Voltage Coefficient of Capacitance

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What capacitance do you get when you buy a multilayer ceramic capacitor? This might sound like an odd question, it is the value specified in the datasheet, surely. The actual answer is down to dielectric type, design and operational conditions, and there is a surprising degree of variation.

There are many factors which affect the actual capacitance value, some well documented, some less so. We all know about tolerance and temperature coefficient of capacitance, they are clearly defined in dielectric classification codes and part numbering systems. Where things become less clearly defined is for VCC or Voltage Coefficient of Capacitance.

	C0G/NP0			X8R	X7R			X5R
Dielectric characteristics	Ultra stable			Stable	Stable			Stable
IECQ-CECC	1B/CG	-	-	-	2C1	2R1	2X1	-
EIA	-	C0G/ NP0	-	X8R	-	X7R	-	X5R
MIL	-	-	CG (BP)	-	BZ	-	BX	-
Rated temperature range	-55°C to +125°C			-55°C to +150°C	-55°C to +125°C			-55°C to +85°C
Maximum capacitance change over temperature range No DC voltage applied	0 ± 30 ppm/°C			± 15%	± 20%	± 15%	± 15%	± 15%
Rated DC voltage applied				-	+20 -30%	-	+15 -25%	-

Figure 1 Capacitance change versus temperature and voltage for common ceramic dielectrics

The effect of VCC

Dielectrics used in MLCC (MultiLayer Ceramic Capacitors) generally fall into two categories; stable and ultra-stable, or class II and class I. Class I are typically C0G or NP0; these are very stable with temperature and voltage so you get what you asked for, but with a relatively low permittivity, so you don't get as much capacitance-voltage product in a given volume as with other dielectrics. Class II are more variable and the lack of definition of VCC is where problems can occur.

VCC is a function of the properties of the dielectric material and the voltage stress applied, typically in volts per micron. The effect is negative and non-linear becoming asymptotic toward the limit of dielectric strength. In effect most of the loss occurs long before the part reaches its operational voltage limit, even with de-rating there will be significant capacitance loss. See fig.2.

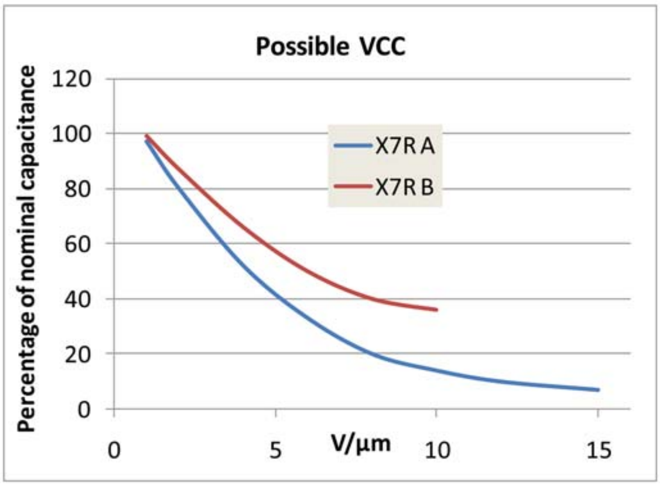

Figure 2 Capacitance change versus voltage stress across dielectric

Let's take EIA X7R for example, at "K" tolerance. The TCC (Temperature Coefficient of Capacitance) is ±15% over the specified temperature range, the tolerance is ±10% so running at the extremities of the specification we may face a variation from nominal capacitance of 23.5%. This will most likely be negative so if we assumed a nominal value of 100nF we now only have 76.5nF. But what about when we apply voltage? The VCC is not defined – look closely at Figure 1 and the EIA definition of X7R – and so there is no onus on the manufacturer to put this in the datasheet. We will assume that our part is 100V rated and we are going to use it at 80V. Using a relatively conservative design this will produce a voltage stress between the electrodes within the body of the component of 3.2V/µm which will result in a drop in capacitance of around 40% (see Figure 2), factor in the effect of temperature and the 10% tolerance and we could end up with only 40nF when we specified 100nF in the first place.

Bad as it sounds, this is by no means the worst it gets. With the pressures of price and size reduction manufactures of MLCCs are forever reducing dielectric thickness; for end users voltage de-rating is becoming a thing of the past, particularly because there is always a desire to have the maximum capacitance in the smallest size. Greater than 90% loss of capacitance at rated voltage is not uncommon in the general market place. But this can be avoided for some parts by specifying 2C1 (BZ) or 2X1 (BX) dielectrics rather than standard commercial X7R (2R1). These options have a more tightly controlled VCC at the expense of absolute capacitance value in a given package (see Figure 1 again) – although, observe that a worst-case capacitance drop of 25-30% is still to be expected.

Safety issues

VCC is not just a problem with respect to circuit functionality; there can be legislative implications for certain equipment even if you fully understand VCC. EN 61010-1:2010 Safety requirements for electrical equipment for measurement, control, and laboratory use advises that for voltages up to 15kV equipment is considered hazardous live if it can discharge >45µC and ≥2mA. For above 15kV the same applies for energy levels >350mJ. If we consider a hypothetical high voltage laboratory power supply of 8kV with an accessible capacitive circuit then the 45µC rule restricts us to 5.6nF at 8kV (Figure 3). Let's assume the circuit in question requires a minimum of 2nF to function correctly; we know there will be some instability in the capacitor so we specify 5 x 3640 10kV 1nF parts. Unfortunately, the capacitors turn out to lose 75% of their value under 8kV so we end up with only 1.25nF. We can't just add more capacitors in parallel because it will push us over the 45µC limit; we could matrix parts in series and parallel to reduce the voltage stress and keep the nominal capacitance low but this will take up a lot of space and be costly. A more stable capacitor is required.

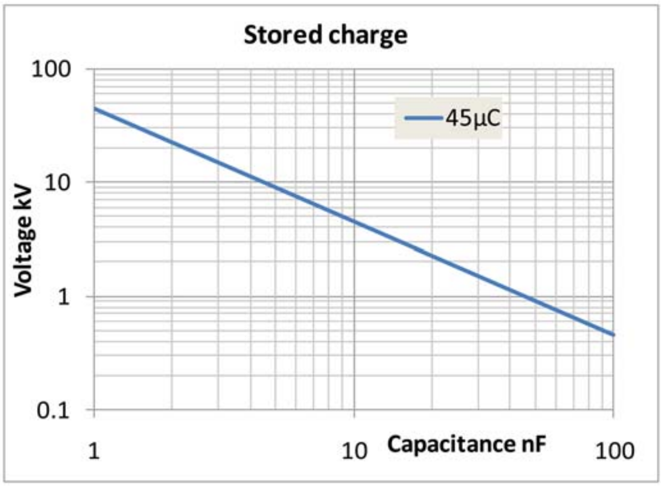

Figure 3 Stored charge of 45µC for voltage and capacitance

Luckily some X7R materials are more stable than others and, if requested, more suitable capacitors can be manufactured. Syfer can manufacture a 3640 1nF 10kV which will have less than 50% capacitance drop at 8kV; using this in the previous example would provide a residual capacitance at operational voltage of around 2.6nF as opposed to 1.25nF which would allow the circuit to function correctly and even allow for a reduction in component count from 5 to 4.

The effect on EMC design

What does this effect mean for EMC-related design issues? There are two principal widespread uses for MLCCs that are relevant to EMC: interface filtering, and decoupling. Whether a change in capacitance has a serious effect on either of these applications depends, more than anything, on frequency. This is because EMC applications cover a broad bandwidth, and the capacitor may be being used either above or below its self resonant frequency.

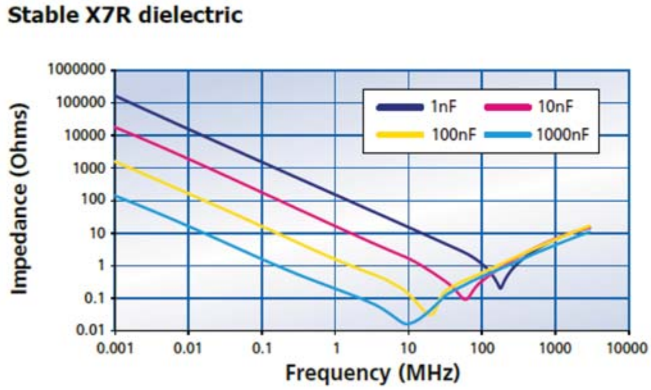

Figure 4 Self resonant frequencies for different capacitor values

Any two-terminal capacitor will show a minimum impedance at self resonance (Figure 4). This is given by $1/2\pi\sqrt{LC}$, where C is the actual capacitance and L is the combined inductance of the package and the vias, pads and tracks which connect to it. Above this frequency, it's not its capacitance value, but its self inductance, which determines the performance. Figure 4 shows the impedance of several values of capacitors. From this it's clear that for values above around 100nF and frequencies above 10MHz, the impedance (and hence loss of circuit effect) is rising with frequency, due to inductance.

Decoupling

Digital decoupling applications are normally most important in the VHF range and above, where clock harmonics on the power rails can cause high levels of emissions, or where incoming RF or transient interference can create undesirable disturbances. Decoupling local to each IC prevents this noise from circulating widely in the power distribution network, but practical components are acting as inductors in this region, so the actual capacitance value is less critical than the inductance. Package size and shape, and PCB layout, are the most important parameters; the capacitance must simply be large enough to keep the impedance at self resonance low.

A secondary reason (from the EMC perspective) for decoupling is to prevent significant voltage ripple on the power rails from exceeding the ICs' DC operating thresholds. This may require a minimum value of total capacitance in the system. Since it's usual for a decoupling regime to have many capacitors in parallel, it becomes a straightforward matter to calculate (e.g. using Figure 2 or similar data) by how much to increase the overall required capacitance, given a particular DC rail voltage and capacitor rating, to allow for the VCC.

Filtering
The situation with filter capacitors is somewhat different. Here, lower frequency applications are more typical. For both supply conducted emissions and conducted immunity the bottom frequency is 150kHz for commercial applications, and considerably lower for military and aerospace. In the kHz region, supply filtering is largely a matter of getting the maximum capacitance in the smallest space for a given voltage, with secondary issues such as leakage current and surge protection also being important. In signal line filtering, an additional aspect is that the capacitor should not affect the desired signal bandwidth, so there can be a critical trade-off between this limitation and the lowest effective filtering frequency.

In either case there is real pressure on the MLCC characteristics, and it will be important to evaluate the effect of VCC on the filter's performance. A necessary consequence is that pre-compliance design EMC testing should be done with worst case DC voltages, low as well as high, present across the relevant components; or, a margin should be incorporated with respect to the LF emissions limits. For a single component filter, a 50% loss of capacitance will result in a degradation of attenuation of 6dB. For conducted immunity, over-testing by a factor of 2 – applying 20V rather than 10V, for instance – would be needed. One consequence of using a capacitor with a high VCC in an AC circuit, particularly (for instance) an X7R capacitor as an X- or Y-rated mains filter component, is that the filter attenuation will be modulated by the AC voltage. This effect, of course, would be hard to disentangle from other sources of 100/120Hz modulation in the power supply noise signature. Also, for multi-voltage DC supplies (such as 12/24V vehicle or marine applications) the VCC change could cause a filter to have substantially different characteristics at the different supply voltages – again, hard to separate from other causes of variation.

If your aim is only to control radiated emissions above 30MHz, by applying filter capacitors to cable interfaces, then the pressure is less since capacitance value is usually less critical; but as Figure 4 shows, capacitors in the range 1-10nF can expect to have self resonances in the range from 30 to 200MHz, which is the danger zone for cable coupling. It may well be that the self resonance is especially (and perhaps unexpectedly) effective at stopping a particular emission frequency, but then any variation in capacitance will shift this resonant frequency (by $\sqrt{\Delta C}$) with greater than expected results for the emission.

Conclusions
VCC is an important component characteristic which is often overlooked and can cause significant problems in certain applications. Voltage de-rating – running a capacitor significantly below its rated voltage – will limit the degree to which capacitance value degrades, but this generally involves a trade-off with package size. The same is true of choosing an ultra-stable dielectric such as C0G/NP0. Standard off the shelf components will vary in their performance so it is best to seek the advice of your supplier at the initial design stage to avoid the need for corrective action.

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