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APPLICATION NOTE 5663

Passives Aren't Really So Passive: Part 1, Capacitors

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Jul 08, 2013

Abstract: Active components like transistors and integrated circuits change signals using energy from the power supply. Conversely, passive components like resistors, capacitors, inductors, and connectors do not consume power—or so we like to assume. However, passive components actually can and do change the signal in unexpected ways because they all contain parasitic components. This application note, the first in a 3-part series, discusses parasitic capacitance.

A similar version of this article appears on *Electronic Design*, June 4, 2013.

Click here for an overview of the wireless components used in a typical radio transceiver.

Introduction

Active components and passive components—is engineering design really this black and white?

Transistors and integrated circuits are considered active components because they change signals using energy from the power supply. Meanwhile, we call components like capacitors, resistors, inductors, connectors, and even the PC board (PCB) passive because they do not seem to consume power. However, these apparently passive components can, and do, change the signal in unexpected ways because they all contain parasitic portions. So, in fact, many supposedly passive components are not so passive. In this application note, Part 1 of a 3-part series on passives, we look at the active role of capacitors.

The Not-So-Passive Capacitor

Passive can be defined as inert and/or inactive. But passive electronic components can become an active part of a circuit in unexpected ways. Consequently, a capacitor that is purely capacitive simply does not exist. All capacitors inherently have parasitic components (**Figure 1**).

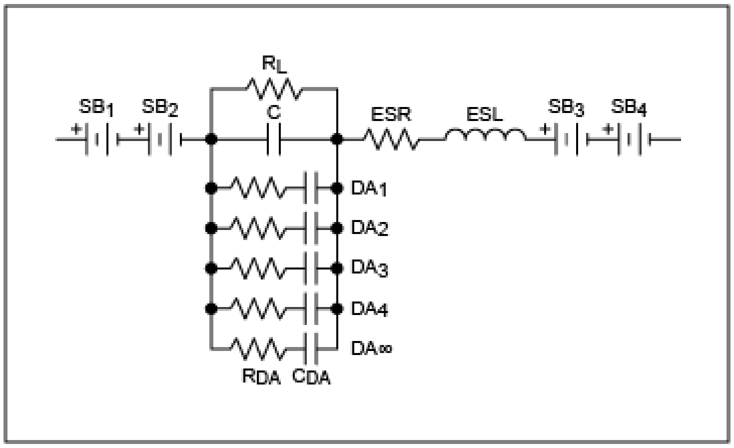

Figure 1. The capacitor (C) and its largest parasitic components.

Let's take a closer look at the active parasitic components in Figure 1. The capacitor labeled "C" is the one thing that we would like to see; all the rest of the components are unwanted parasitics.[1] The parallel resistor, R_L, causes DC leakage, which can change the bias voltage of the active circuits, spoil the Q factor in filters, and defeat the holding ability of a sample-and-hold circuit.[2] The equivalent series resistance (ESR) reduces the capacitor's ability to reduce ripple and pass high-frequency signals because the equivalent series inductance (ESL) creates a tuned circuit (i.e., a circuit with self-resonance). This means that above the self-resonance frequency, the capacitor looks inductive and can no longer decouple high-frequency noise from the power supply to ground. The dielectric can be piezoelectric, adding noise from vibration (AC), which would look like a battery inside the C capacitor (not drawn). The piezoelectric effect from the stress of cooling solder can change the value of the capacitor. Polarized electrolytic capacitors can also have parasitic diodes in series (not drawn) and those diodes can rectify high-frequency signals and change bias or add unwanted distortion.

The small batteries SB_1 through SB_4 indicate Seebeck junctions[3] where dissimilar metals (parasitic thermocouples) create voltage sources. When we connect our test equipment, we need to consider the Seebeck effect of common connectors. Appendix J, Figure J5 in Jim Williams' application note[4] shows that the thermoelectric potential of pairs of BNC and banana connectors ranges from 0.07µV/°C to 1.7µV/°C. This variance is just for a simple connection that we do every day in the lab. Multiply that seemingly small offset gain by one thousand and we have 1.7mV—and that is before we actually do anything productive.

SB_2 and SB_3 could be inside the capacitor where foil connects to the leads or the metallization connects to the plating or solder in a surface-mount part. SB_1 and SB_4 indicate the junction from the part through the solder to the copper PCB trace. Solder was once simple 63% lead and 37% tin. But today one has to ask about the contents of the alloy because lead-free RoHS solders can vary greatly and influence the voltage around the capacitor.

Dielectric absorption, DA, or what Bob Pease called "soakage," can be modeled as an infinite number of different RC time constants, DA_1 through $DA_{INFINITY}$. Each of those time constants is composed of a resistor, R_{DA}, and a capacitor, C_{DA}. Bob Pease gave us some practical examples of when "soakage" matters, and I recall an interesting experience with soakage in the Appendix.

"Well, if you turn your color TV off and open up the back, what's the first thing you have to do before you start working on it? Put a grounding strap on a screwdriver and reach under the rubber shroud on the HV plug to discharge the CRT. OK, now that capacitance has been discharged, how much voltage will "soak" back into the "capacitance" of the picture tube if you let it sit for about 10 minutes? Enough to make a visible arc when you discharge it the SECOND time...now that's what I call dielectric absorption."[5]

So capacitors can change capacitance with applied voltage. Then add typical aging, temperature dependence, and the many ways that capacitors can be physically damaged,[6] and this simple passive component becomes far more complex.

Now we should say something about self-resonance, the most common capacitor issue with decoupling capacitors and poor grounds. No capacitor can do its job if the ground is poor. Capacitance self-resonance is dominated by the effect of the ESL shown in Figure 1. But do not discount the effect of the PCB vias either. At radio frequencies, those vias will affect the self-resonance point of small capacitors. Examine **Figure 2** and concentrate on the 1µF curve.

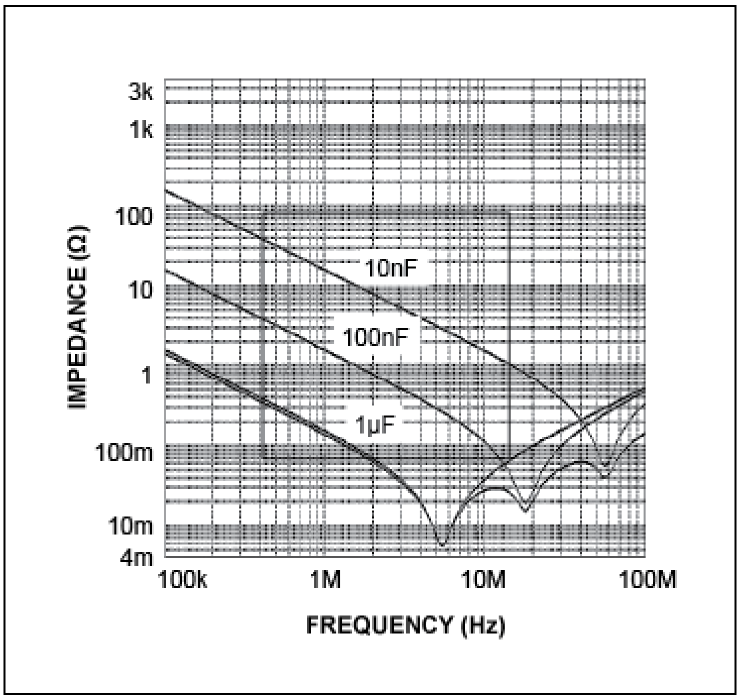

Figure 2. Self-resonance (lowest point on the graph) of three capacitors. Graph shows that capacitors do not all perform identically. On the left side as the traces (impedances) are moving downward, the capacitors act as capacitors. However, when they reach their lowest point and start upward, they become inductors (ESL) and are no longer effective as decoupling capacitors.

The 1µF trace finds a minimum at 4.6MHz. Above that frequency, the ESL dominates and the capacitor operates like an inductor. This tells us that the decoupling capacitor is a two-way conduit for high frequencies: high frequencies on the power bus are shared with the ground, and vice versa. The capacitor homogenizes the difference between the power and ground.

Thinking more about signal frequencies and capacitors, we might forget about the harmonics or sideband that we create. For example, a real 50MHz square-wave SPI clock will have odd harmonics to infinity. Most systems, but not all systems, can ignore harmonics above the fifth harmonic because the energy is so low that it is below the noise floor. However, the harmonics can still cause problems if they become rectified in a semiconductor and can be transformed into new lower frequency interference.

Manipulating Manufacturing Tolerances

Figure 2 shows that not all capacitors are created equal. In general, high-quality capacitors are quite repeatable, while some inexpensive capacitors can trade large manufacturing tolerances for lower cost. Some manufacturers "bin" (**Figure 3**) or select capacitors with a tight tolerance and that will sell for a premium price. This can be detrimental if that capacitor is used to set a time or frequency in the system.

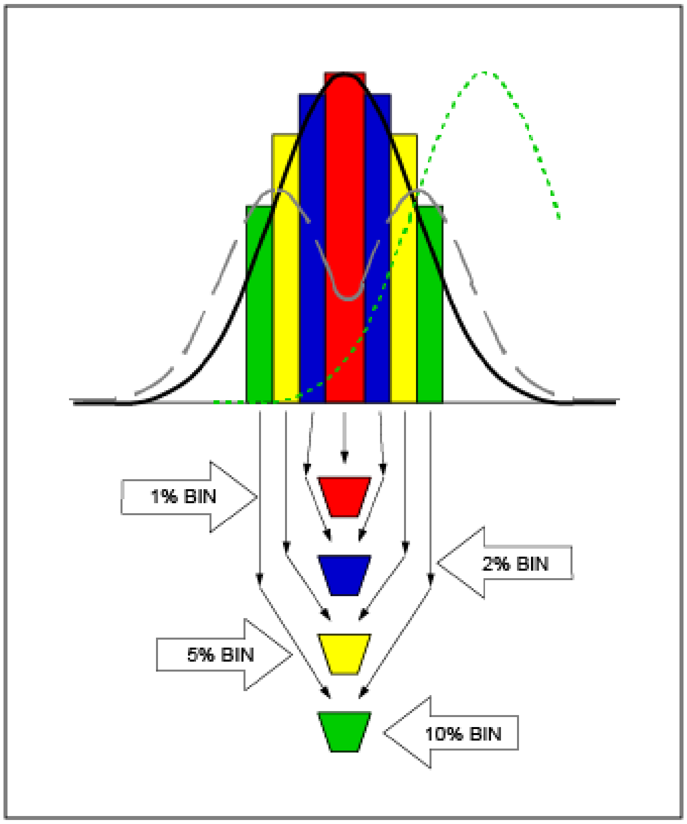

Figure 3. Binning, or sorting, of manufacturing tolerances affects capacitor performance in different ways.

The solid (black) curve in Figure 3 is the standard deviation of a good manufacturing process. Although we used this illustration for resistors in Maxim Integrated's application note 4301, "The Zero-Transistor IC, a New Plateau in IC Design," the data apply equally for capacitors. As the manufacturing tolerances move, the number of parts in each bin changes. The tolerance could move to the right (the green dotted line), resulting in no yield at 1% tolerance. It could be bimodal (gray dashed line) with many 5% and 10% tolerance parts and few 1% and 2% tolerance parts.

Binning "seems" to ensure that the 2% tolerance parts are only from minus 1 to minus 2 and plus 1 to plus 2 (i.e., no 1% parts). It also "appears to" remove any 1% and 2% tolerance parts from the 5% bin. We say "seems to" and "appears to" because sales volume and human nature also influence the mix. For example, the plant manager may need to ship 5% tolerance capacitors, but he does not have enough to meet the demand this month. He does, however, have an overabundance of 2% tolerance parts. So, this month he throws them into the 5% bin and makes the shipment. Clearly deliberate, human intervention can, and does, skew the statistics and method.

What does this mean for our passive capacitors? We must understand that the tolerance we might expect, for example ±5%, may have a ±2% hole in the middle. We need to allow for this if the capacitor controls a critical frequency or timing. It also could mean that we need to plan on correcting wider variation with calibration.

How Soldering Can Influence Passive Performance

Soldering introduces stress in the capacitors, and especially in surface-mount parts. That stress can cause piezoelectric voltages with vibration and even crack the capacitor so it later fails.

It is impressive to see proper reflow soldering. The surface tension of the melting solder causes the parts to rotate into alignment as if by magic. But poor solder-temperature profiles can really damage the device. Have you seen capacitors stand up on one end like a tombstone? This can happen if the solder temperature ramp is wrong. Always follow the manufacturer's solder-profile recommendations. Some components are more sensitive to temperature, so the board assembly may require two or more solders with different melting temperatures. Most components in a circuit are soldered first with the highest melting point solder and then any "sensitive" components are soldered at lower temperatures. The solders must be used in the right order so that those parts soldered early in the process are not unsoldered later.

Summary

When we speak of passives like capacitors, we must remember that these devices all contain parasitic portions that can change a signal. The impact of this, of course, depends on the signal strength. If we want to measure microvolts, then everything counts: grounding (star points), shielding decoupling capacitors, guarding, layout, the Seebeck effect, cable construction, and soldering connectors. Our schematics usually gloss over this, which is acceptable until we are looking for small noise or voltages.

Remember that a passive capacitor is just one component and is really more active than it appears. There are subtle effects of component parasitics, tolerance, calibration, temperature, aging, and even assembly methods and practices that will influence the device's performance. Knowing that, we need to understand the potential errors that can accumulate with numerous capacitors. In future application notes in this 3-part series, we will discuss other so-called passive components: resistors, potentiometers, switches, and, surprisingly, the lowly PCB.

Finally, AVX and Kemet are capacitor companies that specify parasitic components and provide free Spice tools.[7] These Spice tools allow us to graph the actual performance of the capacitors. The application notes on both of their websites are also very informative.

References

1. For information on distortions caused by capacitors, see "Capacitor Distortion Mechanisms," TWEM (The Electric Web Matrix of Digital Technology), www.co-

bw.com/Audio_Capacitor_Distrotion_Mechanisms.htm. Note: the author realizes that the word “distrotion” in this URL is misspelled, but the URL is correct as shown.

2. Bob Pease, “What's All This Capacitor Leakage Stuff, Anyhow?,” Electronic Design, March 29, 2007, http://electronicdesign.com/analog/whats-all-capacitor-leakage-stuff-anyhow.

3. Jim Williams used an “x” to indicate a Seebeck junction. He would count the junction in parallel paths and purposely cut the PC trace and solder them back together to make equal numbers of junctions. See Jim Williams et al, application note 86, “A Standards Lab Grade 20-Bit DAC with 0.1ppm/°C Drift,” http://cds.linear.com/docs/en/application-note/an86f.pdf. See also Bob Pease, “Understand capacitor soakage to optimize analog systems,” http://yawp.com/ref-library/App%20Notes/Bob%20Pease/Understand%20capacitor%20soakage%20to%20optimize%20analog%20systems.pdf. For more general information on the Seebeck effect, you can start at http://en.wikipedia.org/wiki/Thermoelectric_effect.

4. Williams et al, “A Standards Lab Grade 20-Bit DAC.”

5. Bob Pease, “What's all this soakage stuff, anyhow?,” Electronic Design, May 13, 1998, http://electronicdesign.com/analog/whats-all-soakage-stuff-anyhow.

6. John Maxwell, “TECHNICAL INFORMATION, CRACKS: THE HIDDEN DEFECT,” AVX Corporation.

7. Spice tools for Kemet® can be found near the bottom of the page at www.maximintegrated.com/cal.

8. Keith Snook, “WHAT’S ALL THIS TRAPPED CHARGE AND DIELECTRIC COMPRESSION STUFF ANYHOW?,” www.keith-snook.info/capacitor-soakage.html.

Appendix

Dielectric Absorption, Soakage, and Voltage Discharge from a Supposedly Passive Capacitor

My first experience with soakage was a pleasant one, not like my first experience measuring a power transformer.

When I was a teenager, a local “ham” operator (a mid-twentieth century term for an amateur radio hobbyist—am I giving away too much of my age?) repaired TV sets in his garage. I learned a lot from him, some by practical demonstration. He had a disconnected power transformer with bare leads lying on the bench. He suggested that I could measure the resistance with an ohm meter on the same bench. Naively, I grabbed the two probes and pinched each probe to a bare wire. Zing! Even though the meter was only powered by 3V, the inductive kickback was enough to make me remember not to do that again.

When it came to soakage, he took pity on me. (He wanted me to remember, not to kill me.) This time he grounded out the CRT like Bob Pease did and showed me what charge remained in a few minutes. Then I did it too and was amazed at how long the charge remained—it seems to go on forever. (I think that after a while, I just stopped trying out of boredom.) Keith Snook[8] continues the DA discussion. It is a great subject that deserves more attention.

The answer is inherent in what we all have learned: we can never charge a capacitor completely, unless we wait for infinity. Most circuits are considered practically charged after five time constants when the voltage is at 99.3 percent of the total applied voltage. The reverse is also true when discharging a capacitor. In the case of a CRT starting at a high voltage, it will deliver a painful shock for a long time.

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