Power Film Capacitors for Industrial Applications

Paola Bettacchi, Davide Montanari , Daniele Zanarini,
Davide Orioli, Gianluca Rondelli, Antonio Sanua

KEMET Electronics Corporation, 2835 KEMET Way, Simpsonville, SC 29681

Kemet Italy Location via San Lorenzo 19, 40037 Sasso Marconi (Bologna), Italy
Tel: +39 51 939 225, Fax: +39 51 939 324, e-mail: DavideMontanari@kemet.com

ABSTRACT

The demand for energy savings and for alternative energy sources has called for an accelerated introduction of products such as Solar Converters and Wind Generators. A DC to AC inverter is a key system for the operation of these devices. The inverters require AC Filtering (to reduce the harmonic components overlapped to the fundamental frequency), Snubber (connected in parallel with semiconductor components to damp dangerous voltage spikes) and DC-Link (to support a DC network by supplying periodically high currents and filtering the AC ripple) Capacitors with high operating voltages and ripple currents in order to increase the power. Other important parameters are low inductance to limit the switching transient voltages, high frequency capability, large range of working temperature, long expected life time, low dissipation factor and low ESR, high stability vs. time of the Capacitance value, withstanding of high peak voltage, mechanical strength, maximum flexibility of adaption to the shape of the available space, customized termination technology (through hole wires, tabs, bus-bars, lead frames), and low total cost. The Film capacitor is the type of capacitor that comes closest to satisfying these requirements. Several choices of film technologies are available: Wound Flat in Box Type, Wound Cylindrical in Round Alu-can and Soft-Winding in Brick. There have been recent advances in these technologies. The Wound and Soft-Winding capacitors have seen significant advances in capacitance, voltage and current capabilities, and expected life time (100kh continuous use). The Soft-winding capacitors have benefited from very thin and high temperature Polypropylene film in combination with a new process of metallization, winding and thermal treatment. This paper will discuss the technical basis for advances in each of these positions inside the circuit (AC Filter, Snubber and DC-Link) and technologies and give some guidance on the optimum areas (capacitance, size, voltage and current) for the application of each technology.

INTRODUCTION

Power capacitors are mounted inside industrial equipments in three main positions: AC Filtering, Snubber and DC-Link. Every field of application prefers the usage of a particular film technology depending on two main factors: Power of the equipment and circuits layouts with different peculiarities. Therefore the market of emerging countries is only driven by prices and often uses old technologies because the competition between suppliers is higher and they can even count on local suppliers. This paper contains the explanation of the different aspects to consider for the choice of the correct capacitor to be used in each position and application. The windmill generators, solar converters, drivers (welders) and UPS represent the different fields where power film capacitors are utilized in the industrial market. Giving particular attention to wind power inverters, the voltage trend is continuously increasing from 450-500Vdc to higher voltages in the range of 700Vdc to 1350Vdc. High voltages have the advantage to reduce power loss in the alternator and to decrease the current values and the total capacitance value of the components. The use of film capacitor reduces the number of components and improves life expectancy of the equipment. Film capacitors fit very well the requirements of these applications: high reliability with excellent self-healing, long useful life and excellent overvoltage capabilities till the maximum class Temperature of the component. Here after the main aspects and parameters that will be treated:

- Dielectrics available for different applications
- Metallization technologies trends;
- Capacitors drawings.
- Manufacturing technologies;
- Circuital position and main characteristics needed to meet the specification;
- Technologies used in every application in the three positions: AC Filtering, Snubber and DC-Link;
- Self heating and ESR
- Typical ESL values of KEMET components
- Lifetime of the components
- Summary

DISCUSSION

DIELECTRICS AVAILABLE FOR DIFFERENT APPLICATIONS

The dielectrics normally used for film capacitors are:

- PP: polypropylene;
- PET: polyethylene terephthalate;
- PEN: polyethylene naphthalate;
- PPS: polyphenylene sulphide.

The Self-healing proprieties (the dielectric ability to regenerate from internal drop of insulation resistance) of the plastic base film take a fundamental place to ensure a safe failure mode in Power applications. The main plastic material for Power film capacitors is PP because of its high self-healing properties and low and stable dissipation factor. PEN and PPS can't meet these requirements sufficiently well and are normally excluded. Generally in industrial applications temperature > +105°C are not required and even PET is not used.

Table 1: Characteristics comparison between plastic film dielectrics

Dielectric	PP	PET	PEN	PPS
Dielectric Constant (@1 KHz)	2.2	3.3	3.0	3.0
Min Commercial Thickness (µm)	2.4	0.9	1.4	1.2
DF (% @ 1kHz)	0.02	0.5	0.4	0.05
TCC (DC/C), -55°C to +125°C	± 2.5%	± 5%	± 5%	± 1.5%
Max Temperature Typical (°C)	105	125	125	125
Max Temperature Extended (°C)	125	150	170	170
Dielectric Breakdown (V/µm)	400	280	300	220
Self-healing	Good	Medium	Medium-Low	Low

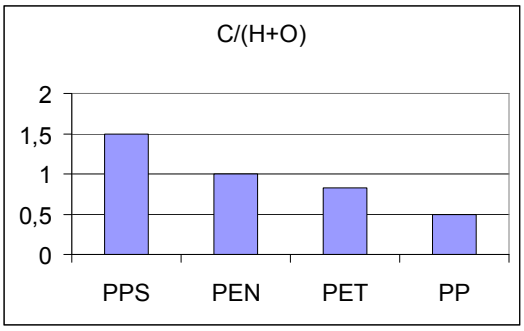


Figure 1: C/(H+O) ratio in different dielectrics.

To compare the self-healing properties of different materials we have to consider its chemical composition. When the ratio between C atoms and H+O atoms is low, the possibility to have residual half-conductive C parts is lower than in the other cases. Naturally there are many other parameters to consider in the self-healing process and the energy content during the clearance process play a key rule: the process needs high energy to be efficient and to insulate the two metal layers.
Many developments are running with the most relevant names of base film manufacturers to increase the performances of the actual dielectrics available on the market. The trend is to overcome the temperature limitations of polypropylene film maintaining its self-healing properties or to develop a new dielectric to bring the market to new generations of components.

METALLIZATION TECHNOLOGIES TREND

The continuous market requests for smaller and price competitive parts brought to strong rising of dielectric strength (V/um values). To follow this trend the base film quality plays a significant rule and the metallization technologies the most effective one.
Some applications have reached 230-250V/µm using high quality PP base film and accurate metallization profiles. The metallization process of plain film is performed by evaporation of metals; the two main materials are Aluminum and Zinc often combined together to obtain the proper performances in every zone of the film. The metallization processes take care of base film parameters and adopt different slope profiles with many physical-chemical treatments to increase the adhesion of the evaporated metals on the dielectric and to protect the thin metallization layers of Al and Zn.
Free margins technologies are more and more accurate in particular if combined with some particular drawings like segmentations. These ones, together with the proper profile, are able to increase the safety margins of the final components, increase its life time decreasing the probability of short circuits.

The right combination between metallization profile and segments reduces the catastrophic failures, increase the lifetime expectancies and limits the end of life failure mode to drop of capacitance.

MANUFACTURING TECHNOLOGIES

With several basic technologies of film capacitors available we are able to customize and produce capacitors for all the important power generating and management applications. The primary applications for capacitors in Industrial sector are for inverter AC Filtering, Snubbers and DC-Links. In this field the technologies available are listed below:

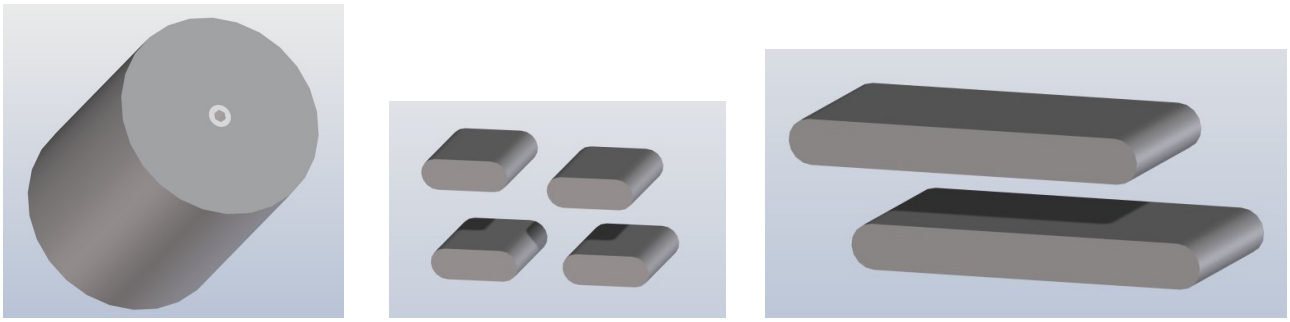


Figure 2: Winding Technologies (Round for Cans, Flat for Boxes, Soft-Winding for Brick).

Wound in Round Can: the winding is non-inductive type with internal plastic core and round shape, the element/s are inserted in an aluminum can with threaded bolt closed by a plastic/metallic deck with high current screw terminals. It is a dry construction, filled by solid resin for DC-Link & Snubber applications; for AC Filtering there are both dry and wet components where the oil expansion permits the safety-device functioning.
Wound in Box: the winding is non-inductive type with flattened oval shape, the element is inserted in a solvent resistant and flame retardant plastic box execution, the terminals are 2/4 tinned copper wires or 2 tinned copper lugs. It is a dry construction, sealed by resin.
Soft-winding in Brick: the capacitor element is composed of several non-inductive windings with large flattened oval shape, the windings are soldered together with the bus-bar and inserted in a metal or plastic case; the bus-bar and the terminal materials are tinned copper or tin/nickel plated brass. It is a dry construction, sealed by resin.

CAPACITOR CONFIGURATIONS

The today's increasing demand for energy savings and for alternative energy sources, has boosted the research and development in strategic inverter-driven products like Solar Converters and Wind Generators.
All of them profoundly rely on a better management of the energy conversion. High reliability, withstanding of tough ambient conditions, long expected life, are just some targets of the agenda of the technical innovation initiatives today.

The strong advancement of inverter products calls for DC-Link capacitors with high mechanical flexibility with ability to be attached to the semiconductors (IGBTs and MOSFETs) in the best possible way. Technologies for producing the internal construction are available in Wound and Soft-winding constructions. These internal constructions can be packaged in a large range of configurations in order to offer, according to the application, the smallest possible size and inductance, or the highest possible voltage and ripple current, or the best possible connections.

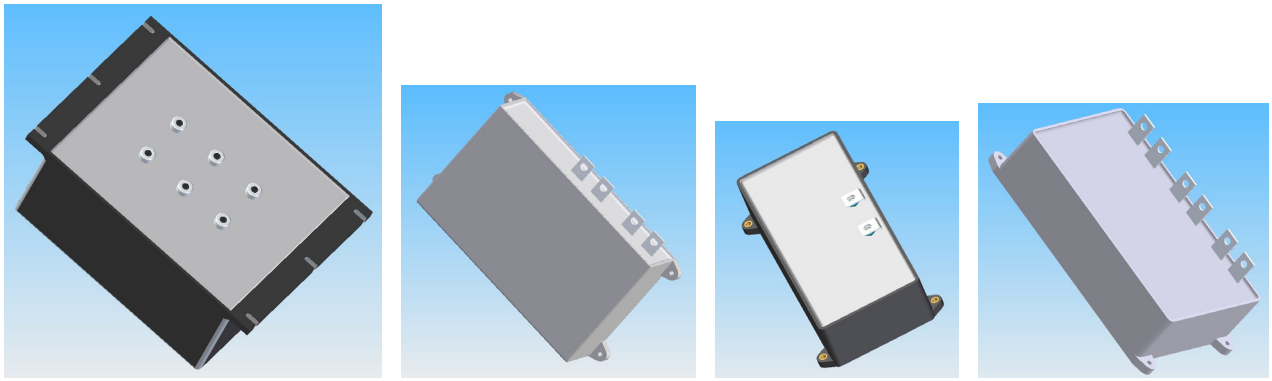


Figure 3: Various configurations of KEMET's film capacitors (Brick, Alu-can, Round-can and Box) in thru-hole, screws, lugs and bus-bar assembling solutions.

The KEMET's Technologies for Film Capacitors can offer extremely adaptable solutions to any type of installation requests, especially for high adaptation to the space and the terminals connections (Table 2).
The available shape, size and connections of the customer application can be met by the high flexibility of the Technologies

Table 2: Terminals solutions

Technology	Terminals Connections
Wound in Round Can	Male and Female Screws, Fast-on
Wound in Box	Trough-hole Wires ; Lugs
Soft-winding in Brick	Bus-bar ; Male and Female Screws

CIRCUITAL POSITION AND MAIN CHARACTERISTICS NEEDED TO MEET THE SPECIFICATION

Film capacitors are employed in 3 main positions:

1) AC Filter: eliminates the harmonics at higher frequencies on the low frequency waveform.
2) Snubber: suppress the spikes continuously generated by the switchers operating inside the converters.
3) DC-Link: is the power supply when the line voltage decreases.

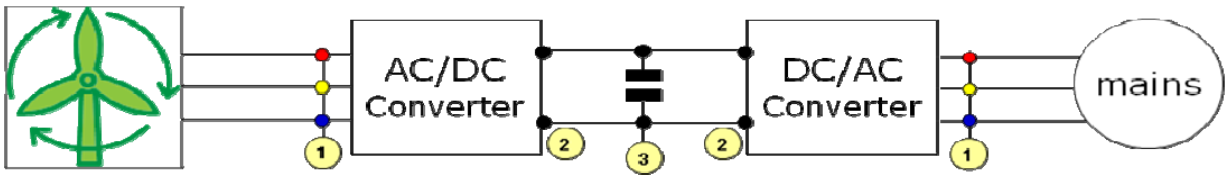


Figure 4: Example of Wind mill energy generator scheme

Here after we consider for each circuital position the customer's requests based on the different application fields and on the power of the equipment followed by KEMET series proposal and the main characteristics of capacitors.
Additionally the C/V (Capacitance/Volume) trend based on the film technologies evolution in particular in DC-Link applications, the trend of ESR/freq (Equivalent Series Resistance/frequencies) and the self-heating graph of some examples of our components.

The self-heating reduction of the capacitor caused by ripple currents has a positive effect on the total energy efficiency of the system. KEMET is hardly working to reduce the ESR by implementing a new metallization profile of the film and by using new construction of the elements and the bus-bars.

AC Filtering

The AC-Filtering capacitors have the scope to reduce the high frequencies contributes on the fundamental frequency (50-60Hz); usually the first harmonic is at 2.5 – 6 kHz, this depend on the field of application of the filter.

In output filtering both delta and star configurations are commonly used.

All the components in these positions use metallized Polypropylene film in Wound or Soft-Winding configurations depending on the application field and conditions and on the equipment lay-out. The importance of an accurate thermal treatment on the internal elements is one of the key factors during the process. In some cases the use of component equipped with safety devices is suggested; this technology is available in Alu-can components filled with liquid resin.

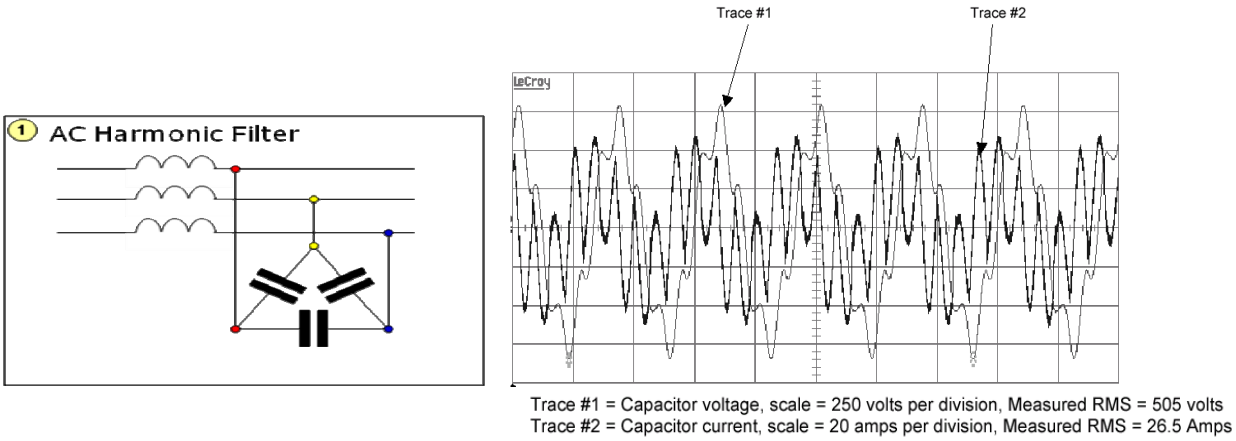


Figure 5: AC Filter Delta-scheme & typical waveform in AC-Filtering caps

Some examples of customer's specifications and KEMET series proposal:

Table 3: AC-Filtering application data and KEMET series characteristics

Application Field	Power of the equipment	Voltage range (Vac)	KEMET Products	Technology	Base Film	Internal Technology	Cmax (µF)	Umax (V-)
Wind Mill Generators	1÷3.3MW	≥690 Vac	C20	Alu-can	PP	Wound	600	1000Vac
Solar Converters	10kW÷500kW	140÷440 Vac	C4A C44	Box Brick	PP	Wound	60 600	850 Vdc 300 Vac
AC Drives	10kW÷1MW	440÷530Vac	C44 - C20	Alu-can	PP	Wound	600	1000Vac
UPS	10kW÷1MW	250÷440 Vac	C4A C44	Box Alu-can	PP	Wound	60 600	850 Vdc 500 Vac

In Wind-Mill application the trend is still on Alu-can mono-phase components with safety devices (C20 series); solar market is starting to evaluate the Brick configurations with dry resins.

Snubber

The Snubber capacitors have the scope to reduce the high Voltages (1000-4000Vpk) and high peak Currents generated during the fast transition of semiconductor switches.

The position in the circuit is close to the switchers that creates high Temperature close to the capacitor and on its terminals.

The film technology suggested in this application is Double Metallized Polyester Film to obtain a robust component with high mechanical stability during the spikes combined with Polypropylene film to contain the Dissipation Factor and increase the self-healing properties of the component. This internal construction is suggested even because of the severe ambient Temperature and the stabilization process with a severe and accurate thermal treatment permit to the products to be reliable and to maintain the component characteristics. Dry resin completes the component and protects the core of the element from external ambient conditions.

Since this year we have introduced in our production Mini-Brick components (C4ES series) able to reach the Rated Voltage of 4000Vdc and able to support peak voltages till 6000Vpk. This new series has many different size and terminal constriction to meet our customer's custom projects with high technologies both for film design and mechanical drawing properly combined with the adequate manufacturing process.

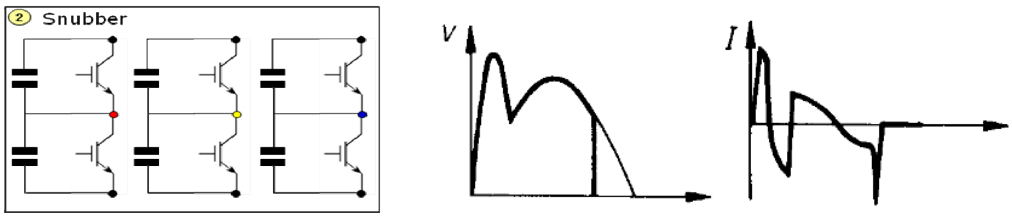


Figure 6: Snubber circuit scheme & typical waveforms on Snubber caps

Some examples of customer's specifications and KEMET series proposal:

Table 4: Snubber application data and KEMET series characteristics

Application Field	KEMET Products	Technology	Base Film	Internal Technology	Cmax (µF)	Umax (Vdc)
All	C4AS C4BS	Box with wires or lugs	D-met PET + PP	Wound	5 µF	3000 Vdc

C4DS (Plastic round component with axial construction with 2 female screws) is used in some applications in medical like X-ray analysis

DC-Link

The DC-Link capacitors have the scope to stabilizing the voltage after the rectifier providing enough current to the load and to filter the AC ripples on the bus.

The Voltage DC bus range is usually between 450-1500Vdc depending on the particular field of application and the ambient Temperature is higher than in AC-Filtering because the position of DC-Link is closer to the switchers.

To supply this big energy generally the Capacitance values and the Voltage requested are high, then the market needs compact solutions and its trend goes to economic but reliable modular products without compromising the caps performances and expected life. The bus capacitor is needed for absorbing the ripple generated by the switching IGBTs modules at 1kHz - 20kHz that could damage the semiconductors, batteries or other elements of the circuit.

KEMET has several technologies and cover most of the industrial applications for range of Voltages and Capacitance values, shape of components, dimensions and terminals.

The caps process technologies are; Wound-flat in Box; Wound cylindrical with plastic core for Round components and Soft-Winding for Brick caps. All these technologies are combined with High-Tech metallized Polypropylene film to meet the severe ambient conditions and restricted and customized spaces; the ongoing drawings can reach 230-250V/µm in most of the series and the trend is the continuous increasing of this value even in dry technology. To reach high dielectric strength all the step of the process are important, in particular the winding process and the stabilization process with thermal treatments inside a controlled camera to create parts with high and uniform performances. For these applications all the components are sealed with dry resin.

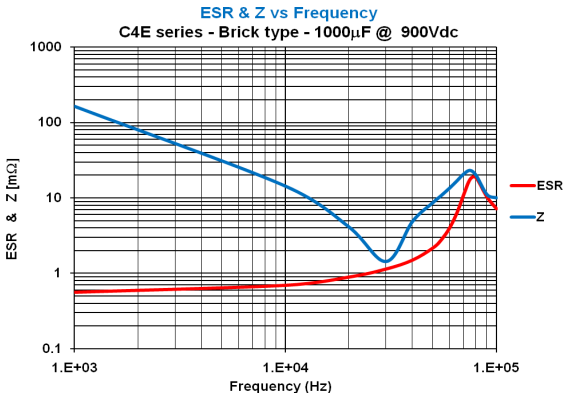
Figure 7: Snubber circuit scheme & typical waveforms on DC-Link caps

Some examples of customer's specifications and KEMET series proposal:

Table 5: DC-Link application data and KEMET series characteristics

Application Field	Power of the equipment	Voltage range (Vdc)	KEMET Products	Technology	Base Film	Internal Technology	Cmax (µF)	Umax (Vdc)
Wind Mill Generators	1÷3.3MW	various	C44U C4E	Alu-can Brick	PP	Wound Soft-Winding	2000 20000	1300 1500
Solar Converters	10kW÷500kW	900-1300 700-1350	C4AE - C44U C4E	Box -Alu-can Brick	PP	Wound Soft-Winding	100 - 2000 20000	1300 1500
AC Drives	10kW÷1MW	various	C44U C4DE	Alu-can Plastic-can	PP	Wound	2000 380	1300 1000
UPS	10kW÷1MW	various	C4AE C4DE	Box Plastic-can	PP	Wound	100 380	1100 1000

Impedance (Z) & Equivalent Series Resistance (ESR)



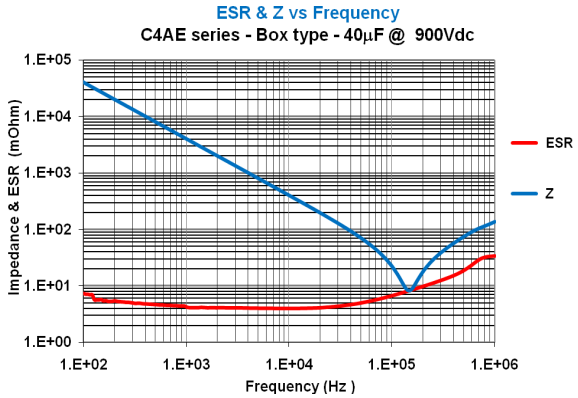


Figure 8: Brick components: ESR & Z vs. Frequency **Box components: ESR & Z vs. Frequency**

Capacitance Density and Voltage

In many new applications there are specifications for high rated voltage and over voltage.
The most innovative applications also require high capacitance per volume that means it is necessary to use a thinner film than has been the practice in the past. The average value of film thickness decreasing and gradient of voltage increasing of the different series is moving from 200V/µm to 230-250V/µm in dry technology, this kind of density was proper of wet technology in the past years.

More energy in less space, that's the ambitious and challenging goal for new power designs involving film capacitors.

This scenario strongly contributes to creation of a new generation of metallized film capacitors for Power Electronics applications, a typology that along with the well established characteristics of self-healing, stable performances vs. time and high ripple current / capacitance ratio, now also can count on more reliable Polypropylene base films and on new techniques of metallization.

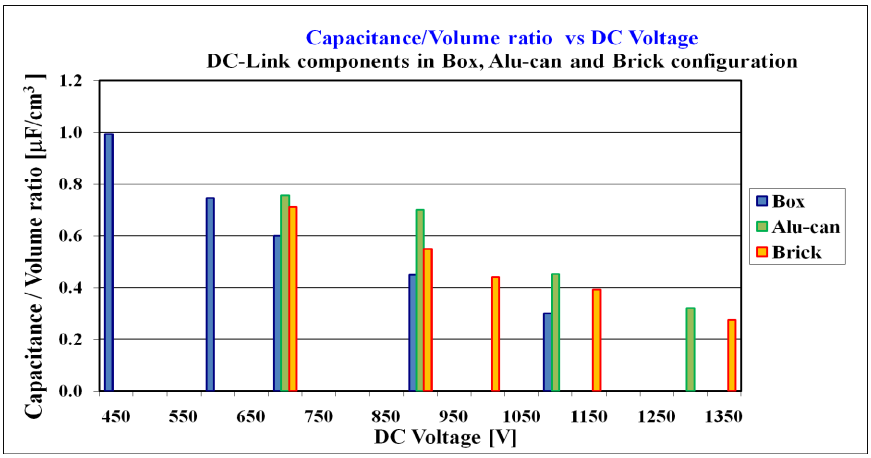


Figure 9: Capacitance Density on Voltage

Thanks to the increasing of Capacitance Density and the widening of available shapes and dimensions, we are able to overcome the 100µF in Box typology, the 2000µF in Alu-can and the 20000µF in Brick components.
Here below a summary of the Power Density of DC-Link components (C x Un x Irms/Volume) vs. different technologies. Most of the components increased the Power Density of more than 20% each couple of years.

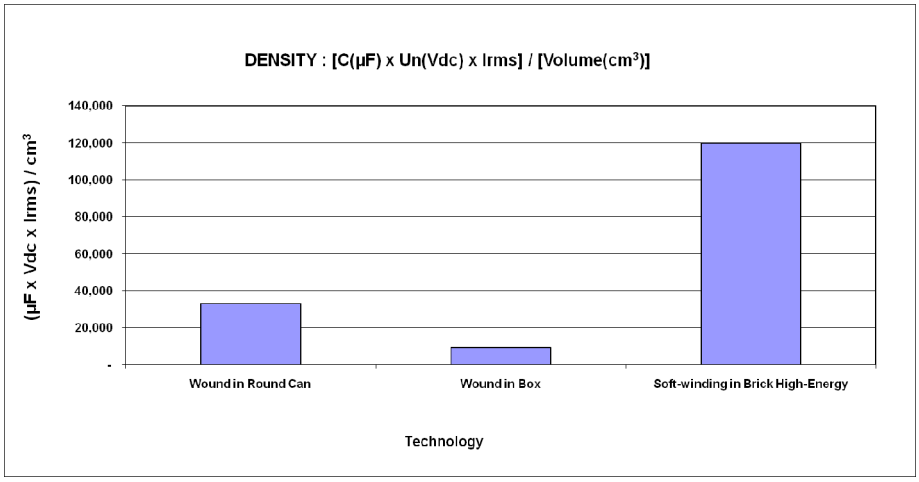


Figure 10: Density [C(µF) x Un(Vdc) x Irms] / Volume(cm^3) of KEMET's DC-Link Film Technologies

Ripple Current and Thermal Stability (Irms)

DC-Link current harmonics are the predominant factor to be considered for the design of the DC-Link capacitors. The capacitor dimensions basically are linked with these items: maximum Voltage, maximum Ripple Current, ambient Temperature and life time requirements.

The components has to support a ripple current due to the switchers, a voltage deflection due to the generator and the overvoltage due to the circuit inductance that absolutely need of a dielectric with high self-healing properties.

AC ripple current causes the losses (both dielectric and resistive) that can be calculated using the capacitor's ESR (Equivalent Series Resistance) at the proper Frequency.

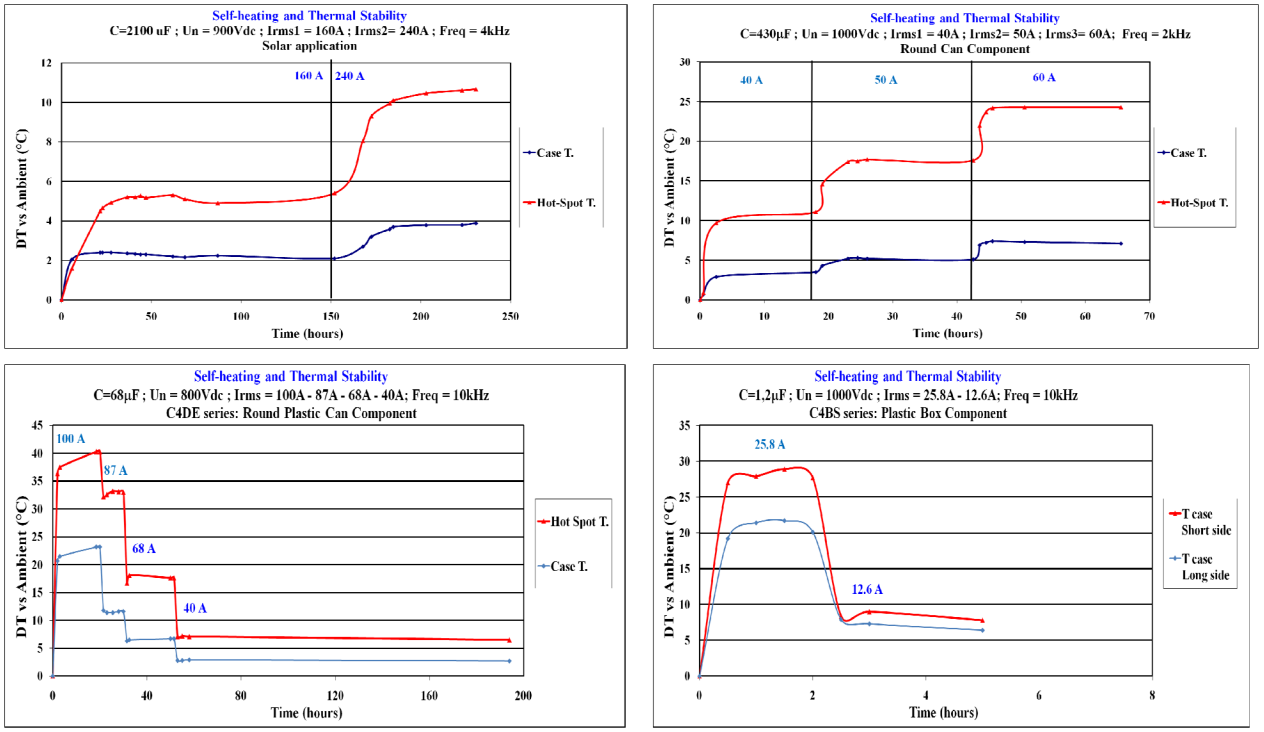


Figure 11: Self-heating and Thermal Stability - Soft-winding - Round Aluminum can - Round Plastic can – Box Technologies.

TYPICAL ESL VALUES IN KEMET COMPONENTS

In order to limit over-voltages due to semiconductor commutation, most designs are using Snubber capacitors geometrically close to the switching circuits to decrease the bus-bar global inductance.

Kemet is working in co-operation with its customers, and can offer a complete range of film capacitor technologies:

- Wound in Round Can
- Wound in Box
- Soft-winding in Brick

For any kind of semiconductor modules and mechanical lay-out of the inverters, it is possible to develop a capacitor with the best technologies in order to minimize the internal ESL and the ESL of the bus bar connections.

Table 6: Equivalent Series Inductance examples (ESL)

Technology	C	Un	Tamb	Freq	Irms	ESL
	(µF)	(Vdc)	(°C)	(kHz)	(A)	(nH)
Wound in Round Alu-Can	1100	1100	60	10	52	**≤ 85**
Wound in Round Alu-Can	2000	900	50	10	90	**≤ 80**
Wound in Box	25	1100	70	10	17	**≤ 35**
Wound in Box	100	450	70	10	17	**≤ 35**
Soft-winding in Brick	2400	900	80	3	300	**≤ 25**
Soft-winding in Brick	6600	1350	57	2.5	300	**≤ 65**
Soft-winding in Brick	18000	700	50	3	180	**≤ 60**

LIFETIME OF THE COMPONENTS

Industrial Applications require a long life time that can be accomplished by utilizing new metallization configurations of the film together with plastic or metallic housing sealed by dry resins. Manufacturing machineries and new production process are oriented to preserve and maintain the thermal treatment.

Working life time at rated voltage (Un) vs. Hot Spot Temperature for capacitors fabricated using soft-winding & round-winding technology. 100,000 hours of life can be achieved at temperatures up to 75°C and approximately 30,000 hours of life can be achieved at 85°C.

Higher number of hours could be reached in particular conditions and with a Voltage significantly lower than the rated voltage and moderate ripple content. For polypropylene film capacitors we estimated a maximum lifetime of 200khours, after that every estimation is purely theoretical.

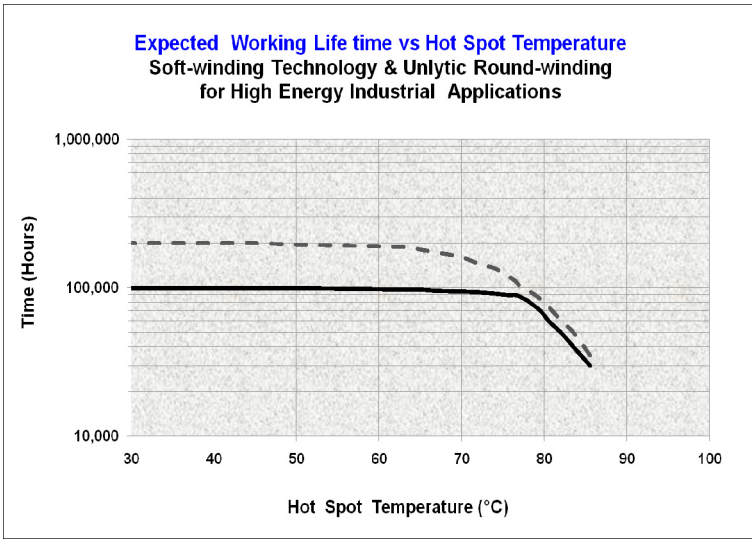


Figure 12: Working Life Time – Soft-winding & Round-winding Technology for High Energy.

SUMMARY

The KEMET's film capacitors for Industrial Applications, with the latest technology developments, can meet all the requirements of the new generation of Power Electronics, used for the control, the transformation and the management of the energy through solid-state switches, which require AC-Filtering, Snubber and DC-Link Capacitors with high operating characteristics:

- High Voltage → high nominal voltages
- High Ripple Current → low and stable ESR
- High Self Healing properties → optimum PP performances for self-healing
- Low Dissipation Factor and low ESR → low self-heating
- Low ESL → low switching transient voltages
- High frequency → optimum PP performances and stable ESR
- Long Life Time → high circuit reliability
- Large range of Working Temperature → stability of characteristics in a wide range of Temperatures
- Low volume and weight → high Capacitance Density
- High mechanical strength → robust components in metallic or plastic case
- Maximum flexibility of adaptation to the shape of the available space
- Customized termination technology → bus bars and flat or screw terminals
- Low total cost → evaluating globally cost, dimensions, reliability.

BIBLIOGRAPHY

1. Davide Montanari, Kimmo Saarinen, Fabio Scagliarini, Dietmar Zeidler, Matti Niskala, Claes Nender – KEMET Electronics Corp., "Film Capacitors for Automotive and Industrial Applications", 2009 CARTS Proceedings, April 2009, Jacksonville, FL, USA