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Grounding and Decoupling: Learn Basics Now and Save Yourself Much Grief Later! Part 3: Decoupling Continued

By **Walt Kester**

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In the last article we covered the basics of decoupling and its importance in achieving desired performance levels from integrated circuits (ICs). In this article, we explore the details of capacitors—the fundamental circuit component used for decoupling.

Real Capacitors and Their Parasitics

Figure 1 shows a model of a real capacitor. The nominal capacitance (C) is shunted by a resistance, R_P, which represents insulation resistance or leakage. A second resistance, R_S (equivalent series resistance, or ESR), appears in series with the capacitor and represents the resistance of the capacitor leads and plates.

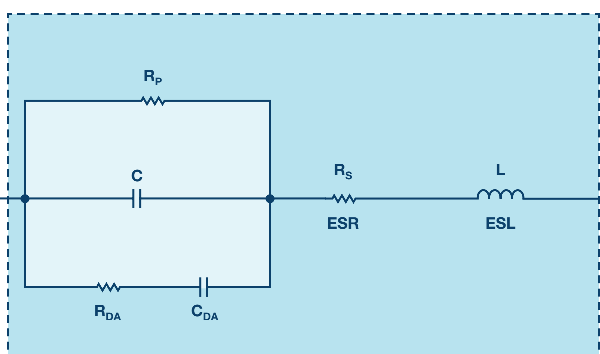

Figure 1. A real capacitor equivalent circuit includes parasitic elements.

Inductor L (the equivalent series inductance, or ESL) models the inductance of the leads and plates. Finally, resistance (R_{DA}) and capacitance (C_{DA}) together form a simplified model of a phenomenon known as dielectric absorption (DA). When a capacitor is used in a precision application, such as a sample-and-hold amplifier (SHA), DA can cause errors. In a decoupling application, however, the DA of a capacitor is not important and will be ignored.

Figure 2 shows the frequency response of various types of 100 µF capacitors. Theory tells us that the impedance of an ideal capacitor decreases monotonically as frequency is increased. In actual practice, the ESR causes the impedance plot to flatten out. As we continue up in frequency, the impedance will start to rise due to the ESL of the capacitor. The location and width of the knee will vary with capacitor construction, dielectric, and value. This is why in decoupling applications we often see larger value capacitors paralleled with smaller values. The smaller value capacitor will typically have lower ESL and continue to behave like a capacitor at higher frequencies. The parallel combination of capacitors covers a wider frequency range than either one of the combinations.

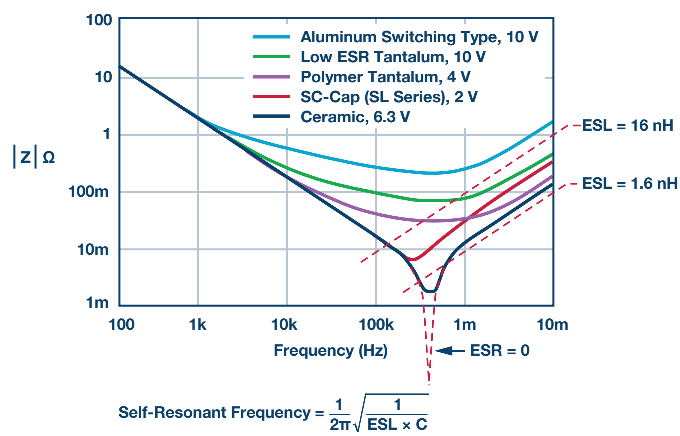

Figure 2. Impedance of various 100 µF capacitors.

The self-resonant frequency of the capacitor is the frequency at which the reactance of the capacitor (1/ωC) is equal to the reactance of the ESL (ωESL). Solving this equality for the resonant frequency yields:

$$f_{RESONANCE} = \frac{1}{2\pi\sqrt{ESL \times C}}$$

All capacitors will display impedance curves that are similar in general shape to those shown. The exact plots will be different, but the general shape stays the same. The minimum impedance is determined by the ESR and the high frequency region is determined by the ESL, which in turn is strongly affected by package style.

Types of Decoupling Capacitors

The electrolytic family of capacitors provides an excellent, cost-effective low frequency filter component because of the wide range of values, a high capacitance-to-volume ratio, and a broad range of working voltages. The family includes general-purpose aluminum electrolytic switching types available in working voltages from below 10 V, up to about 500 V, and in sizes from 1 µF to several thousand µF (with proportional case sizes).

All electrolytic capacitors are polarized and thus cannot withstand more than a volt or so of reverse bias without damage. They have relatively high leakage currents (this can be tens of µA) that are strongly dependent upon specific family design, electrical size, and voltage rating versus applied voltage. However, leakage current is not likely to be a major factor for basic decoupling applications.

General-purpose aluminum electrolytic capacitors are not recommended for most decoupling applications. However, a subset of aluminum electrolytic capacitors is the switching type that is designed and specified for handling high pulse currents at frequencies up to several hundred kHz with low losses. This type of capacitor competes directly with the solid tantalum type in high frequency filtering applications and has the advantage of a much broader range of available values.

Solid tantalum electrolytic capacitors are generally limited to voltages of 50 V or less, with capacitance of 500 µF or less. For a given size, tantalums exhibit higher capacitance-to-volume ratios than the aluminum switching electrolytics do and have both a higher frequency range and lower ESR. They are generally more expensive than aluminum electrolytics and must be carefully applied with respect to surge and ripple currents.

More recently, high performance aluminum electrolytic capacitors using organic or polymer electrolytes have appeared. These families of capacitors feature appreciably lower ESR and higher frequency range than the other electrolytic types, with an additional feature of minimal, low temperature ESR degradation. They are designated by labels such as aluminum-polymer, special polymer, POSCAP™, and OS-CON.™

Ceramic or multilayer ceramic (MLCC) is usually the capacitor material of choice above a few MHz, due to its compact size and low loss. However, the characteristics of ceramic dielectrics widely vary. Some types are better than others for power supply decoupling applications. Ceramic dielectric capacitors are available in values up to several µF in the high K dielectric formulations of X7R. Z5U and Y5V types can be at voltage ratings up to 200 V. The X7R type is preferred because it has less capacitance change as a function of dc bias voltage than the Z5U and Y5V types.

NP0 (also called COG) types use a lower dielectric constant formulation, have nominally zero TC, plus a low voltage coefficient (unlike the less stable high K types). The NP0 types are limited in available values to 0.1 µF or less, with 0.01 µF representing a more practical upper limit.

Multilayer ceramic capacitor (MLCC) surface-mount capacitors are increasingly popular for bypassing and filtering at 10 MHz or more, because their very low inductance design allows near optimum RF bypassing. In smaller values, ceramic chip caps have an operating frequency range to 1 GHz. For these and other capacitors for high frequency applications, a useful value can be ensured by selecting a capacitor that has a self-resonant frequency above the highest frequency of interest.

In general, film type capacitors are not useful in power supply decoupling applications because they are generally wound, which increases their inductance. They are more often used in audio applications where a very low capacitance vs. voltage coefficient is required.

And finally, always remember to select a capacitor that has a breakdown voltage at least twice the supply voltage or you may get an unwanted surprise when you power up the circuit.

Effects of Poor Decoupling Techniques on Performance

Figure 3 shows the pulse response of AD8000, a 1.5 GHz, high speed current feedback op amp. Both of the oscilloscope shots were taken using the evaluation board. The left hand trace shows the response with proper decoupling and the right hand trace shows the same response on the same board with the decoupling capacitors removed. The output load in both cases was 100 Ω.

The oscilloscope shots show that without decoupling the output exhibits unwanted ringing that is primarily due to shifts in the power supply voltage with load current.

We will now examine the effect of proper and improper decoupling on a high performance data converter, the AD9445, a 14-bit, 105 MSPS/125 MSPS ADC. While a converter will typically not have a PSRR specification, proper decoupling is still very important. Figure 4 shows the FFT output of a properly designed circuit. In this case, we are using the evaluation board for the AD9445—note the clean spectrum.

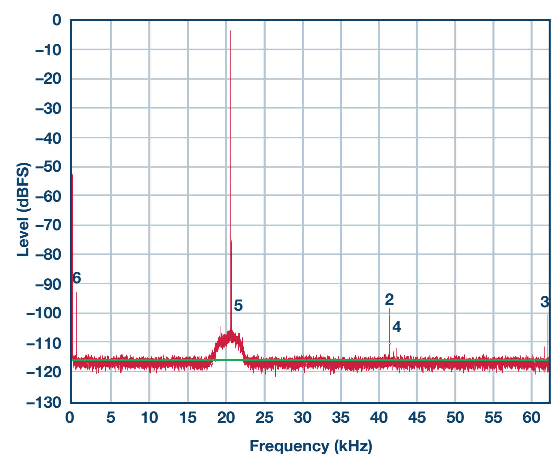

Figure 4: FFT plot for the AD9445 evaluation board with proper decoupling.

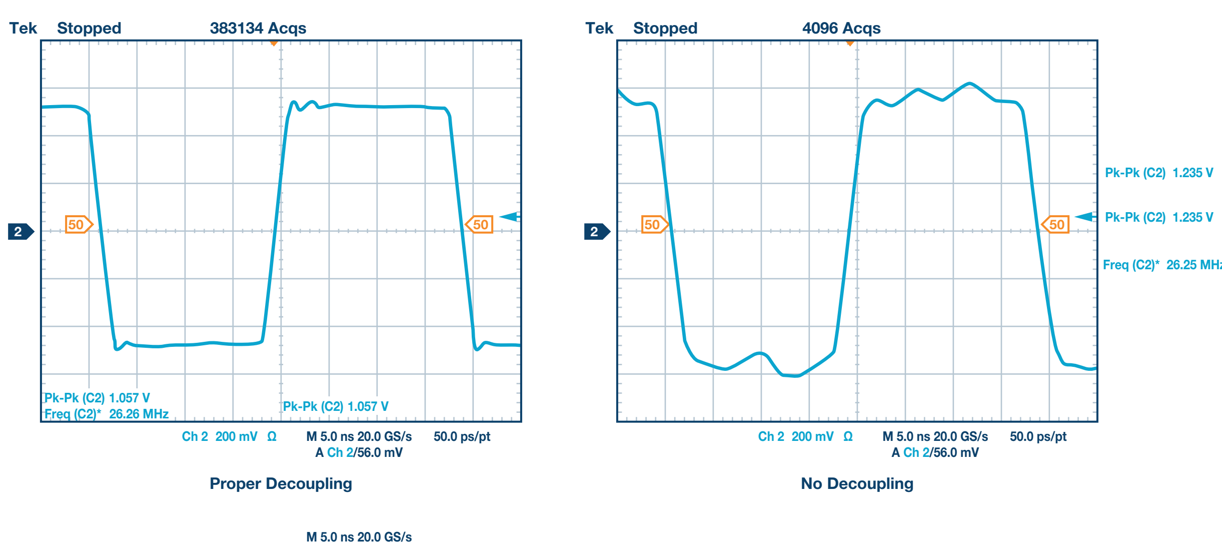

Figure 3. Effects of decoupling on performance of the AD8000 op amp.

The pinout of the AD9445 is shown in Figure 5. Note that there are multiple power and ground pins. This is done to lower the impedance of the power supply (pins in parallel).

There are 33 analog power pins. 18 pins are connected to AVDD1 (which is 3.3 V 5%) and 15 pins are connected to AVDD2 (which is 5 V ±5%). There are four DVDD (which is 5 V ±5%) pins. On the evaluation board used in this experiment, each pin has a 0.1 µF ceramic decoupling cap. In addition, there are several 10 µF electrolytic capacitors as well along the power traces.

Figure 6 shows the spectrum with the decoupling caps removed from the analog supply. Note the increase in high frequency spurious signals, as well as some intermodulation products (lower frequency components). The SNR of the signal has obviously decreased. The only difference between this figure and the last is removal of the decoupling capacitors.

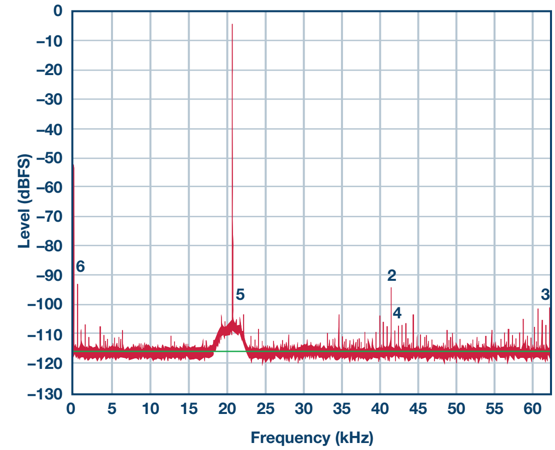

Figure 6. FFT plot for an AD9445 evaluation board with decoupling capacitors removed from the analog supply.

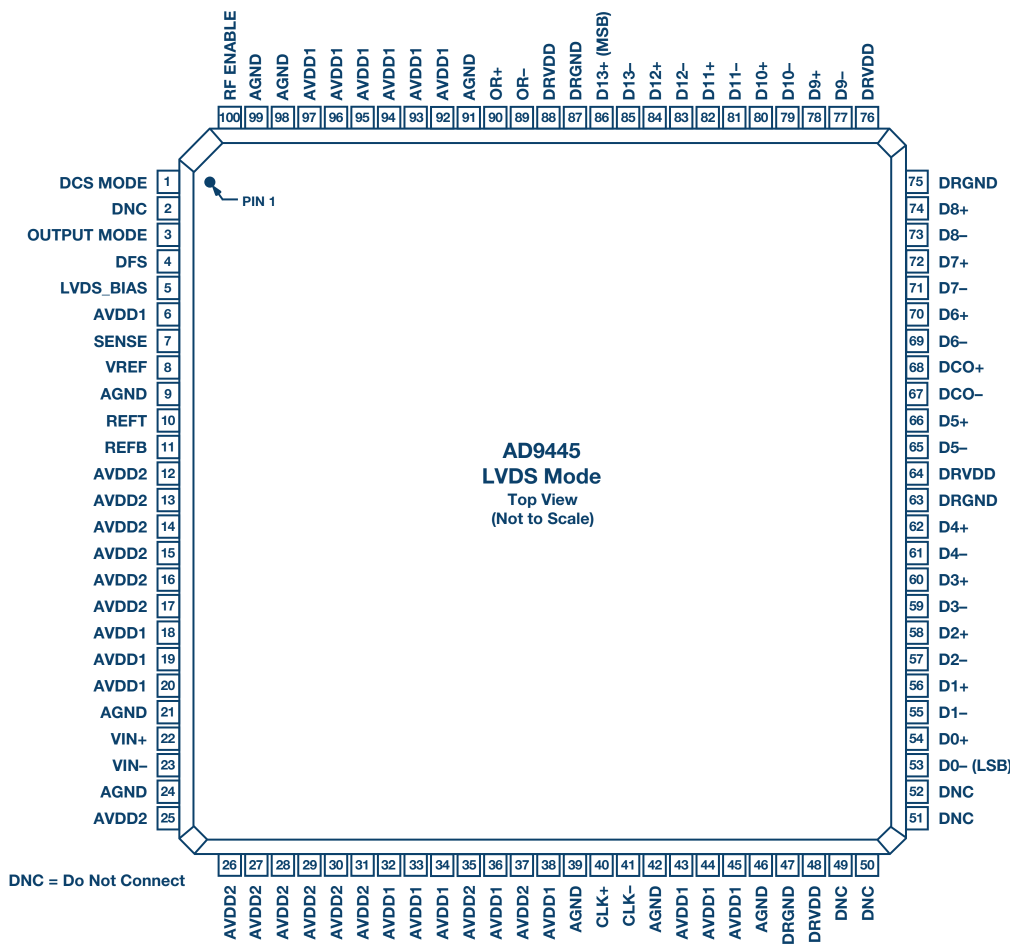

Figure 5. AD9445 pinout diagram.

Figure 7 shows the result of removing the decoupling caps from the digital supply. Again, note the increase in spurs. Also, note the frequency distribution of the spurs. Not only do these spurs occur at high frequencies, but across the spectrum. This experiment was run with the LVDS version of the converter. We can assume that the CMOS version would be worse, because LVDS is less noisy than saturating CMOS logic.

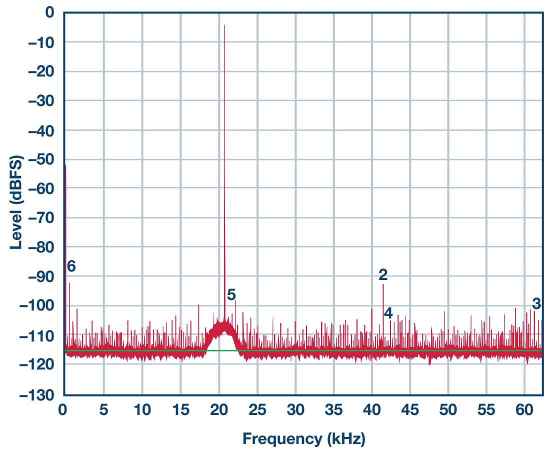

Figure 7. SNR plot for an AD9445 evaluation board with decoupling capacitors removed from the digital supply.

While these experiments show the performance degradation by removing most or all of the decoupling capacitors, it is difficult to analyze or predict the degradation of leaving off one or two. The best philosophy is to put in the capacitor in when doubt. It is usually well worth the slight additional cost, rather than risking performance.

Decoupling Summary

There is much more to say about decoupling but we hope you get the general idea of its role in achieving desired system performance. Although the basic guidelines outlined in these articles illustrate the key concepts, you should refer to the other references for more detailed information. Another great source for guidance are the manufacturers' evaluation boards, which are available for most IC products. In many cases you can download the schematic, layout, and parts list, and see what was done with respect to decoupling without having to actually purchase the board itself. You can be sure these boards have been carefully designed to achieve optimum performance for the IC under evaluation.

So now, we end the article with the traditional circuit quiz shown in Figure 8.

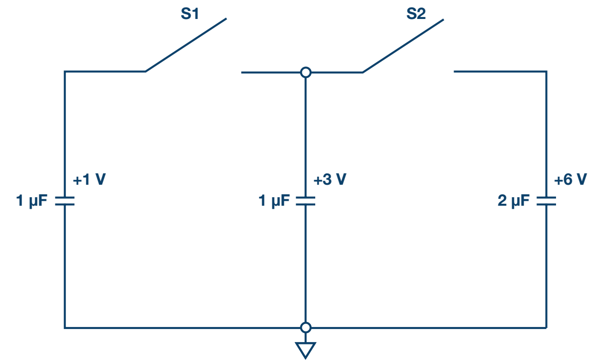

Figure 8. Quiz: The three ideal capacitors are charged to the voltages shown. What is the final voltage across the bank after closing S1 and then S2? What is the final voltage across the bank if the order of switch closings is reversed?

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Walt Kester [walt.kester@analog.com] is a corporate staff applications engineer at Analog Devices. During his many years at ADI, he has designed, developed, and given applications support for high speed ADCs, DACs, SHAs, op amps, and analog multiplexers. An author of many papers and articles, he prepared and edited 11 major applications books for ADI's global technical seminar series; topics include op amps, data conversion, power management, sensor signal conditioning, mixed-signal circuits, and practical analog design techniques. His latest book, *The Data Conversion Handbook* (Newnes), is a nearly 1000-page comprehensive guide to data conversion. Walt has a B.S.E.E. from NC State University and an M.S.E.E. from Duke University.

Walt Kester