CAPACITOR BASICS II – Capacitor Types

In practice, capacitors are available in many different forms. They can vary by the type dielectric utilized, the size, shape and nature of the electrodes used and the type of packaging employed. All of these variables can strongly affect the characteristics of the capacitor and the type of application for which these devices are most suitable. The basic design, benefits, drawbacks and operational parameters associated with a number of the more common capacitor choices are shown below and in Table II:

- **Aluminum Electrolytic Capacitors** – Super capacitors aside, electrolytic capacitors are recognized as having the ability to achieve extremely high levels of capacitance per unit volume when compared to other technologies available. Their ability to achieve these levels is based in part on their use of extremely thin dielectric material in the form an oxide layer (Al_2O_3) that is developed thru electrolysis on the surface of a suitable metal foil, such as aluminum. In addition, the amount of capacitance can be further augmented by pre-etching of the aluminum surface prior to oxidation. This etching process increases the area of contact between the oxide and the remaining aluminum foil, which serves as the anode or positive conductor in the capacitor circuit.

  Once this aluminum anode / dielectric foil has been properly prepared it is wound into a capacitor element along with another piece of high purity aluminum foil and an electrolyte paper interleaf, placed in an aluminum housing, and then impregnated with an electrically conductive electrolyte. This electrolyte along with the pure aluminum foil serves as the cathode or negative conductor in the capacitor circuit.

  Although used in almost every segment of the electronics industry, electrolytic capacitors come with several drawbacks that may affect their suitability for a number of applications. Due to the nature of these designs, a strict adherence to polarity must be maintained during installation. In addition, these capacitors suffer from high levels of instability, a gradual loss in capacitance and a significant loss in life when subjected to higher operating temperatures. Lower temperature operation also poses an issue inasmuch as exposure will adversely affect the conductivity of the electrolyte, lower the effective capacitance value and increase both the dissipation factor and ESR of the device. Usage at higher elevations may result in not only a lower ambient temperature condition, but differences in atmospheric pressure between the environment and the inside of the capacitor may result in unintended out gassing of the unit, which could inhibit its performance and potentially contaminate the system. Even storage for an extended period of time in a seemingly benign environment may result in a degradation in performance, whereby the leakage current of the capacitor increases, especially if the storage temperature is elevated.

  Unfortunately, the ability of an electrolytic capacitor to achieve higher capacitance values comes with a significant level in equivalent series resistance, which becomes especially important for higher frequency applications. In these instances the design engineer may be forced to place several capacitors in parallel to lower the overall ESR, a requirement that otherwise would not be necessary if he were to choose an alternative capacitor technology like ceramic that exhibits a much lower inherent level of ESR.

  Finally, electrolytic capacitors utilize toxic components and materials and as such they may pose an environmental concern. Continually evolving regulations, both domestic and foreign, may make disposal problematic, not to mention expensive.

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- **Tantalum Capacitors** – Also classified as part of the electrolytic family, tantalum oxides are generally considered to offer the more desirable characteristics, but their higher costs and outrageous lead times generally limit their economic usefulness to those applications where size and weight are important and aluminum is not suitable.
  Tantalum capacitors are manufactured from a powder or relatively pure tantalum metal that is compressed around a tantalum wire and vacuum sintered at high temperatures to form a tantalum pellet. This structure, which serves as the anode, achieves excellent mechanical integrity and is highly porous in nature, which results a large internal surface area. The tantalum pellet is then subjected to an electrochemical process called anodization, whereby a layer of tantalum pentoxide is formed over the anode to become the dielectric. For a wet tantalum capacitor a liquid electrolyte is utilized in conjunction with the case to create the anode. Solid tantalum capacitors represent the vast majority of tantalum capacitors utilized and generally speaking for this type of design, a layer of manganese dioxide is formed over the tantalum pentoxide, followed by a layer of colloidal graphite and a layer of silver paint. Finally, with no liquid used in this process the solid unit can be sealed with an epoxy dip or preferably a molded body.

  One of the key concerns with tantalum capacitors is that the dielectric layer is inherently prone to defects and although the manganese dioxide layer provides a certain level of self healing, if a problem is too severe, the high level of oxygen associated with the cathode material can fuel an exothermic reaction, which will lead to a catastrophic short circuit failure condition and in some extreme cases a risk of fire. Obviously, the probability of failure would be magnified in those applications where a bank of capacitors may be required. Additionally, this design requires a strict adherence to polarity and is not overly tolerant of excessive charge and discharge currents, especially those of a repetitive nature.

  The ESR for a tantalum capacitor can be even higher than that of an aluminum electrolytic, and as such the same considerations apply when compared to ceramic capacitor options. This ESR distinction becomes even more obvious at frequencies above 100 kHz, where microstructural differences in resistance at the anode / cathode interface prompts a roll off in capacitance by as much as 50%. In addition, dielectric thickness limitations restrict the majority of designs to a maximum working voltage of 50 Vdc and upper temperature ratings of +85 to +125ºC. Use of tantalum capacitors above +85ºC requires a linear derating to 67% of the name plate voltage at +125ºC. Higher voltage ratings of up to 125 Vdc, or operating temperatures as high as +200ºC are available, but choices are limited, and these units generally require a significant further reduction in voltage rating and other key performance characteristics.

  Finally, like their aluminum counterparts, tantalum capacitors utilize toxic materials and may present an environmental or disposal concern.

- **Film Capacitors** – Film capacitors fall into two basic categories, metallized film and film / foil construction. For metallized film, the electrode plates are applied thru vacuum deposition onto a dielectric material like polyester or polypropylene. Compared to the film / foil alternative, where separate film and metal foil sheets are utilized, the physical properties of a metallized design allows for a number of advantages including smaller size, lower mass, a lower cost per microfarad and the ability to self heal. Self healing refers to a mechanism whereby an overvoltage transient or flaw in the dielectric creates a momentary short circuit condition. The energy associated with this condition is sufficient enough to heal the capacitor, by vaporizing the metallized aluminum around the fault site.

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In addition, this "clearing" process occurs in microseconds, a time that is short enough to prevent irreparable damage, other than an insignificant loss in capacitance.

Film / foil alternatives by design are intended for higher current applications, whether the current is continuous as in a resonant circuit or a transient condition normally associated with a snubber circuit. It is also utilized in very small capacitance value applications where there is little difference in size between the two options and the metallized film approach may be more cost prohibitive.

When selecting an appropriate dielectric material, the engineer needs to consider several factors including dielectric constant, dissipation factor, insulation resistance, operating temperature, temperature coefficient and dielectric absorption. Polyester for example has the highest dielectric constant, can operate up to +125ºC and is able to deliver the best volumetric efficiency for the lowest cost. It does however exhibit a higher DF of around 1% and a subsequent lack of adequate power dissipation at higher temperatures, essentially precluding its use for high frequency, high current AC voltage applications. In addition, although the ∆TC for polyester is a respectable ±1% for the temperature range of 0 to +50ºC, this value increases to as much as ±5% when operated in the range of -55 to 0ºC and +50 to +125ºC, making it unsuitable for precision circuitry.

Polypropylene as a dielectric, has a low dissipation factor that make this the preferred choice for high voltage / high frequency AC requirements and high current DC applications. It also exhibits a comparatively high insulation resistance and low dielectric absorption which make it suitable for precision circuitry. Polypropylene might very well be the preferred choice for film capacitors if not for its lower dielectric constant, a lack of thin gauge film which results in a larger package size and a maximum operating temperature of +105ºC.

Other material options like polyphenylene sulfide have found use for applications requiring tight TC characteristics over temperature ranges up to an including +150ºC. This material has also become the dielectric of choice for replacement of polycarbonate capacitors but tend to be cost prohibitive for a wide range of applications.

Film capacitors as a whole, offer a significant improvement in ESR and ESL characteristics Vs electrolytic capacitors, but are not able to approach the levels seen with ceramic alternatives. Like ceramic, higher voltage ratings are achievable, but a 50% linear derating of the nameplate voltage is required between +85ºC and the maximum operating temperature limit of the device. In addition, for AC applications, a strict adherence to the maximum voltage rating is essential to ensure that corona does not develop in the insulation system causing the dielectric to carbonize and eventually short the capacitor. Finally, film capacitors specify a maximum +15ºC temp rise, not to exceed the upper operating limit, a restriction that is tighter than the +25ºC allowable for ceramic.

- **Ceramic Capacitors** – Ceramic capacitors describe the family of capacitors that utilize a wide range of different ceramic materials as their dielectric to achieve specific performance characteristics. The typical method for manufacturing of these components involves a process, whereby the dielectric, in suspension, or slurry as it is typically called, is cast in sheets and dried to the point where a metal conductor can be screened onto its surface. The next step involves a bakeout process in which the solvents are driven off leaving a dried, but extremely fragile assembly. From here, the unit is placed in a kiln and exposed to a high temperatures environment, where the ceramic is fired. This process, which is also known as sintering, is completed by applying heat or energy to promote a complex high temperature reaction of materials, which effectively transforms the unit into a much more dense assembly that can be easily handled, terminated and employed in a variety of applications.

Other methods commonly in use for less complex designs may involve pressing, extruding or even spraying of the dielectric. The pressing and / or extruded processes are generally tailored towards single layer discs or tubular designs and the sprayed version to a tubular design with a small number of buried electrodes.

Once fired, ceramic is characterized as an extremely strong material in compression, but has limited strength in tension and as such is very susceptible to damage when exposed to high mechanical stress conditions. In addition, the inherently brittle nature of the material also makes these types of dielectrics at risk to thermal shock. Acknowledging that these hazards are present, there are a number of design considerations and process controls at the engineers disposal that when properly employed, limit these risks.

Assuming that the thermal and mechanical concerns have been properly addressed, ceramic offers several advantages over alternate dielectric designs. The dielectric constant, which is directly proportional to the capacitance value, is generally much higher than alternative technologies varying anywhere from a low of around 15 for the more stable materials, to as high as 22,000 for others. It is the capability of these materials to achieve a higher dielectric constant and their ability to increase electrode overlap area through the use of multilayer configurations, that allows ceramic to participate in high capacitance, high energy applications. Actual selection will depend on the intended function of the capacitor and whether the application can tolerate inherent differences in performance characteristics, which tend to become more exaggerated with higher K options.

Ceramic capacitors are non polar devices which can be connected in any configuration and they are designed to operate continuously at full rated voltage across their entire operating temperature range. Furthermore, they exhibit extremely low levels of ESR, which is especially critical for high frequency applications and generally allows the engineer to achieve similar performance to an electrolytic or film design, with less capacitance. In addition, ceramic capacitors exhibit inherently low levels of ESL and the simplicity of their design can allow for an even further reduction thru a straight forward reorientation of the electrode pattern.

Finally, further material developments in the area of ceramic capacitor technology have allowed manufacturers to keep pace with the ever evolving demands of the Restriction of Hazardous Substances directive (RoHS) and the Regulation, Evaluation, Authorization and Restriction of Chemical substances initiative (REACH).

Characteristic[1]	Ceramic						Film		Electrolytic	
	NPO	X7R	X5R	X5U	Y5V	Z5U	Polyester	Polypropylene	Aluminum	Tantalum
Operating Temperature	-55 to +125ºC	-55 to +125ºC	-55 to +85ºC	-55 to +85ºC	-30 to +85ºC	+10 to +85ºC	-55 to +125ºC	-55 to +105ºC	-40 to +105ºC	-55 to +125ºC
Dielectric Constant	15 - 150	600 - 5000	600 - 5000	3500 - 7000	7000 - 22000	7000 - 22000	3.1 - 3.3	2.1 - 2.3	7 - 10	24
DF	0.10%	2.5%	2.5%	2.5%	5%	5%	1%	0.10%	8%	20%
Voltage	5 V - 50 KV	5 V - 50 KV	5 V - 50 KV	5 V - 50 KV	5 V - 50 KV	5 V - 50 KV	100 - 600	100 - 600	3- 550 V	6 - 125 V
ΔTC	+/-30 PPM / ºC	±15%	±15%	+22 / -56%	+22 / -82%	+22 / -56%	±12%	±1%	+10 / -40%	±15%
ΔVC	Negligible	Good	Good	Fair	Fair	Fair	Minimal	Minimal	N/A	Minimal
ESR	Excellent	Good	Good	Good	Fair	Fair	Fair	Fair	Poor	Poor
ESL	Low	Low	Low	Low	Low	Low	Fair	Fair	High	High
Dielectric Absorption	0.50%	2.50%	2.50%	2.50%	N/A	N/A	0.50%	0.10%	10%	N/A
Frequency Response	Superior	Excellent	Excellent	Excellent	Excellent	Excellent	Average	Average	Poor	Poor

Table II - Performance Characteristics Common Capacitor Types

Note:

1. Material characteristics shown in Table II are presented for reference purposes only. They represent typical values or a range of values and as such may not reflect actual maximum or minimum limits for a specific dielectric type.

For additional information on Capacitor Basics, please refer to Application Notes AN109-1, “How Capacitors Work” and AN109-3, “Mechanical Configurations”, or contact CalRamic Technologies, LLC with your questions. We are always here to help!

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