

Selecting a Capacitor to be Used as a Switch-Mode Power Supply Filter

Introduction

Two key functions of SMPS filter caps are Input Filtering and Output Filtering. Many capacitor technology choices are available to the designer and care should be taken to choose the capacitor with attributes that best fit the needs of each filter requirement.

Input Filter caps need to be able to supply a quick burst of energy and to suppress noise generated in the switch circuit. Important considerations for the Input Filter cap are ESR, ESL, and ripple current. High CV density is preferred in the Input Filter caps in order to reduce board space, although it is not as critical as for the Output Filter caps.

Output Filter caps must allow charging and discharging in concert with the rise and fall of the ripple current at the output. Both ESR and ESL are important considerations for the Output Filter capacitor. High CV density is preferred in the Input Filter caps in order to reduce board space as capacitance demands of Output Filters are typically high.

This paper discusses several popular capacitor technology choices and their relative strengths and weaknesses. In many cases, the best choice may not seem black and white so careful comparison of the competing technologies should be made to be sure the best option is chosen.

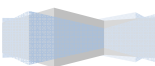
Technology Options

Electrolytic Capacitors

Historically, **Electrolytic Capacitors** have been the most popular choice for SMPS filters, especially Input Filters. They offer very high CV density per package size typically at comparably low cost. The problem is that the high CV density comes at a rather high price in terms of technical disadvantages. There are two popular types of **Electrolytic Capacitors**, so-called **Aluminum Electrolytics** and **Tantalums**. Each technology has specific performance characteristics based on the design and construction of the caps.

Aluminum Electrolytics (AE)

Aluminum Electrolytics employ an ultra-thin dielectric composed of Aluminum Oxide deposited on a thin, etched Aluminum foil. The etched surface increases the surface area of the dielectric, increasing the CV density significantly.



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AE caps are often the popular choice for use as SMPS filters due to their very high capacitance density and relative low cost. Offsetting these advantages, **AE caps** have several significant disadvantages that the circuit designer must consider:

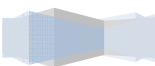
- Due to their construction, **AE caps** exhibit inherently high ESR. As frequencies increase, this ESR disadvantage becomes more of a problem for circuit designers. To make up this high ESR, in many cases designers will have to parallel many **AE caps** to reduce the ESR to meet the application requirements. This paralleling may require from 10 to 100X the theoretical cap value in order to achieve the required ESR.
- **AE caps** are polar devices and failure to maintain polarity can have catastrophic consequences.
- High temperature usage and even high temperature storage can cause instability including increasing leakage current (reduced Insulation Resistance), loss of capacitance, and reduced usable life.
- **AE caps** have limited life due to possible evaporation of the electrolyte fluid over time. Most manufacturers quote the life time as 5000 or 10,000 hours due to this evaporation issue.
- **AE caps** can explode in an over-voltage condition and may release a toxic fluid.
- **AE caps** contain potentially toxic ingredients that may be harmful to the environment.

Tantalum Capacitors (TA)

Tantalum capacitors employ an extremely porous anode material which offers a large dielectric surface area. This allows for a very high CV density.

TA caps generally have more favorable characteristics for SMPS filtering than **AE caps**, however, raw material availability has driven up price and lead-times for **TA caps**. In addition to price and lead-time issues, **Tantalum** capacitors also have several disadvantages that the circuit designer must consider:

- **TA caps** are polar devices and failure to maintain polarity can have catastrophic consequences.
- **TA caps** exhibit very high ESR, typically higher than their **AE cap** cousins. The ESR significantly increases at frequencies higher than 100 Hz.
- **TA caps** typically exhibit significant capacitance loss at higher frequencies.
- **Tantalum** capacitors degrade when exposed to multiple charge/discharge cycles.
- **TA caps** are not typically available in higher voltage ratings. Normally, the maximum voltage rating that can be achieved is 50VDC and many **TA** manufacturers recommend that the TA devices not be used at greater than 50% of the rated voltage, making the effective maximum voltage 25VDC, even at room temperature.
- **TA caps** are not usable at temperatures over 125°C and their voltage ratings typically apply at 85°C, and must be derated between 85°C and 125°C.
- Higher leakage currents of **TA caps** make them less suitable in many applications.
- Due to their construction, **TA caps** often fail by means of a runaway exothermic reaction which sometimes results in fire or the release of toxic/acidic contents onto other components on the PC board.
- **Tantalum** capacitors cannot handle overvoltage spikes as well as ceramic capacitors, therefore more consideration needs to be given to inductive loads.
- **Tantalum** capacitors contain potentially toxic ingredients that may be harmful to the environment.



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Film Capacitors

Film capacitors offer advantages that make them a good choice for high current applications and applications where transients are likely such as snubber circuits. In the case of polypropylene dielectric **film caps**, the low dissipation factor makes them ideal for AC applications, especially at higher frequencies such as 400Hz.

Film caps (MLP)

MLP caps are constructed by metalizing polymer films and either winding or stacking the film into layers. **MLP** caps are available in a wide variety of dielectrics and are uniquely able to self-heal under certain failure conditions. **Film** caps also possess inherent characteristics that may challenge circuit designers and must be given due consideration:

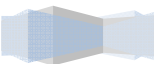
- Although MLP caps offer better ESR/ESL performance than **AE** or **TA** caps, they typically do not match the ESR/ESL of NPO **MLCC** ceramic designs.
- **Film** caps are typically limited to 105°C temperature rating. 125°C operation is typically not possible.
 - Some polyester dielectric **Film** caps can be rated at 125°C but their inherent lossiness limits their use in high frequency AC applications.
- **MLP** caps can be rated at high voltages but at temperatures >85°C, the voltages must be derated by as much as 50%.
- When used in AC applications, corona can cause the film to carbonize and fail short circuit if the voltage rating is exceeded.
- Temperature rise is limited to +15°C and cannot be allowed to exceed the maximum rated temperature of the **MLP** device.
- Recent trends in the availability of films have resulted in extraordinarily long lead times for some **MLP** caps.
- Some **Film** caps contain potentially toxic ingredients that may be harmful to the environment.

Ceramic Capacitors

Ceramic capacitors offer properties that work well in SMPS applications and in some cases offer a good compromise between cost/availability issues and the technical properties required for SMPS filtering.

Single Layer Ceramic Capacitors (SLCC)

SLCC caps or ceramic disk capacitors are constructed of a ceramic slug or disk that is metalized on the two sides. **SLCC** caps are typically through hole (Radial Leaded) capacitors that are popular in many legacy circuit designs. **SLCC** devices offer high voltage ratings, $\geq 10\text{KV}$, and stable performance over the entire temperature range.



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Recent trends toward higher CV density multilayer ceramic capacitor (**MLCC**) designs has had impact on availability of the **SLCC** products, as manufacturers have decreased capacity and announced end-of-life for numerous part numbers. In addition to the availability issue, **SLCC** designs have disadvantages that the circuit designers should consider:

- **SLCC** caps are typically only available in radial leaded format narrowing board design choices.
- Lead spacing and size are comparatively large, especially as voltage ratings increase.
- **SLCC** CV density is very limited due to the “single layer” design.

Multilayer Ceramic Capacitors (MLCC)

MLCC's are constructed of multiple layers of a thin ceramic materials which are metalized and alternately stacked. The device is sintered into a monolithic block and then the exposed electrodes are metalized forming end caps. Multiple thin dielectric layers allow for high capacitance to be achieved in a relatively small package size.

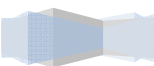
MLCC became the dominant design for ceramic capacitors as the manufacturing technology was perfected decades ago. **MLCC** design allows multiple layers of very thin ceramic dielectric to be connected in parallel to achieve relatively high CV density. In recent years, the high cost precious metals utilized in the electrode layers of previous **MLCC** designs have been successfully replaced with lower cost base metals such as Copper and Nickel. This evolution has not reached all types of **MLCC** design and some of the larger **MLCC** devices still utilize precious metals. In addition to the CV density improvements, special high voltage designs using voltage dividing techniques are often employed which allow for very high voltage ratings in spite of the relatively thin dielectric layers.

MLCC devices can be manufactured from a wide variety of dielectric ceramics including both Class I (Ultra-stable) and Class II (Stable) materials. The most common ceramic dielectric for SMPS applications is X7R, an EIA standard for Class II dielectrics. This is because Class II dielectrics including X7R offer a relatively high dielectric constant (K) whereas Class I dielectrics have a very low K. With the higher K of the Class II dielectrics, a much higher CV density can be achieved.

MLCC devices do not have any significant wear out mechanism other than their inherent predicted failure rate (FIT's). Broadly speaking, MLCC reliability is at least 10X better than TA or AE.

MLCC designs offer extremely low ESR. Especially at higher frequencies, this low ESR allows the circuit designer to use lower capacitance values in **MLCC** as compared to **AE**, **TA**, and **MLP** devices. The low ESR reduces the power loss (heating) of the capacitor when handling high inrush current (d_i/d_t) to support increased power requirements. In addition, when used as an output filter, the lower ESR of the MLCC device decreases output ripple voltage.

MLCC designs typically are also lower in ESL than **AE**, **TA**, and **MLP** but product format needs to be considered for ESL. Radial leaded capacitors, for instance, have higher ESL than surface mount capacitors due to the inductance added by the leads. **MLCC** offers better ripple current capability than other technologies. **MLCC**'s are non-polar and their voltage rating is good over the entire range of temperature ratings. **MLCC**'s are available in environmentally friendly RoHS compliant designs.



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Additionally, **MLCC's** come in many physical formats, ranging from surface mount chips to leaded stacked capacitors. Other formats include leaded capacitors (widely used in legacy designs) and other specialty configurations. Holy Stone offers two advantageous optional designs worth mentioning:

- SuperTerm®
 - This method of metalizing the end caps of the **MLCC** surface mount devices includes a “flexible layer” in the termination structure. This construction effectively absorbs external forces (including thermal and mechanical stresses), reduces the incidence of cracking, and improves overall product reliability.
- Arc Prevention Coating
 - This protective coating, which utilizes a very high insulation resistance material, coats the surface with a smooth and non-porous layer that prevents moisture from entering the surface pores and aids in post-soldering cleaning. This is very effective for high voltage designs where arcing may occur during test or in use on the PC board.

Stacked capacitor designs of **MLCC** are especially useful for SMPS filters because these applications typically require high capacitance or high CV density. The “stacked” design allows the capacitor manufacturer to build multiple surface mount caps into stacks and achieve up to 5X the CV product for a given footprint. In addition, the lead frames used in stacked capacitor designs offer excellent protection against both thermal and mechanical stresses that might be introduced during soldering or during handling board handling after assembly. The stacked MLCC design may reduce microphonic noise, which typically affects audio circuits that may exist in surface mount circuit designs.

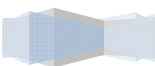


Some designers shy away from stacked capacitors because of worries about shock and vibration stresses introduced in harsh environments. Although the higher center of gravity and larger mass of the stacked caps do make them more susceptible to shock and vibration, they have been and are being successfully utilized in very harsh environments, including aerospace, military hardware, and down-hole drilling applications.

MLCC devices are also available in high temperature ratings, up to 250°C. These are ideal for automotive applications, engine controllers, down-hole drilling and a host of other high temperature applications. Most **MLCC** devices are delivered as RoHS compliant but many are available with Pb solders on request for applications which demand it.

In addition to the possible harsh environment susceptibility concerns for stacked cap **MLCC** designs, **MLCC** devices have some disadvantages that circuit designers should take into consideration:

- The CV density of **MLCC's** cannot match that of **AE**, **TA**, and some **MLP** devices, but given the significantly improved ESR and ESL of the **MLCC's**, the circuit design may not require the same amount of capacitance as a similar circuit using **AE**, **TA**, or **MLP** caps.



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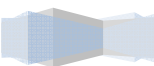
- Ceramic materials utilized in the **MLCC** design are weak in tension and as such need to be handled carefully. In addition, the ceramic materials are poor in thermal conductivity so precautions must be taken during soldering. Larger sizes are more susceptible than smaller surface mount devices.
 - Holy Stone has published a technical paper entitled “Soldering and Handling Recommendations for Large Size **MLC Capacitors**”. It is highly recommended that the recommendations included in this paper be adopted for both **MLCC** handling and soldering.
- Class II dielectrics used in **MLCC** design are piezoelectric materials and **MLCC** devices do exhibit some piezoelectric characteristics.
- Class II devices exhibit aging and temperature characteristics:
 - Aging is a logarithmic decay in capacitance value over time. Typical X7R aging runs around -1%/decade hour for **MLCC’s**. Aging can be reversed by heating the device to a temperature exceeding the Curie point of the ceramic (typically ~ 120°C).
 - The temperature characteristics of X7R dielectrics must be within ± 15% of the room temperature cap reading over the temperature range of -55°C to 125°C to comply with the EIA standard. Different vendors’ X7R materials’ TCC’s vary so the exact TCC of the device being purchased should be researched.
 - As an example, Holy Stone offers at least one X7R material which has a positive TCC from 25°C out to approximately 150°C, well beyond the maximum EIA temperature of 125°C.
- Class II dielectrics decrease in capacitance when a DC bias voltage is applied. The effect of DC bias on the net capacitance is a direct function of the chosen dielectric and the dielectric thickness chosen for the design and worst case, can be as much as -80% as the RV of the capacitor is approached.
- Class II(X7R) dielectrics exhibit a Dissipation Factor (DF) of from 1.5 to 2.5 % typically. This loss factor is fine for DC applications but may cause heating to occur in AC applications, especially when frequencies exceed 60 Hz.

Summary

Each technology has its own strengths and weaknesses for SMPS filtering. Given the extremely low ESR and ESL of **MLCC** devices, CV density may not be a disadvantage, depending on the circuit. With very good d_r/d_v , lack of polarity, high temperature performance, long life, environmentally-friendly construction, among other positive attributes, **MLCC’s** make good choices for SMPS filtering needs.

Recommended reading:

- *Holy Stone Tech Papers titled:*
 - *Soldering and Handling Procedures for large size **MLC Capacitors**.*
 - *Capacitor Dielectric Comparison*



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Comparison of Various Capacitor Technologies for Use in SMPS Filtering Applications

