BY MARK FORTUNATO • MAXIM INTEGRATED

Why your 4.7-μF ceramic cap becomes a 0.33-μF cap

AN INVESTIGATION INTO TEMPERATURE AND VOLTAGE VARIATIONS IN X7R CAPACITORS UNDERSCORES THE IMPORTANCE OF DATA SHEETS.

A few years ago, after more than 25 years of working with ceramic capacitors, I learned something new about them. I was working on an LED-light-bulb driver, and the time constant of an RC circuit in my project simply did not seem to be right.

I immediately assumed that there was an incorrect component value installed on the board, so I measured the two resistors serving as a voltage divider. They were just fine. I desoldered the capacitor from the board and measured that component; the cap, too, was fine. Just to be sure, I measured and installed new resistors and a new capacitor, fired up the circuit, checked that the basic operation was proper, and then went to see whether the component swap had resolved my RC time-constant problem. It had not.

A TEMPERATURE PROBLEM?

I was testing the circuit in its natural environment: in its housing, which itself was in an enclosure to mimic a "can" for ceiling lighting. The component temperatures in some instances reached well over +100°C. Even in the short time it had taken me to retest the RC behavior, things had become quite hot.

My next conclusion, of course, was that the temperature variation of the capacitor was the issue. I was skeptical of that conclusion even as I drew it, however, because I was using X7R capacitors, which to my recollection varied only ±15% up to +125°C. I trusted my memory, but to be sure, I reviewed the data sheet for the capacitor that I was using.

That is when my ceramic-capacitor reeducation began.

BACKGROUNDER

Table 1 shows the letters and numbers used for various ceramic-capacitor types and what each means. The table describes Class II and Class III ceramics. Without getting too deep into details, Class I capacitors include the common COG (NPO) type; these are not as volumetrically efficient as the ones listed in the table, but they are far more stable over varying environmental conditions, and they do not exhibit piezo effects. The capacitors listed in the table, by contrast, can have widely varying characteristics; they will expand and contract with applied voltage, sometimes causing audible (buzzing or ringing) piezo effects.

Of the many capacitor types shown, the most common, in my experience, are X5R, X7R, and Y5V. I never use the Y5Vs, because they exhibit extremely large capacitance variation over the range of environmental conditions.

When capacitor companies develop products, they choose materials with characteristics that will enable the capacitors to operate within the specified variation (third character; Table 1) over the specified temperature range (first and second characters). The X7R capacitors that I was using should not have varied more than ±15% over a temperature range of –55°C to +125°C, so either I had a bad batch of capacitors or something else was happening in my circuit.

TABLE 1 COMMON CERAMIC-CAPACITOR TYPES

First character: low temp		Second character: high temp		Third character: Change over temp (max)	
Char	Temp (°C)	Num	Temp (°C)	Char	Change (%)
Z	10	2	45	A	±1
Y	30	4	65	B	±1.5
X	55	5	85	C	±2.2
—	—	6	105	D	±3.3
—	—	7	125	E	±4.7
—	—	8	150	F	±7.5
—	—	9	200	P	±10
—	—	—	—	R	±15
—	—	—	—	S	±22
—	—	—	—	T	22, –33
—	—	—	—	U	22, –56
—	—	—	—	V	22, –82

NOT ALL X7Rs ARE CREATED EQUAL

Since my RC time-constant problem was far greater than would be explained by the specified temperature variation, I had to dig deeper. Looking at the data for capacitance variation versus applied voltage for my capacitor, I was surprised to see how much the capacitance changed with the conditions I had set. I had chosen a 16V capacitor to operate with a 12V bias. The data sheet indicated that my 4.7-µF capacitor would typically provide 1.5 µF of capacitance under those conditions. Now, that explained the problem my RC circuit was having.

The data sheet then showed that if I just increased the size of my capacitor from the 0805 to the 1206 package size, the typical capacitance under the specified conditions would be 3.4 µF. This called for more investigation.

I discovered that Murata Manufacturing Co (www.murata.com) and TDK Corp (www.tdk.com) offer nifty tools on their Web sites that let you plot the variations of capacitors over different environmental conditions. I investigated 4.7-µF capacitors of various sizes and voltage ratings. Figure 1 graphs the data that I extracted from the Murata tool for several different 4.7-µF ceramic capacitors. I looked at both X5R and X7R types, in package sizes from 0603 to 1812 and with voltage ratings from 6.3 to 25V dc. Note, first, that as the package size increases, the capacitance variation with applied dc voltage decreases—and does so substantially.

A second interesting point is that, for a given package size and ceramic type, the capacitor voltage rating seems often to have no effect. I would have expected that using a 25V-rated capacitor at 12V would result in less variation than using a 16V-rated capacitor under the same bias. Looking at the traces for X5Rs in the 1206 package, it's clear that the 6.3V-rated part does indeed perform better than its siblings with higher voltage ratings.

TABLE 2 CAPACITANCE OF X7R CAPS WITH A 12V BIAS

Size	C (µF)	% of Nominal
0805	1.53	32.6
1206	3.43	73
1210	4.16	88.5
1812	4.18	88.9
Nominal	4.7	100

If we were to examine a broader range of capacitors, we would find this behavior to be common. The sample set of capacitors that I considered in my investigation did not exhibit the behavior to the same extent as the general population of ceramic capacitors would.

A third observation is that, for the same package, X7Rs have better temperature sensitivity than do X5Rs. I do not know whether this holds true universally, but it did seem so in my investigation.

Using the data from this graph, Table 2 shows how much the X7R capacitances decreased with a 12V bias. Note that there is a steady improvement with progressively larger capacitor sizes until the 1210 size; going beyond that size yields no real improvement.

CHOOSING THE RIGHT CAPACITOR

In my case, I had chosen the smallest available package for a 4.7-µF X7R because size was a concern for my project. In my ignorance, I had assumed that any X7R was as effective as any other X7R; clearly, this is not the case. To get the proper performance for my application, I had to use a larger package.

I really did not want to go to a 1210 package. Fortunately, I

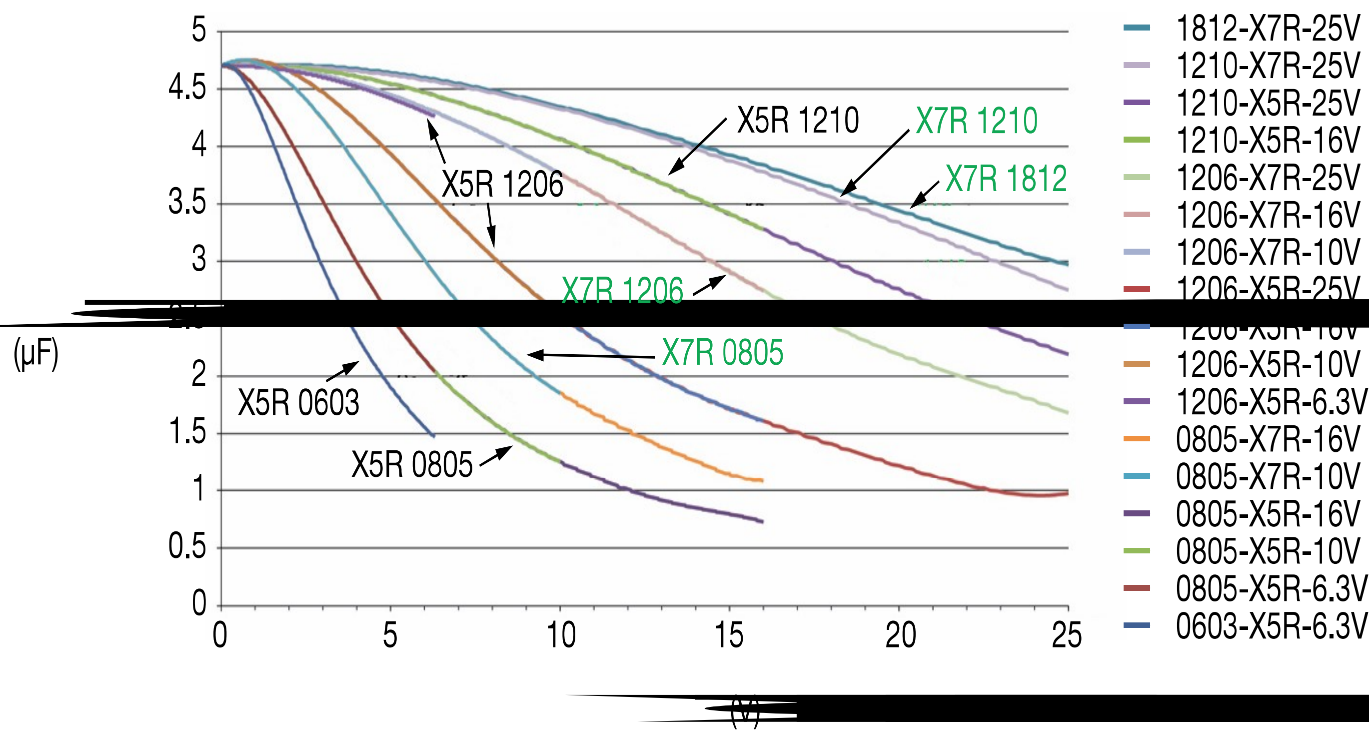

Figure 1 As this graphic representation of temperature variation versus dc voltage for select 4.7-µF capacitors shows, as the package size increases, the capacitance variation with applied voltage substantially decreases.

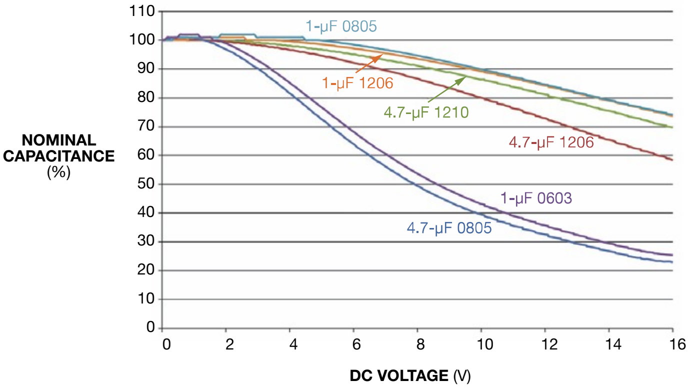

Figure 2 This graph, which plots the voltage performance of 1-μF and 4.7-μF capacitors, shows similar performance for the 1-μF 0603 and the 4.7-μF 0805.

had the freedom to increase the values of the resistors involved by about 5× and thereby decrease the capacitance to 1 μF.

Figure 2 graphs the voltage behavior of several 16V, 1-μF X7R caps versus that of 16V, 4.7-μF X7Rs. The 0603 1-μF capacitor behaves about the same as the 0805 4.7-μF device. Both the 0805 and 1206 1-μF capacitors perform slightly better than the 1210 4.7-μF size. Thus, by using the 0805 1-μF device, I was able to keep the capacitor size unchanged while getting a capacitor that only dropped to about 85% of nominal, rather than 30%, under bias.

But I was still confused. I had been under the impression that all X7R caps should have similar voltage coefficients because the dielectric used was the same, namely X7R. So I contacted a colleague and expert on ceramic capacitors, TDK field applications engineer Chris Burkett, who explained that there are many materials that qualify as “X7R.” In fact, any material that allows a device to meet or exceed the X7R temperature characteristics, ±15% over –55°C to +125°C, can be called X7R. Burkett also explained that there are no voltage-coefficient specifications for X7R or any other ceramic-capacitor type.

This is a critical point, so I will repeat it. A vendor can call a capacitor X7R (or X5R, or any other type) as long as the cap meets the temperature-coefficient specs, regardless of how bad the voltage coefficient is. This fact reinforces the old maxim (pun intended) that any experienced applications engineer knows: Read the data sheet!

As capacitor vendors have turned out progressively smaller components, they have had to compromise on the materials used. To get the needed volumetric efficiencies in the smaller sizes, they have had to accept poorer voltage coefficients. Of course, the more reputable manufacturers do their best to minimize the adverse effects of this trade-off.

Consequently, when using ceramic capacitors in small packages—indeed, when using any component—it is extremely important to read the data sheet. Regrettably, often the commonly available data sheets are abbreviated and will provide little of the information you’ll need to make an informed decision, so you may have to press the manufacturer for more details.

What about those Y5Vs that I summarily rejected? For kicks, let’s examine a common Y5V capacitor. I chose a 4.7-μF, 0603-packaged capacitor rated at 6.3V—I won’t mention the vendor, because its Y5V cap is no worse than any other vendor’s Y5V cap—and looked at the specs at 5V and +85°C. At 5V, the typical capacitance is 92.9% below nominal, or 0.33 μF.

That’s right. Biasing this 6.3V-rated capacitor with 5V will result in a capacitance that is 14 times smaller than nominal.

At +85°C with 0V bias, the capacitance decreases by 68.14%, from 4.7 to 1.5 μF. Now, you might expect this to reduce the capacitance under 5V bias from 0.33 to 0.11 μF. Fortunately, however, those two effects do not combine in this way. In this particular case, the change in capacitance with 5V bias is worse at room temperature than at +85°C.

To be clear, with this part under 0V bias, the capacitance drops from 4.7 μF at room temperature to 1.5 μF at +85°C, whereas under 5V bias the capacitance increases with temperature, from 0.33 μF at room temperature to 0.39 μF at +85°C. This result should convince you that you really need to check component specifications carefully.

GETTING DOWN TO SPECIFICS

As a result of this lesson, I no longer just specify an X7R or X5R capacitor to colleagues or customers. Instead, I specify specific parts from specific vendors whose data I have checked. I also warn customers to check data when considering alternative vendors in production to ensure that they do not run into the problems I encountered.

The larger lesson here, as you may have surmised, is to read the data sheet, every time, without exception. Ask for detailed data when the data sheet does not contain sufficient information. Remember, too, that the ceramic-capacitor designations X7R, Y5V, and so on imply nothing about voltage coefficients. Engineers must check the data to know, really know, how a specific capacitor will perform under voltage.

Finally, keep in mind that, as we continue to drive madly to smaller and smaller sizes, this is becoming more of an issue every day.EDN

ACKNOWLEDGMENT

The author thanks Chris Burkett, field applications engineer at TDK, for his explanation of why ceramic capacitors of the same nominal type can have widely divergent voltage coefficients.

AUTHOR’S BIOGRAPHY

Mark Fortunato is senior principal member of the technical staff in the Communications and Automotive Solutions Group at Maxim Integrated (San Jose, CA). He has spent much of the past 16 years helping customers tame analog circuitry. Before that, Fortunato worked on products ranging from speech-recognition systems to consumer electronics, millimeter-wave instrumentation, and automated

teller machines. He regrets that he never got to meet Jim Williams or Bob Pease.