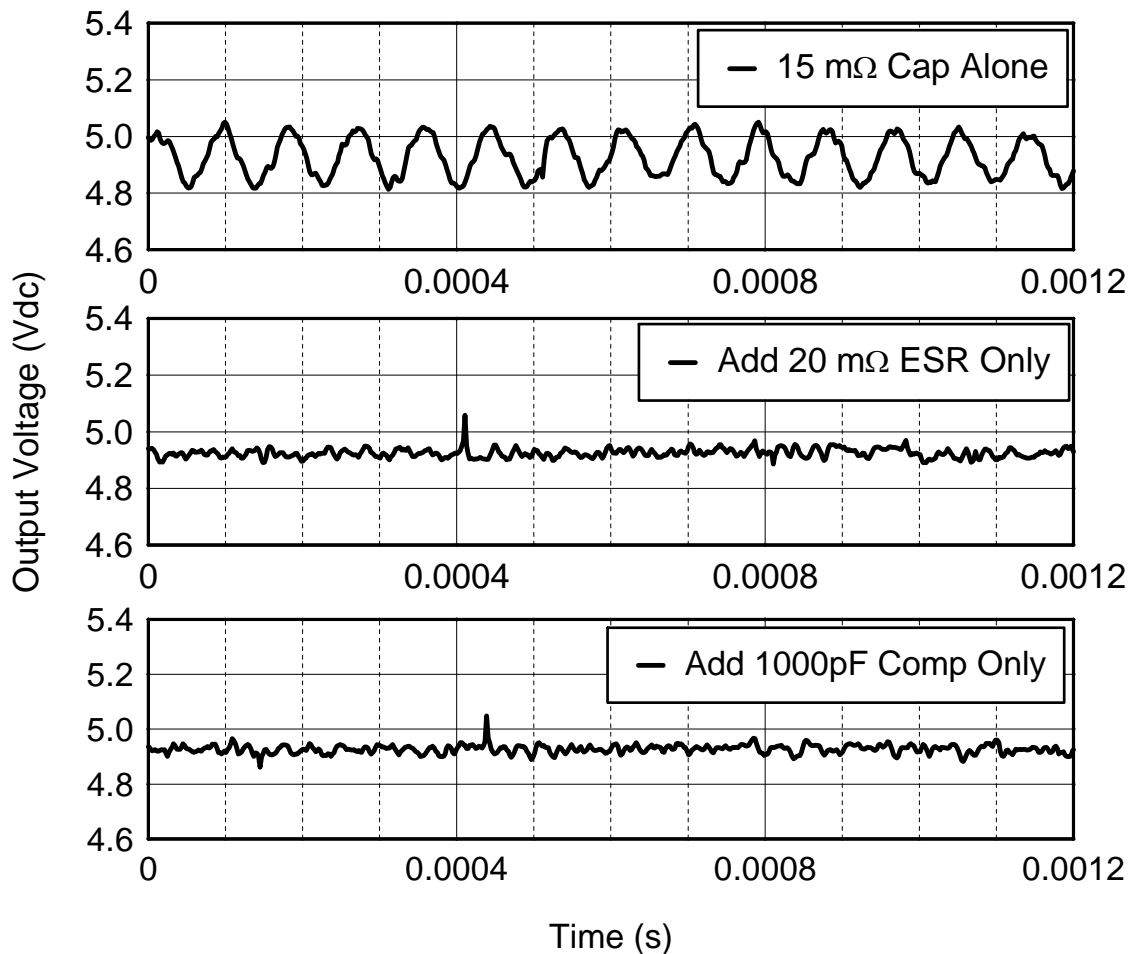


Figure 4. Output Voltage Waveforms for Single-Chip-Controller Power Supply Circuit in Various Configurations.

When the 20 mΩ resistor is added to the 15 mΩ capacitor, the phase margin increases to above 30 degrees at 4 kHz and to above 45 degrees at the original troublesome frequency of 5 kHz. The improved output waveform for this configuration appears in Figure 4.

The final configuration involves removing the added 20 mΩ resistor and adding a 1000 pF capacitor in parallel with the upper resistor of the feedback circuit’s voltage divider. Adding this external phase compensation capacitor more uniformly raises the phase margin to roughly 45 degrees without sacrificing any of the advantages that can be obtained by using a low-ESR filter capacitor. The output waveform for this configuration also appears in Figure 4.

Overall improvement of the waveforms of Figure 4 by adding the 1000 pF capacitor, versus simply adding ESR, is small. But it does appear that the prominent switching spike is somewhat attenuated. The waveforms are not particularly noise-free in general. It is likely that some of this noise is introduced by connection of the external stimulus and measurement circuitry needed for the gain/phase measurements.

One Remaining Mystery

One additional detail of the data of Figure 4 is worthy of comment. Observe that the frequency of oscillation in Figure 4 is about 12 kHz, while the frequency of the bad phase margin in Figure 3 for the unstable case is 5 kHz. One would think that the oscillation should occur at a frequency close to 5 kHz. Moreover, since there isn't any phase margin problem at 12 kHz (the gain is only 0.35 [-9 dB] when the circuit is excited only at 12 kHz), oscillation at this frequency is not likely. So what is going on?

A possible answer to this question appears in Figure 5. Figure 5 is the Fast Fourier Transform of the time-domain oscilloscope record of the V1 and V2 data collected with 5 kHz excitation and only the 15 mΩ filter capacitor connected in the circuit. What is observed is that excitation at 5 kHz not only generates the expected large response at 5 kHz, but also generates strong responses between about 9 and 14 kHz, the strongest of which is at 12 kHz with gain greater than one (V2>V1). So excitation at 5 kHz appears to facilitate responses with gain greater than one near 12 kHz.

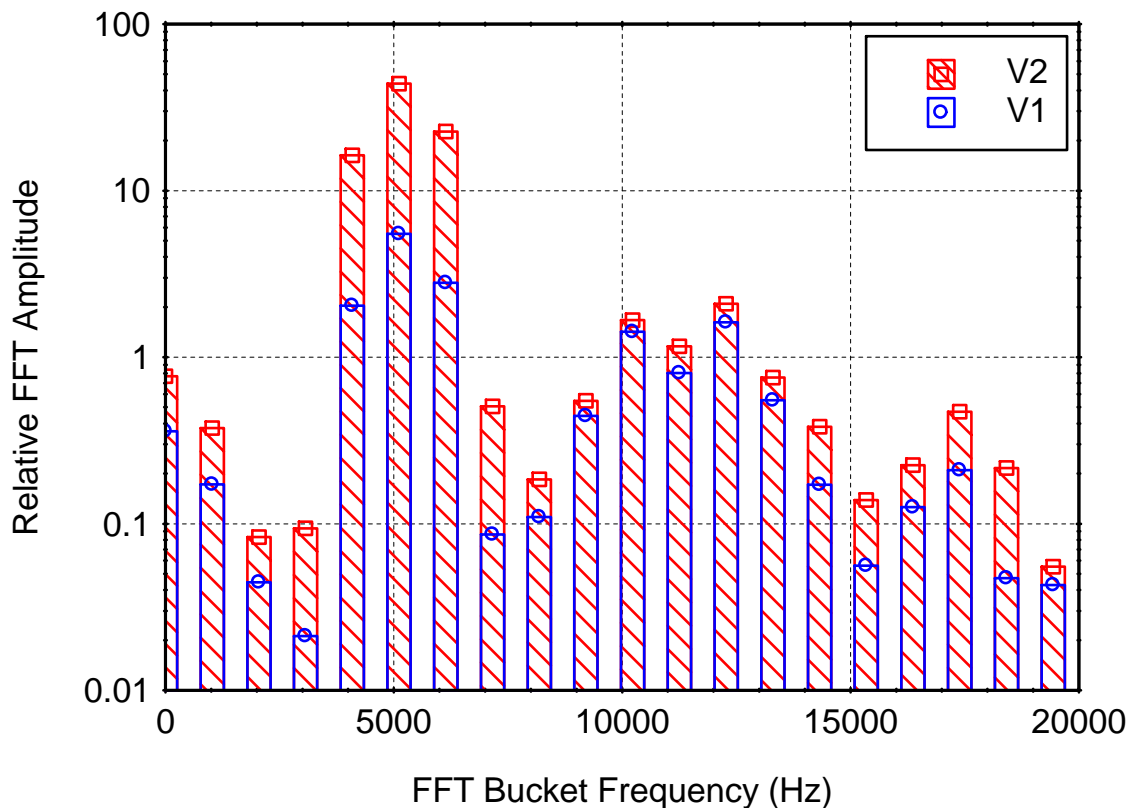


Figure 5. FFT of V1 and V2 Waveforms with 5 kHz Excitation.

Noise spikes from switching in switch-mode power supplies are very rich in spectral content. It appears that these noise spikes may be exciting a response at 5 kHz and, via the 5 kHz response, a secondary response at roughly 12 kHz. But the control loop is selectively encouraging the secondary 12 kHz response and that is the response that actually survives at the output of the power supply when there is no external sinusoidal excitation. This interpretation is consistent with the low phase angle observed near 12

kHz for the unstable case in Figure 3 that could support oscillation, if there were simply more gain, and the fact that gain actually appears at 12 kHz only when the power supply is excited at 5 kHz.

Summary and Conclusions

Switching power supplies are classified in this paper as a special case of automatic feedback control systems. Under ideal circumstances in such systems, a sample of the output signal is inverted (shifted by 180 degrees) and added to a reference signal to generate an error signal. The error signal is amplified and either increases or decreases the output signal. If all goes according to plan, the output remains stable at the desired level and is substantially independent of line or load conditions.

But since phase shift occurs in the control loop, it is possible that the phase of the feedback signal can shift away from the ideal 180 degrees by the time it is compared with the reference signal. If the phase shift reduces the phase margin below roughly 30 degrees before the gain falls to one, it is known from control theory that unstable responses can be expected.

One part of a power supply that contributes to phase shift is the output filter capacitor. The phase shift caused by a low-ESR capacitor is different from, and frequently larger than, the phase shift of a higher-ESR capacitor at a given frequency. Also, combinations of capacitors and inductors can lead to resonant behavior which causes large phase shifts at the same time it introduces additional loop gain.

Phase compensation circuitry is added to controlled power supplies to improve low phase margin. But some power supply control circuits are fully integrated into a single chip and are manufactured with a pre-designed compensation circuit. In this case, if the phase compensation circuit is designed for a higher-ESR filter capacitor, the circuit may become unstable if a low-ESR capacitor is used instead. This is because the pre-designed compensation circuit does not provide appropriate phase compensation to allow acceptable phase margin.

A marginally unstable power supply circuit was investigated to demonstrate and better understand the origin of the instability. It was determined via gain and phase measurements that the power supply's phase margin was inadequate when the low-ESR capacitor was employed. But when additional ESR is added or when additional external phase compensation is introduced, the instability can be substantially removed.

One lesson that can be learned from this case is that it is possible to make things too simple. By integrating the entire control circuit into a single chip, the manufacturer allows his customers to save design time, cost, and board space. All of these are good things. But you never get something for nothing. The price in this case is loss of flexibility to use a higher-performance capacitor in the circuit. So when a low-ESR output filter capacitor is used, the circuit becomes unstable because of inadequate phase compensation.

But the rules of control theory still apply. It was determined that adding some "good" phase shift to the feedback circuit improved the phase margin sufficiently to provide the desired stability while still allowing the advantages of using a very low ESR capacitor.

It is the purpose of this paper to describe this experience in simple terms so that capacitor customers using these simplified power supply circuits can better understand what is "going on under the hood" of these devices. This is especially important when performance does not meet expectations. Finally, it would be unfair for the low-ESR capacitor to take all the blame for the troublesome unstable power supply behavior.

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