TECHNICAL PAPER

Output Filter Capacitors for Mission Critical Applications

Parasitic Parameters Impact on Power Quality

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Abstract:

The constancy and regularity of output voltage in a DC/DC output network is critical in SMPS (switched-mode power supplies) electronic performance. When different input and output voltages are required in the circuitry, output filter capacitors are required to maintain current uniformity and reduce noise.

This document discusses the effect of capacitors on output power quality. It evaluates and provides a comparison of different capacitor technologies, their high reliability qualification availability from COTS+ to space level, and their impact on the output filtering capabilities in switching power supplies primarily used for mission critical applications.

Output Filter Capacitors

Parasitic Parameters Impact on Power Quality

Introduction and Overview

The constancy of output voltage in a DC/DC output network is critical to SMPS (switched-mode power supply) electronic performance. When different output voltages are required by the circuit application, output filter capacitors are required to maintain current uniformity and reduce noise. Output capacitors play a major role in optimizing the design characteristics.

Linear regulators can be used to regulate circuit voltage. Excess energy from the voltage source is dissipated as heat. Dissipation of heat is a large waste of energy and results in system inefficiency.

In today's designs, switching regulators in switched-mode power supplies are being used. The effectiveness of an SMPS is based on energy storage within the system. Switches divert the current to storage elements such as capacitors and inductors in order to filter the input supply noise and reduce ripple. The charging and discharging actions of capacitors reduce voltage droop and reduce the amount of superimposed noise. The input voltage can be stored in the capacitor which then essentially becomes the DC source.

Capacitors do not act ideally as described in theory. Along with their desired properties, there are non-ideal characteristics of capacitors that are based on their materials and construction. The equivalent model can be seen below.

In theory: ***In actuality:***

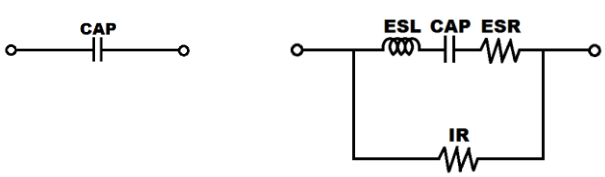


Figure 1. Theoretical (left) and Actual (right) models of a capacitor.

In the actual model of a capacitor, the parasitics can be defined as ESL, ESR and IR. ESL (equivalent series inductance) and ESR (equivalent series resistance) are the inductive and resistive properties of the metals incorporated into the capacitors construction (electrodes and leads). The IR (insulation resistance) is the resistance of the dielectric material used in the capacitor. Choosing the correct materials and proper construction techniques has a direct impact on the performance of the capacitors as ripple filters.

Typically, output filter capacitors require very low ESR. Low ESR values, in accordance with specific capacitance requirements, will increase power quality significantly. If designed well, the SMPS can approach maximum efficiency (Figure 2).

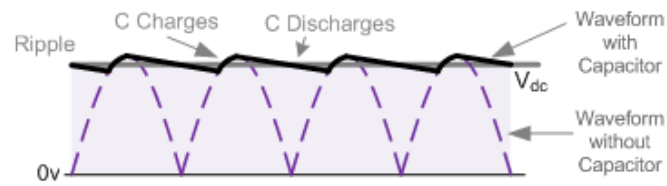


Figure 2. DC waveform filtered with an output filter capacitor. (Storr 2011)

Simulation Software

Before looking at which technology best suits a given application, this section gives a review of the tools that allow the designer to quickly characterize each technology over their application range.

To ensure that the correct capacitors are chosen, there are specific software programs to simulate ESR, ESL, correct operating frequency, and even temperature effects. This software can plot trends and provide the necessary information for optimum capacitor selection.

Component Simulator

AVX Component Simulator is a useful tool in the component selection process. Choosing from various component types, sizes, dielectrics, cap values and voltages allow the user to calculate the ESR, impedance, and Q factor.

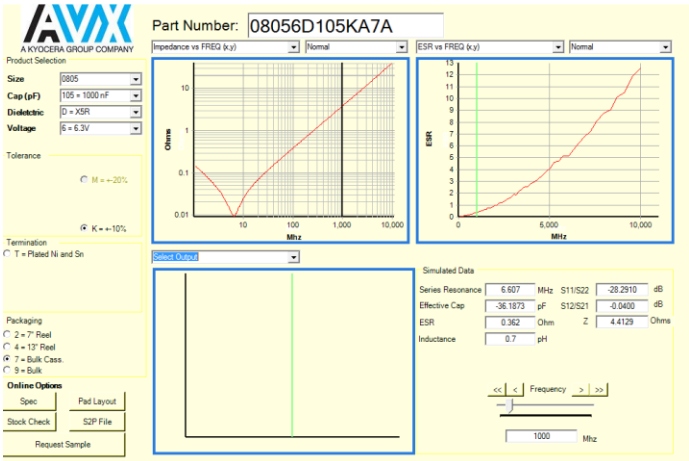


Figure 3. Component Simulator

SpiCap, SpiCalci & SpiTan

SpiCap, SpiCalci and SpiTan are very useful engineering tools for AVX component optimization. These programs generate performance characteristics and provide frequency response graphically and numerically. Various parameters such as ripple voltage, leakage current, temperature characteristics and phase angles can be determined using these programs. SpiCap is designed specifically for ceramic chip capacitors, SpiCalci for SMPS capacitors, and SpiTan for tantalum capacitors. Screenshots of these programs can be seen below:

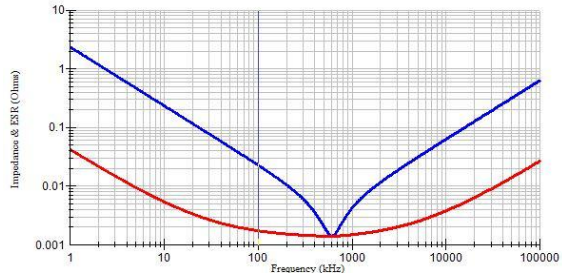


Figure 6. Screenshot of AVX SpiCalci Software ESR plot.

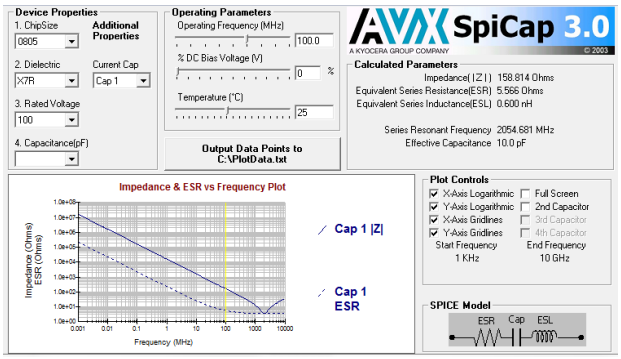


Figure 4. Screenshot of AVX SpiCap Software.

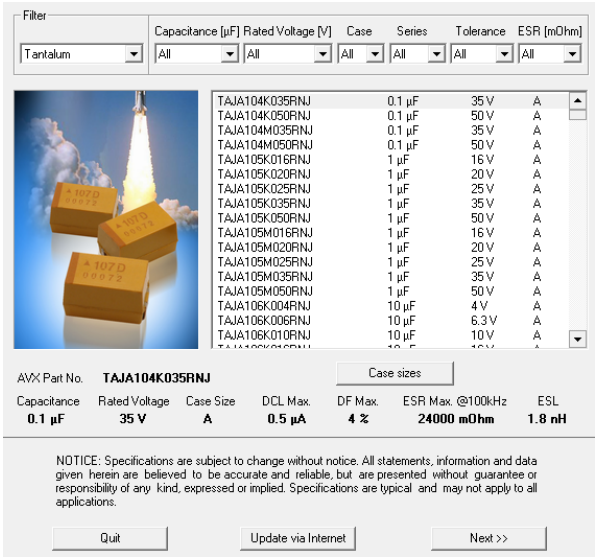


Figure 7. Screenshot of AVX SpiTan Software.

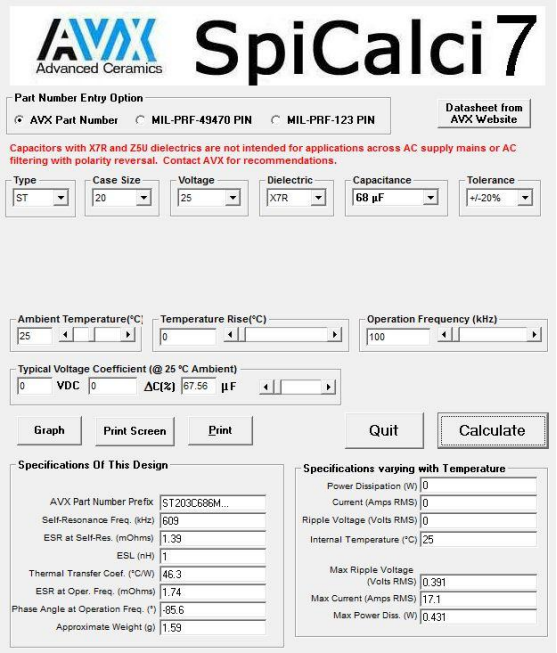


Figure 5. Screenshot of AVX SpiCalci Software.

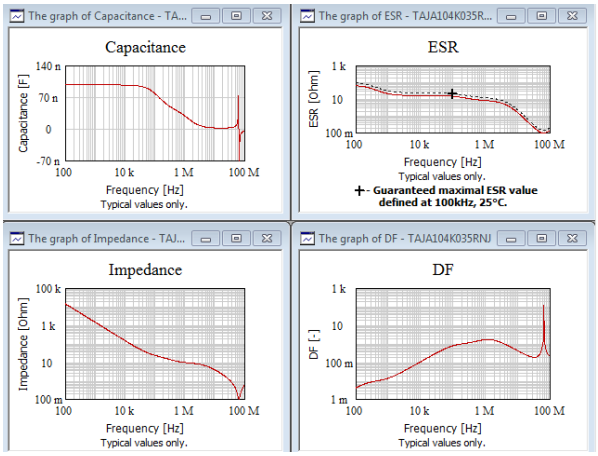


Figure 8. Screenshot of AVX SpiTan Software plots.

Output Capacitor Choices

Capacitance / Voltage and Size Trends

Output capacitors are available in a variety of dielectrics. These dielectrics, for given capacitance and voltage ratings, will determine the capacitors' footprint and size. Different applications will be matched to different dielectric technologies, which will have their own set of associated footprints.

Examples of three output filter capacitors with different dielectric technologies and varying electrical properties can be seen below in Figure 9.

Figure 9. Stacked MLCC (Left), Tantalum (Middle), and Aluminum Electrolytic (Right)

Electrical Characteristics Considerations

As discussed in the previous sections, ESR is a very important electrical characteristic to consider when choosing a component with a certain dielectric. Power quality in an SMPS is directly impacted by the parasitic resistance associated with the output filter capacitors and is subject to change when a different dielectric is used.

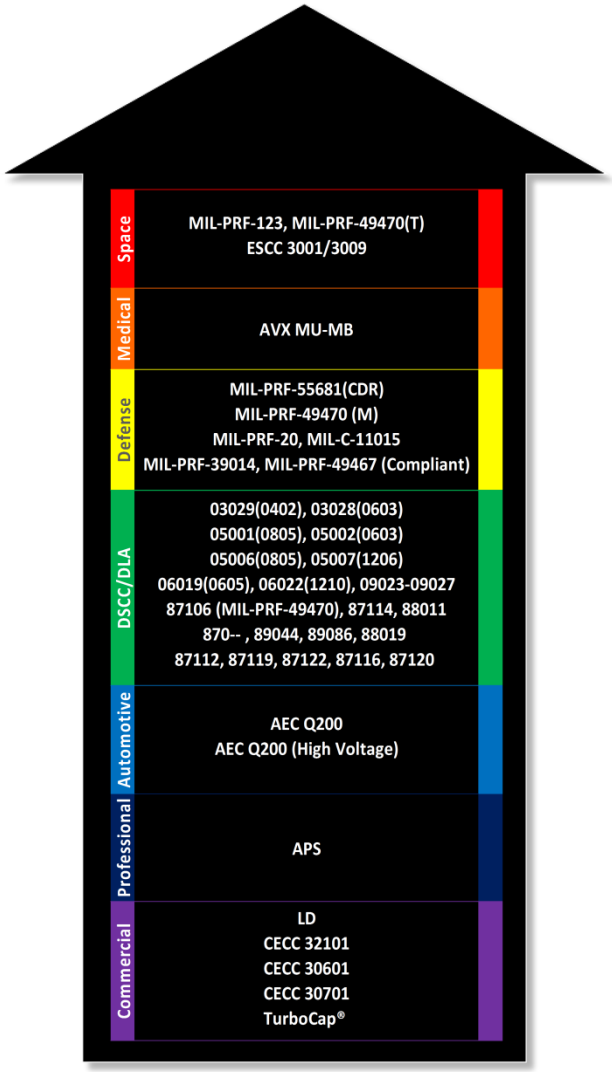
Along with ESR, ESL and DCL are also very important. ESL (Equivalent Series Inductance) is similar to ESR regarding the impedance induced by the dielectric's non-ideal properties.

Another consideration is DCL (Direct Current Leakage). Leakage current is present in capacitors due to the non-zero conduction in the dielectric (insulator). Although these dielectrics are assumed to have perfect insulation properties, there is a small amount of undesirable current leakage even when the switch is off in the circuit. DCL results in the slow discharge of the capacitors.

Equivalent Model of Stacked MLCC, Ta, Film and Aluminum Electrolytics

Four common technology options for these components are Stacked MLCC, Ta, Film and Aluminum Electrolytics. Each option has its electrical advantages and disadvantages.

Stacked Ceramic MLCC capacitors are non-polar devices. MLCC capacitors are made up of many thin ceramic layers. Multiple layers are stacked to increase CV density. To construct these multi-layered capacitors, the electrodes placed between each layer in a staggered overlay pattern and the end terminations connect the electrodes in parallel. MLCC's are a much better option for SMPS filtering due to their much lower ESR and ESL values which reduce energy loss. These ceramic dielectric based output filter capacitors have exceptional ripple current filtering characteristics. Ceramics are also efficient in high temperature applications. AVX ceramic capacitors (stacked or chip) are designed to meet the requirements of various military specifications if requested. The specs that AVX can meet range from Automotive (AEC Q200), DLA/DSCC drawings, MIL-PRF specs and even space level requirements (MIL-PRF-123 and MIL-PRF-49470 T level)



Plastic film, also non-polar, can be used as dielectrics in output filter capacitors as well. The term "Film" capacitor is used due to the construction of these components. A film capacitor is made of an insulating polymer film. Typically polyester or polypropylene materials are used as the dielectric. Polyester is typically used for general applications and polypropylene is used for applications where low power loss is important due to the low dissipation factor of the film and current handling ability. A metal foil can be used or metal can be deposited onto its surface to create the electrode and is then wound or layered to create a capacitor. Film capacitors utilize the polymeric dielectric which has a low rate of energy loss (dissipation factor). The metallization in each layer of the winding is in direct contact with the terminals at both sides of the capacitors, resulting in low parasitic loss (low ESR and ESL). These characteristics make polymer film capacitors very useful in high current applications. Another advantage to film capacitors is the fact that they are "self-healing." This means that a defect can be burned out and evaporate the metallization to create an open circuit at that location, in turn, eliminating the defect. Despite the advantageous nature of film capacitors, they have lower temperature ratings. Also, nearing their temperature limit, there is a significant voltage rating drop.

Tantalum capacitors may also be considered. Tantalum metal forms the anode, while its oxide layer makes up the dielectric. Standard tantalum technology uses manganese dioxide as the counter electrode (cathode) with self-healing properties for long life. A polymer can also be used as the counter electrode for lower ESR. Tantalum capacitors have a larger ESR than ceramics, but lower than aluminum.

Aluminum electrolytic capacitors are typically inexpensive and are widely used in consumer applications. They are constructed of an Aluminum Oxide dielectric, thin Aluminum plates and an ionic conducting liquid. The downfall to these capacitors is the electrolyte incorporated into the construction. High ESR is associated with the acidic electrolyte in aluminum electrolytic capacitors due to the high degree of difficulty in developing chemically stable compositions. The lifetime of these capacitors is also based on the electrolyte and can be shortened upon evaporation and high temperature usage. Finally, Aluminum Electrolytics can fail catastrophically due to the nature of the fluid used in their construction.

A comparison of electrical properties for various dielectric technologies can be seen in Table 1 in the appendix.

Frequency Response

In an ideal situation, impedance decreases while frequency increases. A comparison of ESR vs. frequency of the different dielectrics can be seen in Figure 10 as well as in Table 2.

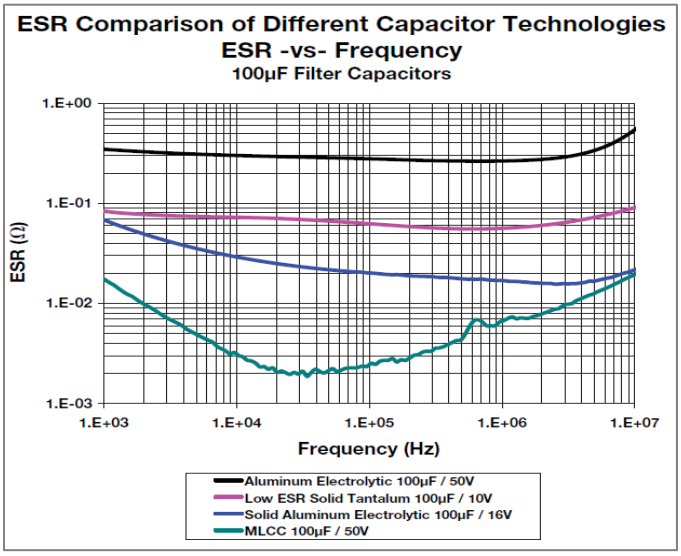


Figure 10. ESR vs. Frequency for different dielectrics

Table 2 below, displays typical ESR performance across a frequency range from 10KHz to 10MHz as observed on a network analyzer. These observations show a consistently low ESR across this frequency range (typical for SMPS applications) for ceramics compared to electrolytics or tantalum capacitors.

Table 2. ESR comparison and frequency performance.

Typical ESR Performance (mΩ)			
Type	Al El 100µF/50	Tantalum 100µF/10	MLCC 100µF/50
ESR @ 10KHz	300	72	3
ESR @ 50KHz	285	67	2
ESR @ 100KHz	280	62	2.5
ESR @ 500KHz	265	56	4
ESR @ 1MHz	265	56	7
ESR @ 5MHz	335	72	12.5
ESR @ 10MHz	560	91	20

After observing the figure 10 and table 2, it can be hypothesized that if a multilayer ceramic capacitor is applied as an output filter capacitor in an SMPS application, then there will be a significant improvement in ripple voltage filtering compared to aluminum electrolytics and tantalum capacitors, due to the nature of their low parasitic construction.

Measurement and Comparison of Open Frame SMPS Output Voltage Quality

Output filtering is necessary to reduce noise measurements in SMPS applications. The undesirable ripple effect and self-heating is based on the internal resistance of the capacitors. The current passing through the internal resistance leads to Joule heating of the system. Since this is unwanted, the reduction of internal resistance is critical.

Aluminum electrolytics have the highest internal resistance, followed by tantalums. MLCC and film capacitors have the lowest internal resistance out of all of the dielectrics. Based on the fact that internal resistance causes power losses, I^2R losses and heating of the system, the efficiency of the SMPS system would be improved if MLCC's or film capacitors were designed-in as output filters.

In an experiment to compare these capacitor technologies and their output ripple filtering, a shielded commercial open frame switcher was selected for testing. A 110V input voltage was applied along with a 3.3ohm load and a ground (test setup below).

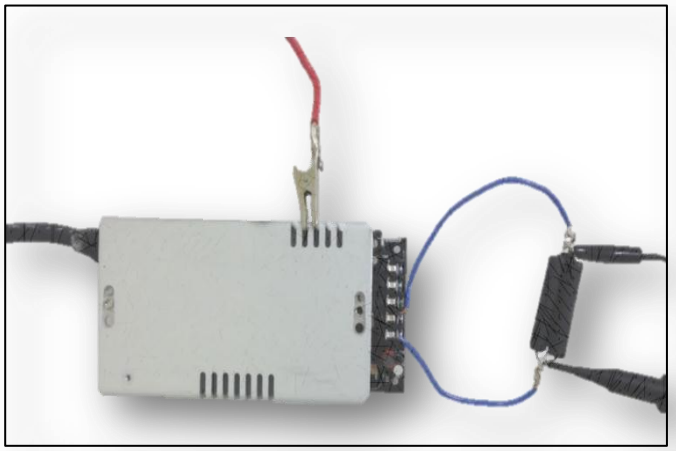


Figure 11: Test Setup for experimental comparison of capacitor technologies used in an open frame switcher.

Identical test setups and procedures were performed using first, two aluminum electrolytic capacitors (2200µF / 16V), and next, two stacked ceramic capacitors (200µF / 25V). The output ripple voltage was measured using a Tektronix TDS784A Oscilloscope and recorded.

The plot in figure 12 displays the results of this study and compares output ripple voltage filtering utilizing different capacitor technologies

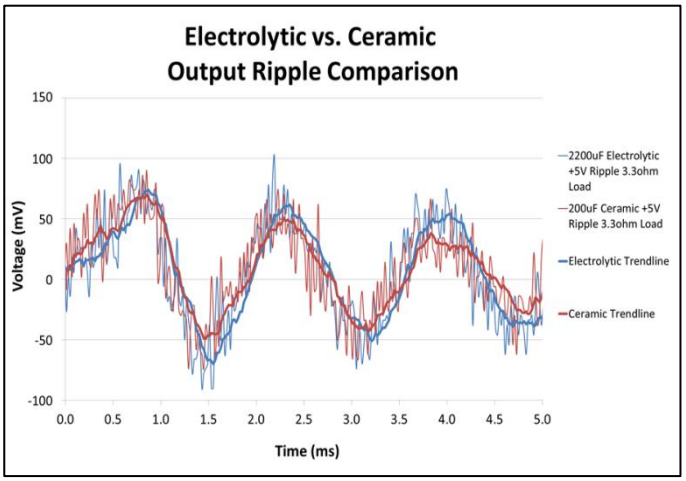


Figure 12. Comparison of output ripple voltage (Aluminum Electrolytic swapped out with a Low ESR Stacked Ceramic)

The results of this experiment comparing a ceramic capacitor with 1/11th of the capacitance value of the electrolytic demonstrate the importance of ESR in filtering applications.

The ceramic capacitor provided a comparable ripple to the electrolytic capacitor while taking up ¼ of the board space and a much lower capacitance value. In general, this is consistent from what has been found by tantalum technology replacing electrolytics in low voltage power supplies. The results were due to lower ESL and ESR based on capacitor technology, materials and construction. ESR and ESL parasitic characteristics are proven to be the key contributors to output voltage quality and utilizing a technology with lower parasitics can significantly improve ripple filtering and lead to board-space reductions.

Future studies will be performed to observe output ripple filtering with higher capacitance value ceramic capacitors in both open frame switchers and inverters.

Effect of Low Inductance Technologies upon Output Voltage Quality

Just as ESR improves DC ripple in power systems, low ESL reduces the reactance and improves power quality. The inductance can be viewed as the current loop defined by the signal path in the application. Size of the current loop in output filter capacitors plays a major role in the determination of output voltage quality. The larger the current loop the larger the parasitic inductance. With this in mind, it is clear that placing the terminations on the short ends of a traditionally rectangular shaped MLCC would give a current loop defined by the long dimension of the chip. This initiated the development of low inductance chip capacitors (LICC).

LICCs incorporate reversed geometrical characteristics by placing the terminations along the sides of the standard rectangular shape rather than the ends. This decreases the size of the current loop significantly and can result in an ESL reduction of approximately 60% of that of a traditional MLCC.

Another advanced technology is the InterDigitated Capacitor (IDC). In these capacitors, opposing current loops are used to reduce inductance. The structure of these capacitors creates shorter current loops and ESL is further reduced due to the opposing current loops. The ESL in an IDC can be up to 80% lower than that of standard MLCC's.

The third technology developed to reduce ESL in output filter capacitors are Land Grid Array's (LGA). LGA's integrate multiple terminals into the capacitors which shorten the current loop and reduce ESL.

On the higher end of low inductance technologies are TurboCap™ and FFVS designs. TurboCaps use vertical stacking construction to shorten the current loop distance to the thickness dimension rather than the previously mentioned length and width. This results in ultra-low inductance of about 1nH.

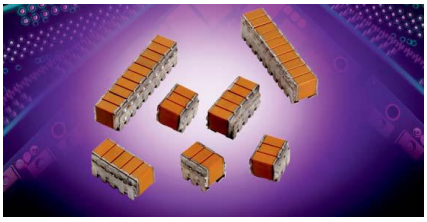


Figure 13. Image of TurboCap™ vertical stacked design.

The next high end technology is the FFVS design. For these very high power applications, busbar mounting is necessary. Specific internal design characteristics lower the parasitic inductance to an extremely low value between 8 and 13nH.

Figure 14. FFVS busbar mounted design.

Based on the previously stated technologies, low inductance designs are being implemented to significantly reduce parasitics and greatly improve power quality. A comparison of the low inductance design techniques can be seen in figure 15 below.

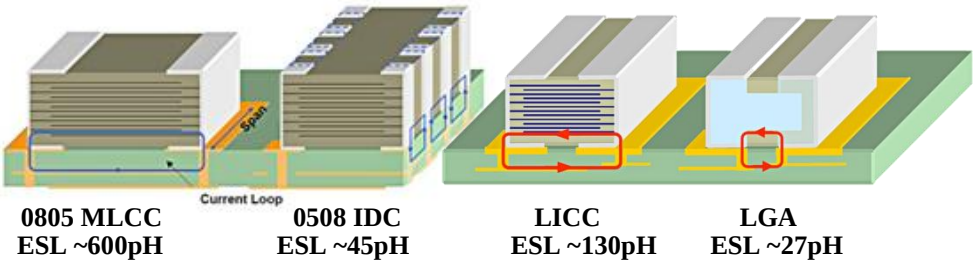


Figure 15. Comparison of low inductance design techniques.

Output Filter Capacitors

Parasitic Parameters Impact on Power Quality

Summary and Considerations

Output filter capacitors are critical components in SMPS in order to ensure a high level of power quality.

SMPS output filter capacitors are used in a variety of advanced applications. They are primarily used in high-voltage power supplies as well as high-current applications. They are used in downhole exploration, high-frequency motor drives and are incorporated into space and aerospace electronics. Any application that calls for high reliability and superior output voltage quality will require an output filter capacitor.

There are many characteristics of an output filter capacitor to consider when improving power quality is the desired outcome.

In the selection process, consider the effects of non-ideal parasitics in a capacitor. Low ESR and ESL are important to ensure that the capacitor is working to its full potential.

Another consideration would be to look at the temperature effects on ESR. Using simulation software, the optimum operating temperature can be observed by viewing the changes in ESR as temperature increases.

Based on the parasitic characteristics of particular dielectrics in output filter components, it can be observed that stacked MLCC output filter capacitors are an adequate specimen for use in SMPS applications. Superior ESR and ESL characteristics, along with advantageous volumetric capabilities, are the main qualities that make the stacked MLCC capacitors ideal for these high reliability applications.

In addition, low inductance technologies and new design techniques can even further improve output voltage quality in SMPS applications by significantly reducing parasitics. Although developed for commercial devices, they are also available with Sn/Pb terminations with additional testing.

Acknowledgments

Chris Reynolds- AVX Corporation
Ron Demcko- AVX Corporation
Stan Cygan- AVX Corporation

References

1. Aluminum Electrolytic Image:

   TTI, Inc., "High Reliability Aluminum Electrolytic Capacitor." Last modified 2013. Accessed March 6, 2013. http://www.ttiinc.com/object/Nichicon-High-Reliability-Aluminum-Electrolytic-Capacitor.

2. DC Wave Filtering Image:

   Storr, Wayne. DNA Technology, "Full Wave Rectifier - The Smoothing Capacitor." Last modified 2011. Accessed March 6, 2013. http://www.dnatechindia.com/Tutorial/Basic-Electronics/Full-Wave-Rectifier.html.

Appendix:

Table 1. Electrical properties of various dielectrics.

Electrical Properties Comparison						
Characteristics		Aluminum Electrolytics	Tantalum	MLCC		
				Class 1: NP0	Class 2: X7R/Z5U	Class 2: X5R/Y5V
Capacitance	Range, mfd	0.5-10^6µF	0.01-1000µF	1pF-0.01µF	1pF-2.2µF	0.001-0.1µF
	Min Tol. Avail. %	± 20%	± 5%	± 0.5%	± 5%	± 20%
	Std. Tol. %	+100% -10%	± 20%	± 5% ± 10%	± 10%	+80% -20%
Voltage Range	Typical, VDC	3-500	6-125	50-200	50-200	25-100
Temperature	Range, °C	-40°C +85°C	-55°C +125°C	-55°C +200°C	-55°C +200°C	-10°C +85°C and -55°C +85°C
	T.C. %ΔC	± 10%	± 8%	± 0.3%	± 15%	+22% -56% and +22% -80%
IR	<.01 µF	N.A.	10^2MΩ	10^5MΩ	10^5MΩ	10^4MΩ
	>.01 MΩ-µF	100	10	1000	1000	1000
Dissipation Factor	Percent @ 1KHz, %	8% (at 120Hz)	8% to 24%	0.10%	2.50%	Up to 12.6%
Dielectric Absorption	Percent Typical, %	N.A.	N.A.	0.60%	2.50%	N.A.
Frequency Response	Freq. Response 10 = Best 1=Poorest	2	5	9	8	8
	Max. Freq. (MHz) For ΔC = ± 10%	N.A.	0.002	100	10	10
Reliability	%/1000hrs. @ Confidence Level	1% @ 90% Conf.	.001-1% @ 90% Conf.	.001%-1% @90% Conf.	.001%-1% @90% Conf.	.001%-1% @90% Conf.
Stability (Aging)	ΔCap vs. time/temp.	10 years predicted lifetime	N/A	N/A	1%	2-3%
Stability (1000 Hrs)	Typical Life Test, %ΔC	10%	10%	0.10%	10%	20%
Polarity	Single Cap	P	P	N.P.	N.P.	N.P.
Climatic Category	Low Temp/High Temp/Damp Heat	55/105/21	55/175/56	55/125/56	55/125/56	55/85/56

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