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TECHNICAL BULLETIN 3.99A

Reprint from the proceedings of the 14th Annual Applied Power Electronics Conference & Exposition (APEC), March 1999. Copyright 1999, Illinois Tool Works

Recent Advances in Capacitor Technology with Application to High Frequency Power Electronics and Voltage Conversion

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INTRODUCTION

Innovation in capacitor technology is being driven by the shrinking size and low height profile needs of high frequency power converters. While physical sizes are reducing, higher ripple and load currents in the power train are also emphasizing the need for efficiency improvements in capacitors under application stress. With this dichotomy of needs, it has proven difficult to meet the dual function of low impedance (high capacitance) and high ripple current capability (low ESR) within only one capacitor technology.

Electrolytic capacitors offer the highest capacitance values, hence the lowest impedance at moderate frequencies below 100 kilohertz, and would appear to be the likeliest choice for low voltage-high current circuits. They are however limited in use due to power inefficiencies. The key to their increased use would be a marked improvement in AC loss factor and a significant increase in operating frequency; in other words better ESR and ESL than is currently available.

Since electrostatic capacitors (ceramic and polymer film) offer extremely low ESR and ESL and have very low impedance at higher resonance frequencies (into the megahertz range), they would appear to be the logical choice for all high-speed circuits. They are limited in use because electrostatic capacitors are only available in relatively "low" capacitance values, usually below 10 microfarads. If the capacitance values could be increased, electrostatic capacitors could be used more extensively in high load current applications, such as output filtering. Because of the inherent stability of electrostatics at high frequency compared to electrolytics, replacing electrolytic with electrostatic capacitors would improve the performance and reliability of the output filter sections.

Electrolytic and electrostatic capacitor manufacturers are working closely with the power conversion industry to reduce component size, extend current handling ratings and improve parasitic behavior in the low and high pass power train circuits germane to power conversion. Some of the more dramatic and market-wise important capacitor component development trends are covered in this short paper. To limit its scope, this paper concentrates on trends for capacitors used in large volume, high frequency power converters.

BACKGROUND

Switching power converter technology is driven by the high volume end user markets of computer, telecom and datacom. A common denominator among these end users is the desire for smaller and more efficient power supplies. The accelerating trend to distributed power and DC to DC conversion from a high quality DC bus voltage has spurred a whole industry of "point of use" or "power on board" miniaturized converters. The increased use of distributed power systems (based upon 48-volt power plants in place of using lower "quality" UPS systems), is an obvious choice for telecommunications grade systems[1]. Because board space has become such an important issue, the use of increasingly higher switching frequencies is allowing for the size reduction and shrinking profile of both the magnetic and reactive components. Standardization of the 48-volt telecom bus with its extended time battery back up feeds a growing market of "brick" and smaller converters[2].

The off-line AC to DC makers have faced somewhat less pressure to miniaturize the components or increase power throughput efficiencies. There is however, some desire to reduce total "shoebox" size and avoid excessive heat generation, which is being facilitated by higher frequency switching. After years of little movement, there is an effort to miniaturize the EMI filters and passive PFC section of the front ends.

Some degree of standardization on a 300-volt computer bus voltage is driving a higher wattage converter sector. Relatively high wattage 300-volt to 5-volt converters perform the local bus conversion at the point of use. The requirement for both 5 volt and 3.3 volt MPU supply is more evident in the computer than the telecom systems. Since direct conversion to 3.3 volts is not efficient, 5 to 3.3 volt voltage converters are gaining in popularity[3].

The personal computer application drives a demand for AC to 12 and 5 volt intermediate bus for displays, disc drives and memories. These power supplies are housed in smaller boxes and towers so efficiency and size are somewhat important. Avoidance of fan cooling with its inherent maintenance and noise problems is also an issue. The trend to lower supply voltages based upon the needs of the newest microprocessors has had a profound effect on both off- line and DC to DC converter makers. The intermediate 5 or 12 volt bus is converted to 3.3 volts by local converters or non-isolated VRM's. The load current demands have increased by the inverse square of the voltage reduction, and the slew rate power demand has increased linearly with the clock speed of the MPU's. The once "simple" job of decoupling the microcircuit is magnified because this is now a low impedance and high frequency and high power chore. Currently, multiples of different capacitors are being used to handle the combination of load current and high-speed power demand.

Progression of Lower Voltage Outputs

Volts	50 Watt Load Current	Minimum "Load" Capacitance
12.0	4.2	5.6
5.0	10.0	32
3.3	15.2	74
2.5	20.0	125
1.8	27.8	247
1.2	41.7	556

Minimum "load" capacitance does not include parasitic ESR, which requires additive capacitance. This "load capacitance" is calculated for a 250Khz switcher @ 50% duty cycle.

MAJOR TECHNOLOGY SHIFTS IN CAPACITORS
(LISTED FROM HIGH TO LOW VOLTAGE)

High Voltage Polymer Films

Looking at capacitor technology in the higher volume power applications, we start at the higher input voltages and film capacitors. The moderate pressure to downsize the Input EMI filters has caused a redesign of Across-the-Line capacitors from PET film to segmented PP film. Segmentation of the metallized patterns on thinner polypropylene (see Figure 1) has allowed higher values and a slight decrease in the package size of the "X" capacitors. This trend toward higher voltage ratings per micron thickness is taking place in all high voltage film capacitors in order to increase capacitance density. The segmentation patterns in the metallized electrode allows a localized fusing and disconnect during high voltage surges. A potential downside to this approach is limited useful life span due to capacitance drop should excessive clearings and defusings occur.

In the downstream high voltage section after the rectifier, RFI filter and bypass capacitors must support a universal input voltage of around 373 volts peak. Stacked or multilayer film capacitors have much higher dv/dt ratings than tubular wound capacitors and attenuate harmonics of the switching noise more successfully. EMI problems can be avoided by using multilayer film capacitors, which have lower ESR and ESL than spiral wound capacitors in the RF range. The newer film capacitors rated at 400 volts are also available in surface mount packages, which has led to increased acceptance.

High Voltage Electrolytics

With the shift to universal input voltage, standardized converters, aluminum electrolytic capacitor ratings have risen to 500 volts from 200 or 450 volts. No other capacitor technology provides as high an energy storage feature as aluminum electrolytics. Electrolytics remain, therefore, essential for primary input ripple filtering and line frequency cycle storage. Improvements to the high voltage technology have been incremental but marginal; mainly directed at increasing the useable life of the product and increasing the ripple current ratings. The high resistivity of high voltage electrolytes (above 100 volts) is a physical result of the chemical methods used to

Data on Typical Capacitor Types

	Selected Value	**DCV**	**Dissipation Factor (1KHz)**	**Dissipation Factor (100KHz)**	**ESR @ 25°C (100KHz)**	**Ripple Current (100KHz)**
Aluminum	1000µf	6	10.0%	15.70%	0.025	1.0
Tantalum	680µf	6	6.0%	9.80%	0.023	3.0
OS-CON	330µf	6	6.0%	4.10%	0.020	3.5
Ceramic - X7R	10µf	100	2.5%	0.94%	0.015	6.0
MLP-PET	10µf	100	1.0%	0.69%	0.011	14.1
			Spec.	Actual	Spec.	

avoid breakdown voltage. This high resistivity is the main contributor to ESR in the system. Selection of multiple units of a smaller diameter has been the most telling effort to lower impedance and increase total ripple handling. The input capacitors remain a quality and system life concern. The newer polymerized electrolyte systems used at low voltage do not appear to be suitable for higher voltage operation at this time.

Medium Voltage Electrostatic Capacitors

The growth of battery back-up power plants and the selection of DC bus voltage distribution have created a large and growing DC to DC Converter market[4]. In telecom, the most popular application is 48 to 5 volt conversion, although other bus voltages and output requirements exist. High frequency switching technology based upon PWM and resonant control set the standard from 200 to kilohertz to 1 megahertz switching frequency. At these switching frequencies, electrolytic capacitor technology gives way to electrostatic types, which have much lower ESR and ESL at high frequency. The input-filtering chore had been underestimated until EMI problems drove the industry to pay more attention to the quality of the input filter capacitors. Miniature input-filter capacitors are now supplied by makers of ceramic and polymer film types. Since tantalum capacitors are not very efficient at 48-volt ratings due to low capacitance values and very high dissipation factor and ESR, the electrostatic capacitors are being used as output filter capacitors in medium voltage telecom applications.

Because 100-volt X7R ceramic capacitors have been historically used in 48-volt bus applications, they have been further refined into larger values and case sizes for the input filter section of the DC to DC converters. Part cracking due to the fragile nature of large ceramic chips led to the mounting of the chips in lead frame carriers. To keep costs down, multiple units were used to add up to the several microfarads of input capacitance dictated by the input current of the power supply. The trend in X7R ceramic capacitors today is the continued use of higher K materials and the thinning down of the dielectric slip in order to increase the capacitance per unit volume. These design moves have made a notable change in part size but have come at the expense of stability under voltage and current.

Multilayer film capacitors evolved from stacked film types to the true surface mount chip styles available today. Since the polymer dielectric(s) have no voltage or current dependency; they are the most stable system at higher voltages (including 24 and 48 volts). The move by polymer film manufacturers to refine ultra thin films in the 1.4-micrometer range for 100-volt applications has allowed for the production of highly stable film chips in relatively large capacitance values. High frequency ESR and ESL is comparable to the ceramic chips in X7R dielectric while the electrical stability is superior[5]. The avoidance of chip cracking and "open" circuit failure mode has been a major feature of this new capacitor system. Further effort is being made to reduce the size of the parts by employing even thinner films and through the application of barrier coatings on the surface of the ultra thin plastic films. Reduction in part size and unit cost is getting further attention.

Low Voltage Electrolytics, Os-Cons[6] and Electrostatics

Because of the power demands of digital circuits, the low voltage area is the largest and fastest changing market. Tantalum capacitors were used almost exclusively on 5-volt output, high-density power supplies because this was the only capacitor system that could deliver the several hundred microfarads needed in the output filter section. Aluminum electrolytic capacitors were not suitable due to their very high AC loss factor, limited useful life, and limited current handling capability. Multilayer ceramic or polymer types were too limited in capacitance in these high current, low voltage circuits. The advent of 3.3-volt bus-rail drove solid tantalum chipmakers to develop low voltage devices up to 1000 microfarads. The AC loss factor of the tantalum chip worsened as the chips were made thicker and denser, so the increase in capacitance provided only marginal improvement to the total ESR. To overcome this high resistivity problem of thicker tantalum anodes, multiple chips are now being ganged and molded into a discrete chip package[7] (see Figure 2). The propensity of solid tantalum capacitors to fail and burn in high current-low impedance circuits remains an issue, no matter how many anodes are contained in the molded package. Part fusing, often discussed in the past, will become more of a factor as the supply voltages drop and the load currents increase. While tantalum capacitor makers have been involved with incremental ESR improvements, the aluminum capacitor makers have made a major breakthrough in low voltage electrolytic systems.

Aluminum electrolytic capacitors employing a polymeric electrolyte are now available below 25 volts and appear to offer a solution for low voltage ripple current and hold up applications. The solid electrolyte system has allowed construction of chip shaped capacitors suitable for reflow soldering in SMT assembly. The size and capacitance value per unit volume is not (yet) as good as solid tantalums, but the high frequency attributes are already far superior. This technology also appears to be scalable to lower voltage and higher capacitance value parts in the future. As of this writing, the major tantalum capacitor manufacturers have announced the development of a polymerized electrolyte system to replace the current technology. This is being fostered to improve the high frequency ESR problem, the issue of capacitance roll off at high frequency, and avoid the catastrophic failure mode of the highly complex manganese dioxide based cathode system used today.

High-speed microprocessors demand current slew rates and very high frequency operation that are not attainable using electrolytic capacitor technology. Due to the relatively high dissipation factor and limited frequency range of electrolytic capacitors, they cannot supply energy fast enough to high speed MPU's. Several electrostatic ceramic capacitors have been proposed including X7R, Z5U, Y5V and as of late, Y5U. The objective has been to produce the highest capacitance value possible while meeting some reasonable stability over the application ambient parameters. Given a 15 amp continuous load, and 30 amps per micro second slew rate, hundreds of microfarads of relatively low impedance is required[8]. The X7R dielectric system is the best choice due to its reasonable stability over temperature, but it has the lowest capacitance values and therefore the highest cost. The other classes of dielectrics are really only usable at room temperature because use at 85°C is not practical due to the enormous drop in capacitance value. However, a 22 microfarad 1812 Y5U chip has recently been proposed that provides the lowest impedance per unit volume and low cost, albeit at moderate ambient temperature use. The aging characteristics (capacitance loss per decade hour) of these semi-stable ceramic capacitors needs to be taken into account early in the design by providing an extra margin of capacitance value. High inrush currents can cause mechanical cracking of ceramic chips, particularly at low temperature start up of ceramic capacitors.

Multilayer polymer (MLP) capacitors have been proposed for and are used in low voltage, high current circuits. Their capacitance stability over temperature and high frequency impedance characteristics are ideal, but unfortunately their capacitance value is limited by the low dielectric constant of homogeneous polymer dielectrics. The development of films thinner than one micron will expand their capacitance value and therefore load current range. Their present low voltage use is limited to higher reliability applications where stability and current handling cannot be matched by any other technology. The MLP capacitors offer the lowest ESR (owing to their low dissipation factor) and are rated to the highest ripple current ratings per capacitance value of any high frequency capacitor. The primary drawback to more extensive use is cost compared to electrolytic and semi stable ceramic types and to a lesser extent part size effecting board space.

APPLICATION CONSIDERATIONS

Voltage sensitivity, capacitance roll off, capacitance drop per volt, aging rate, di/dt limitation, dissipation factor rise over frequency, and ESR increase over time are examples of common application generated parasitics of capacitors. These shortcomings are difficult to find in most catalogs or promotional data sheets and will continue to require in depth research. As capacitor technologies have matured and the need to reduce size and cost became paramount, stability of the parts has been compromised. Much of the "safety margin" inherent in common designs has been trimmed as dielectric thickness per volt has been pushed to the limit in most capacitor systems. The resultant quality level is acceptable only if power supply makers and other customers understand the stability of the parts and can make allowances for worst case conditions. As a good case in point of where the need to match capacitor characteristics to application needs is required, capacitor application data sheets from various manufacturers will show an allowable heat rise under ripple current conditions ranging from a 3°C to a 30°C rise above ambient temperature. The charts and figures listed at the end of this paper cover some of the major capacitor stability issues relevant to power conversion applications.

CONCLUSION

High frequency switching regulators need improved input capacitors to control common mode noise. Because of the mid to high voltage nature of the inputs, MLC and MLP capacitors are the only choice. For very low voltage (and high current) outputs the combination of low ESR and very large load current related capacitance value remains a dichotomy. Electrolytic capacitors remain essential for high current handling while electrostatic capacitors are still needed for fast response and to handle high ripple current. The developments to thinner ceramic slips and thinner polymer films is helping the capacitance value extension of low ESR electrostatic capacitors. The adoption of polymerized electrolyte in aluminum capacitors at low voltage is providing a vast improvement in high frequency impedance. It remains to be seen if the adoption of "plastic" current carriers in tantalum electrolytic capacitors will provide a measurable improvement in the ESR and reliability of that system. Multi stage output filters, already a reality at 48 volts will become more prevalent for high current outputs, either in the converter or as external discrete components.

Reliability of various components under application stresses could not be covered in this paper. This will be the subject of a follow up paper on capacitor technology.

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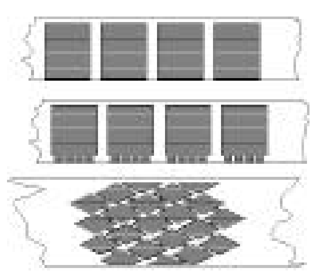

Figure 1 Typical Segmented Patterns On Metallized Film

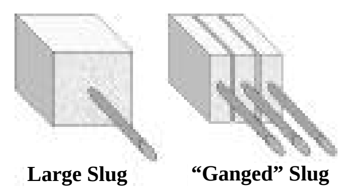

Figure 2 Example of "Ganged" Tantalum Capacitor

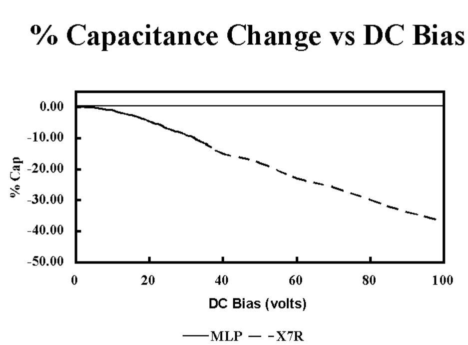

Figure 3 Stability Comparison of Electrostatic Capacitors

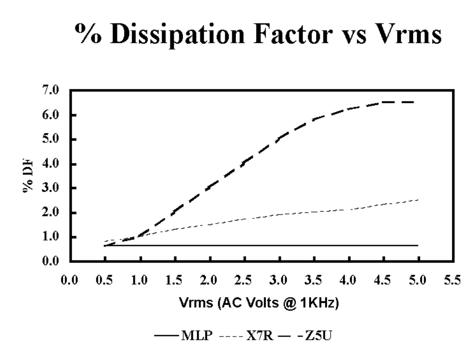

Figure 4 Stability Comparison of Electrostatic Capacitors

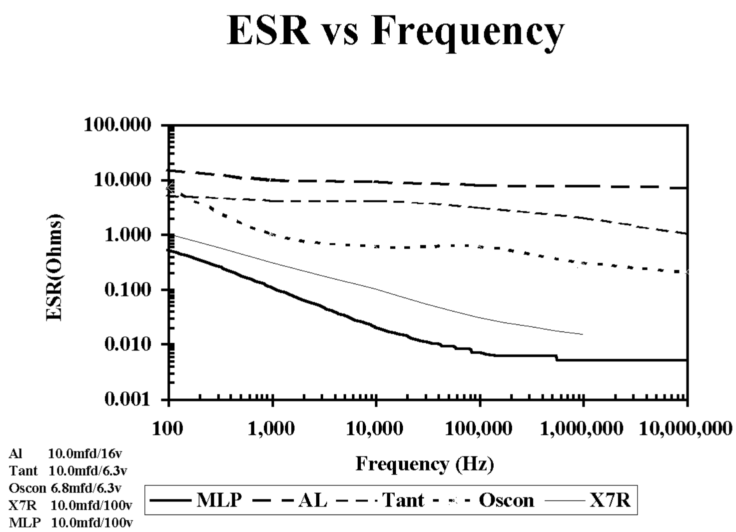

Figure 5

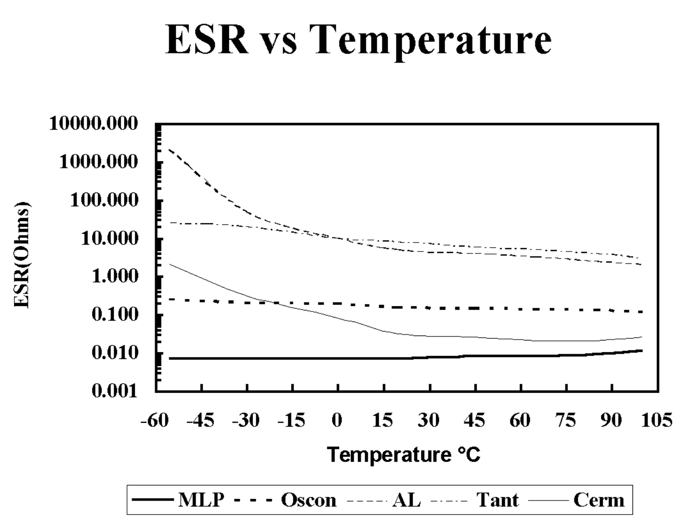

Figure 6 ESR Stability

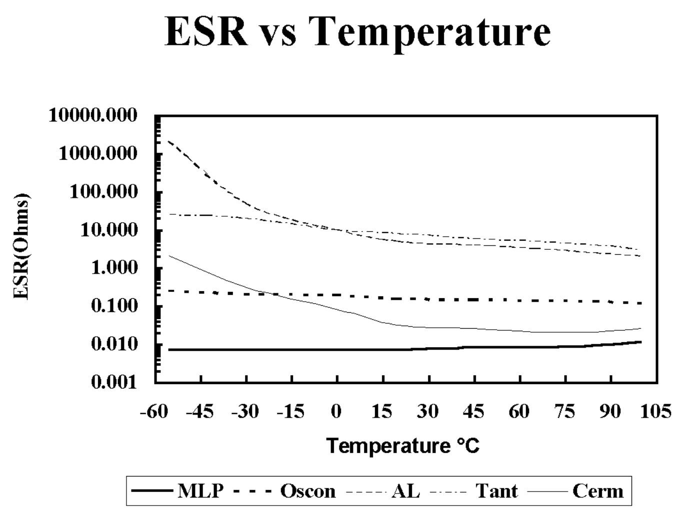

Figure 7 Temperature Coefficient