Capacitor Losses

Dielectrics

Capacitors are constructed of two or more electrodes, separated by a dielectric. The dielectric is commonly ceramic, plastic film, oiled paper, mica, or air. Each one has advantages and disadvantages in regards to dielectric constant, losses, temperature coefficient, and, of course, cost. High dielectric constants result in smaller capacitors, but usually with poorer properties than the lower constant materials. Some properties of various dielectric materials are shown below:

Material	Dielectric Constant	Dissipation Factor	Dielectric Absorption	Temp Coefficient /°C	Notes
Vacuum	1.0	0	zero	0	high power RF
Air	1.0006	0	zero	0	RF & variables
Teflon	2.0	.0001	low	-120 ppm	high rel mil, high end audio
Polystyrene	2.5	.0001	low	-150 ppm	max temp 85°C/very low DF, very low DA
Polypropylene	2.3	.0002	low	-120 to -200 ppm	higher temp sub for styrene
Polyester	3.2	.016	medium	600 to 900 ppm	popular general purpose
Polycarbonate	3.0	.01		65 to 100 ppm	
Paper/wax	2.5				obsolete
Paper/oil	4.0				AC/HV, NOS replacement
Mica	5-9	.0001-.0007	medium	0 to 200 ppm	stable RF and GP, but unexpected dielectric absorption for its DF
Porcelain	6.0			0 to 90 ppm	HV insulators
Bakelite	4.5-7.5				obsolete, rare, may char
Glass	4.5-7.0	.002		140 ppm	rad hard, high stability
AlO_2		.15 varies	high	poor	aluminum electrolytic
AlO_2, pure	9.8	.0002			insulators
MnO_2		.15 varies	high		tantalum electrolytic
Ceramic, C0G	75 typ.	.001		±30 ppm	low tempco RF/GP
Ceramic, X7R	3000 typ.	.025		±15% over temp range	RF/GP
Ceramic, Z5U	8000 typ.	.03		+22 to -56% over temp range	high value RF/GP bypass only
Ceramic, PZT-8	1000	.004			hard low sensitivity piezoelectric
Ceramic, PZT-4	1300	.004			med. sensitivity piezoelectric

Ceramic, PZT-5H	3400	.02	soft high sensitivity piezoelectric

The data in this table comes from many sources, not all of which are in agreement. If you have better information, want to fill in any blanks or have additional entries, please email me with the data and its source.

Low Frequency Losses

How do we specify loss? If you ask most engineers about capacitor loss, they will mumble something about "loss tangent", then disappear for an emergency coffee refill. There are several different ways of expressing capacitor losses, and this often leads to confusion. They are all very simply related, as shown below.

If you drive a perfect capacitor with a sine wave, the current will lead the voltage by exactly 90°. The capacitor gives back all the energy put into it on each cycle. In a real capacitor, the current will lead the voltage by a bit less than 90°. The capacitor will dissipate a small fraction of the energy put into it as heat. Real capacitors can be modeled, at least to a first order, as a perfect capacitor in series with a resistance. This resistance is referred to as the effective series resistance or ESR, and is only valid for a single frequency. For the examples below, assume a 0.47µF capacitor, driven at 5000 Hz, 35 volts RMS, and showing a phase angle of -89.5°. Note that the relationships shown only apply to sine waves. Capacitors can also be modeled using parallel elements, but we'll limit our discussion to the series model. You'll find a collection of "handy formulas" on this site that includes conversions between series and parallel models, plus other useful data.

Dissipation factor, or "D" as it is usually marked on test bridges, is the tangent of the difference between the phase angle of a perfect capacitor, and the capacitor in question. In our example, -90°--89.5°=-0.5° The tangent of -0.5° is -0.00873. We take the absolute value so D=0.00873. Since this number is directly read from most test bridges, other parameters are often calculated from it. It is also known as the loss tangent and is sometimes expressed as a percentage. D=.873%

This is probably a good time to mention that by general agreement capacitive reactances are negative and inductive reactances are positive. A vector impedance meter would display the phase angle of the capacitor in question as "-89.5". Xc, the capacitive reactance would be -1/(2*pi*f*c) or -67.7255 ohms. The sign is often omitted.

Power factor, or "PF", is less common than it used to be, at least as applied to capacitors. It is the cosine of the phase angle itself. In our example, COS(-89.5)=0.00873. Note that for small angles, PF is essentially equal to D, and both are approximately equal to the phase angle expressed in radians. For large angles the situation is quite different. A power factor of 1 is 100% resistive loss whereas D can exceed 1 and approaches infinity for 100% loss.

Q is the quality factor, a dimensionless figure of merit. It is the reciprocal of D. In our example, 1/.0087=114.58, so Q=114.58.

Effective series resistance, or "ESR" is the value of resistance in series with a perfect capacitor that produces the phase angle error. It can be calculated by dividing D by ωC (2 pi F C). In our example, .0087/(6.28*5000*.00000047)=0.589, so ESR=0.589 ohms.

Capacitive reactance is the negative reciprocal of ωC. -1/(6.28*5000*.00000047)=-67.725, so X=-67.725 ohms.

Total impedance of a capacitor is obtained by taking the absolute value of the root sum of the squares of capacitive reactance and ESR. $(67.7252^2+0.5892^2)^{1/2}$=67.727, so Z=67.727 ohms.

Capacitor current is the RMS voltage divided by the total impedance. 35/67.7=0.52 amps.

Power dissipation in the ESR component is calculated from the RMS voltage times current times the ratio of ESR to total impedance. 35*.52*(.589/67.727)=0.16 watts. Or, use I^2 times ESR. The resulting temperature rise depends on the size and heat sinking of the capacitor.

Verifying capacitor ESR on the bench requires both care and good instrumentation. Because ESR is usually small, test lead resistance and poor connections can easily contribute more resistance than the capacitor. Noise pickup from long leads or a hostile environment can make readings unstable. Note that neither D nor ESR is constant with frequency. ESR will decrease rapidly as frequency increases, then drop at a much slower rate above about 1 kHz, until it starts rising again at self resonance. Be sure to make measurements in the same frequency and voltage range that the parts will be used in- test it the way you use it. Be aware that in simulations ESR is a constant unless you take special measures to make it frequency dependent.

Dielectric Absorption is another imperfection. Briefly, the dielectric refuses to give up its full charge, and a previously discharged capacitor will self charge. This can be modeled with additional C-R pairs in parallel with the main capacitor. Dielectric absorption is a particular problem in capacitors used in integrators. There is some debate as to its importance in audio applications. Much that has been written about dielectric absorption remains obscure; at least two standard tests exist, but there is very little published data for specific parts.

Other Effects Capacitors are not 100% linear and may contribute a small amount of distortion to signals, particularly the electrolytic types. Capacitance may vary with DC voltage. Each dielectric type will have some characteristic temperature coefficient. Some capacitors are microphonic, and may also "sing" when driven at high voltages.