Film Capacitors for Automotive and Industrial Applications

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ABSTRACT

The demand for energy savings and for alternative energy sources has called for an accelerated introduction of products such as Hybrid Electric Vehicles, Solar Converters, and Wind Generators. A DC to AC inverter is a key system for the operation of these devices. The inverters require Filter and DC-Link Capacitors with higher operating voltages and ripple currents in order to support the need of increasing 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, low weight, maximum flexibility of adaptation to the shape of the available space, customized termination technology (through hole wires, tabs, bus-bars, lead frames, and SMD), and low total cost. The Film capacitor is the type of capacitor that comes closest to satisfying these requirements. Several choices of film capacitor manufacturing technologies are available: Wound, Soft-Winding, and Stacked. 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 winding and thermal treatment. The Stacked capacitors can now use two base plastic films (Polypropylene and Polyester) and new techniques of metallization and insulation during the cutting process.

This paper will discuss the technical basis for advances in each of these technologies and give some guidance on the optimum areas (capacitance, size, voltage and current) for the application of each technology.

INTRODUCTION

With several basic technologies of film capacitors available we are able to customize and produce state-of-the-art capacitors for all the important power generating and management applications in the Automotive and Industrial sector. The primary applications for capacitors in this sector are for inverter AC filtering and DC-links.
The technology development focuses on :

- Windings in Round Al-Can and Soft-winding in Brick type technologies for Medium and High Power Applications (e.g. Solar Converters and Wind Generators).
- Brick type Soft-winding technology for High Energy DC-Link and AC Filtering (e.g., trains)
- Brick type Soft-winding for Thin Film and Stacked technologies for Low and Medium Power applications (e.g. Hybrid and Electric Vehicle Drives)
- Box type technology for PCB-mounted Low Power applications (e.g., remote Solar Power generation) and DIL (Dual In-Line) in Wound Technology (e.g. SMPS Switch Mode Power Supplies).
- SMD type in Naked Stacked technology for low energy applications (e.g. DC/DC filters) and DIL (Dual In-Line) in Wound Technology (e.g. SMPS Switch Mode Power Supplies).

The availability of these technologies allows the design of capacitors for a wide range of power levels and mounting configurations.

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The commonly used plastic dielectrics for film capacitors include polypropylene (PP), polyethylene terephthalate (PET), polyethylene naphthalate (PEN), and polyphenylene sulphide (PPS). To ensure safe operation with a benign failure mode, the Self-healing proprieties of the film material are very important for Power applications. PEN and PPS can not meet these requirements sufficiently well and are normally excluded. The most frequently used plastic material for Power film capacitors is PP because of its low and stable dissipation factor. In applications that require high temperature operation (> +125C) or for surface mounting PET is used instead of PP because of PP's relatively low melting point.

This paper describes the different technologies used to manufacture these capacitors and performance data for the different technologies and gives some guidance on which technologies should be used in different applications.

EXPERIMENTAL

The capacitor characteristics were measured, tested and verified with following instruments and methods:

- **Agilent E4980** and **HP-4284A Precision LCR meter** at 1 kHz and 1 V_{rms} :
  Capacitance (C), Dissipation Factor (tan δ), Series Resistance (ESR) and Inductance(ESL).
- **HP4192A (Impedance Analyser)** : Resonance frequency, ESR and ESL.
- **Discharge current's curve analysis (Figure 1)**: Resonance Frequency and ESL.
  The test was carried out charging the capacitor to a low voltage (≈ 10 Vdc) and subsequently discharging it through a short circuit by a contactor. The short circuit has to be located as close as possible to the capacitor to avoid stray inductances. A "Rogowsky" current probe was used to measure the discharge current. From the recorded current data, the value of the ESL was easily calculated.

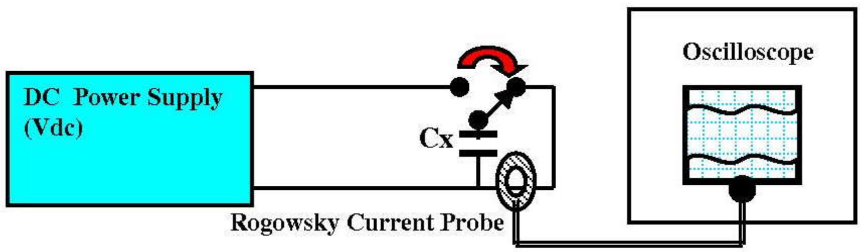


Figure 1 : ESL measurement system

- **Ripple Current Testing with DC Bias (Figure 2)**: Thermal Stability and Self-heating vs Irms
  The test was carried out to simulate the thermal conditions present in e.g in an inverter at the extreme limit of current. The use of several sensors, on the case, close to both terminals and the "hot spot", makes it possible to study the maximum temperature gradients internally.

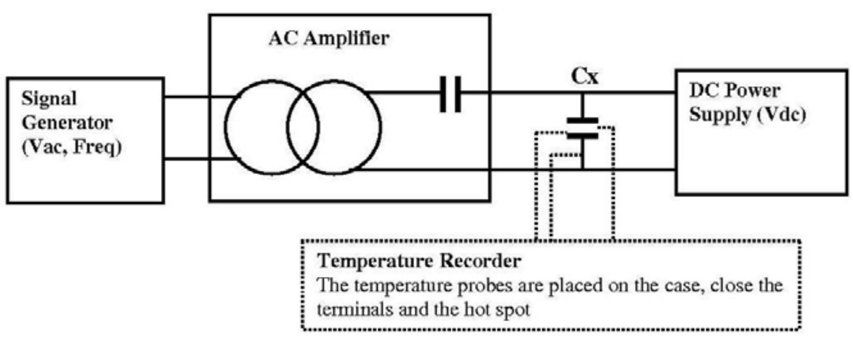


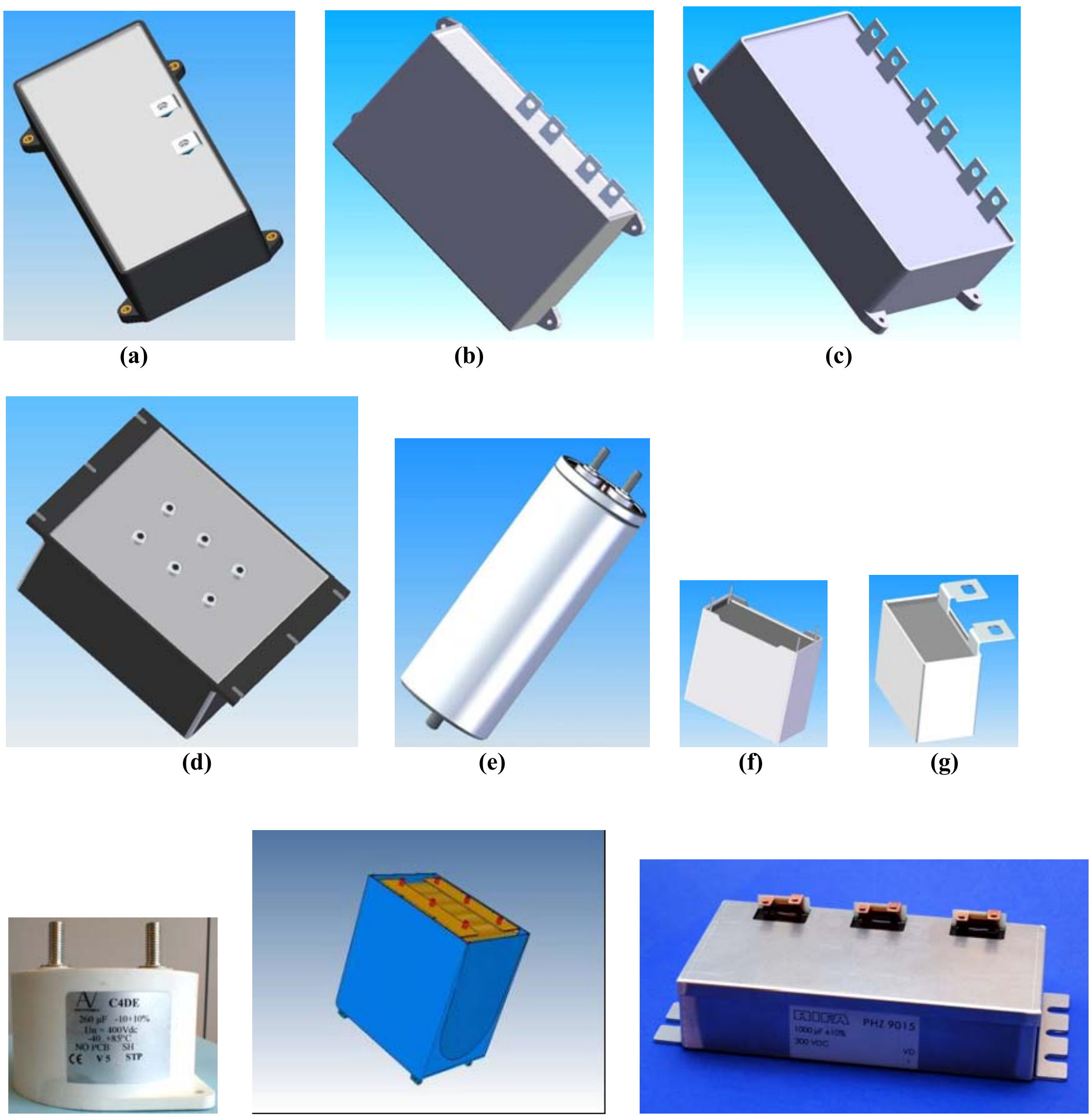
Figure 2 : Schematic of Ripple current test system

DISCUSSION

Technologies and 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, Wind Generators and Hybrid Cars.
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, Soft-winding, Soft-winding for Thin Film and Stacked constructions. These internal constructions can be packaged in a large range of configurations (as shown in some examples in Figure 3, Figure 4) 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.

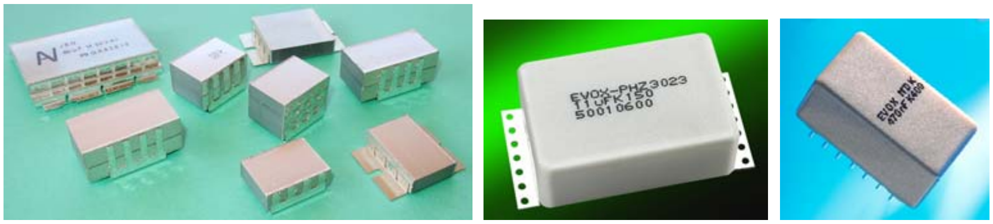


(a) (b) (c)

(d) (e) (f) (g)

(h) (i) (j)

Figure 3 : Various configurations of KEMET's film capacitors in thru-hole or bus-bar assembling solution.



(k) (l) (m)

Figure 4 : Various configurations of KEMET's film capacitors in Stacked SMD (k) and Wound DIL (l, m).

DESCRIPTION OF THE DIFFERENT TECHNOLOGIES

Wound in Round Can : the used dielectric is metallized polypropylene (PP) film, the winding is non-inductive type with internal plastic core and round shape, the element is inserted in an aluminium can with threaded bolt closed by a plastic deck with high current screw terminals. It is a dry construction, filled by solid resin.
Wound in Box : the used dielectric is metallized polypropylene (PP) film, the winding is non-inductive type with flattened oval shape, the element is inserted in a solvent resistant plastic box flame retardant execution, the terminals are 4 tinned copper wires or 2 tinned copper lugs. It is a dry construction, sealed by resin.
Wound in DIL : the used dielectric is metallized polyethylene terephthalate (PET) film, the winding is non-inductive type with flattened oval shape, the element is inserted in a solvent resistant plastic box flame retardant execution, the dual in line terminals are tinned copper leads. It is a dry construction, sealed by resin.
Soft-winding in Brick : the used dielectric is metallized polypropylene (PP) film, the capacitor element is composed of several non-inductive windings with large flattened oval shape, the windings are soldered in parallel with the bus-bar and inserted in a metal or plastic case, the bus-bar and the terminals are tinned copper. It is a dry construction, sealed by resin.
Soft-winding in Brick for Thin Film : the construction is like Soft-winding in Brick, but with thinner PP film (thickness $< 3,5\mu m$) for Automotive application.
Stacked in Brick : the used dielectrics are metallized polypropylene (PP) and polyethylene terephthalate (PET) film, the capacitor element is composed of several stacked cut elements, that are soldered in parallel with the bus-bar and inserted in a metal or plastic case, the bus-bar and the terminals are tinned copper. It is a dry construction, sealed by resin.
Stacked SMD : the used dielectrics is polyethylene terephthalate (PET) film, the capacitor is composed of several stacked cut elements, that are welded in parallel with the tinned copper lead frames. The capacitor is naked and used in SMD reflow soldering process.

The most challenging issues in using film capacitors for Automotive and Industrial Applications are :

- **Voltage :** up to 2800Vdc
- **Capacitance Density :** the naked winding element about $2\mu F/cm^3$
- **Equivalent Series Resistance (ESR) :** $\leq 2m\Omega$ (C=2400µF ; 900Vdc ; Freq.=3KHz)
- **Inductance (ESL) :** $\leq 50nH$ (C=2000µF ; 750Vdc)
- **Ripple Current (Irms):** $\leq 290A_{rms}$ at full power for <5% of the life time (C=2400µF ; 900Vdc ; Freq.=3KHz)
- **Life Time :** up to 100,000Hours for industrial application
- **Configuration flexibility** : adaptation to the shape of the available space and customized terminals

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 actual conditions of the rated voltage (Un) vs the film thickness are :

- Automotive : ≈ 280V/µm (PP film and Soft-winding for thin film)
- Automotive : ≈ 160V/µm (PP film and Stacked)
- Automotive : ≈ 70V/µm (PET film and Stacked)
- Industrial : ≈ 200V/µm (PP film and Soft-winding)

Table 1 : Capacitance and Working Voltage Range for Different Technologies

PRODUCTS	FILM	TECHNOLOGY	C (µF)	Un (Vdc)
C4A - C4B : Box and C44 - C20 – C4DE : Round Can	PP	Wound	**Cmax=1000**	**Vmax=1300**
C4E - PKZ : Brick - High Power	PP	Soft-Winding	**Cmax=12000**	**Vmax=2800**
MDC : DIL SMD Leaded and MDK : DIL Through-hole	PET	Wound	**0,047-36**	**50-900**
MDS : Low Profile DIL SMD Leaded	PET		**0,033-6,8**	**50-900**
MDW : SMD Naked - Leaded	PET		**0,047-36**	**50-900**
SPD : Brick - Automotive	PP	Soft-Winding for Thin Film	**Cmax=2000**	**Vmax=750**
JSN : Naked Stacked SMD	PET	Stacked	**Cmax=330**	**63-400**
JSP : Stacked in Brick - Automotive	PP - PET		**Cmax=1500**	**Vmax=600**

Table 1 shows the capacitance and working voltage range for several different technologies and material sets.

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 plastic base films (Polypropylene and Polyester) and on new techniques of metallization.
The result of this activity is quite evident in KEMET Power Capacitors for DC-Link applications, where the capacitance density was increased roughly by 4, and at the same time keeping the high over voltage rating, high working temperature and high current levels, in combination with extremely long expected life-time at rated conditions (100kh - continuous use).

Equivalent Series Resistance (ESR)

The thermal stability of the capacitor is directly connected to ESR. We have been able 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.
It is very important to reduce the self-heating of the capacitor caused by ripple currents. This reduction has a positive effect not only on the cost of the inverter cooling but also on the total energy efficiency of the system.
DIL (Dual In-Line) and Stacked SMD ensure low ESR and which means good filtering performance at high frequency a very important parameter for SMPS (Switch Mode Power Supplies) applications.

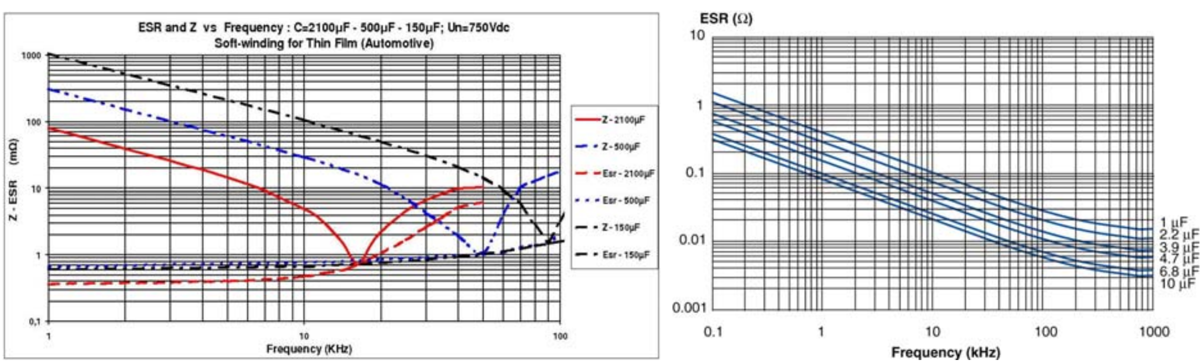


Figure 5 : ESR vs Frequency - Soft-winding for thin Film (Automotive) and Wound DIL.

Equivalent Series Inductance (ESL)

In order to limit over-voltages due to semiconductor commutation, most designs are using snubber capacitors geometrically close to (= low inductance) the switching circuits. To eliminate the need of such snubber capacitors there is an increasing demand for low inductance of the DC-Link capacitors. The DC-Link Capacitor is placed close to the power connection in order to reduce the stray inductance and to improve the dynamic response. The film Technology offers the solution, and responds very well to the new applications.

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
- Soft-winding for Thin Film in Brick
- Stacked in Brick
- Stacked SMD
- Wound in DIL (Dual In-Line)

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 2 : Equivalent Series Inductance examples (ESL)

Technology	C (µF)	Un (Vdc)	Freq (KHz)	Tamb (°C)	Irms (A)	ESL (nH)
Wound in Round Can	1000	900	10	60	50	**≤ 65**
Wound in Box	25	1100	10	70	17	**≤ 35**
Soft-winding in Brick	2400	900	3	80	300	**≤ 60**
Soft-winding in Brick	4000	900	4	60	150	**≤ 50**
Soft-winding in Brick	6600	1350	2.5	57	300	**≤ 40**
Soft-winding for Thin Film in Brick	2000	750	10	90	170	**≤ 50**
Soft-winding for Thin Film in Brick	500	750	10	90	40	**≤ 35**
Stacked with bus-bar in Brick	80	450	10	90	20	**≤ 30**
Stacked with bus-bar in Brick	1000	450	10	90	100	**≤ 20**
Stacked SMD with lead-frame	45	63	150	125	10	**≤ 10**

Metallized polyester film capacitors with DIL (Dual In-Line) and Stacked SMD constructions are suitable for high frequency filtering (input and output), DC-DC converters and high frequency SMPS (Switch Mode Power Supplies). DIL and Stacked SMD ensure low ESR and low ESL values which are the most important characteristics for the SMPS applications. Low inductance (ESL) means that the capacitor works as a capacitor (capacitance) in higher frequencies

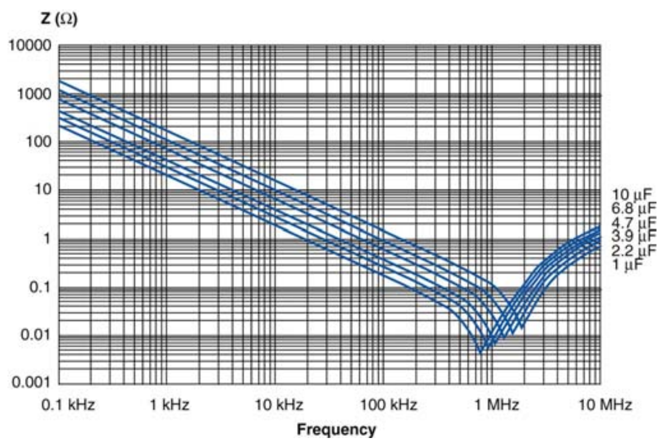


Figure 6 : Z(Ω) and Resonance Frequency – Wound in DIL (MCD series)

<u>Ripple Current and Thermal Stability (Irms)</u>

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 two items, the maximum ripple current and the life time requirements. Both of whose, can directly be connected to the capacitor's power losses and internal self-heating.

The DC-link capacitor filters the ripple current generated by the inverter, and decouples the rectifier, the battery or the DC/DC booster converter from the inverter part of the drive by providing a low impedance path for the high frequency ripple current. It is this AC ripple current that is causing the losses, (both dielectric and resistive) that can be calculated using the capacitor's ESR (equivalent series resistance). In the capacitor specifications, there is a specified maximum ripple current rating vs. the frequency. This is an important design tool that can be used for selecting the correct capacitor for the application. The Figures 7, 8, 9 and 10 show some examples of Self-heating and Ripple Current.

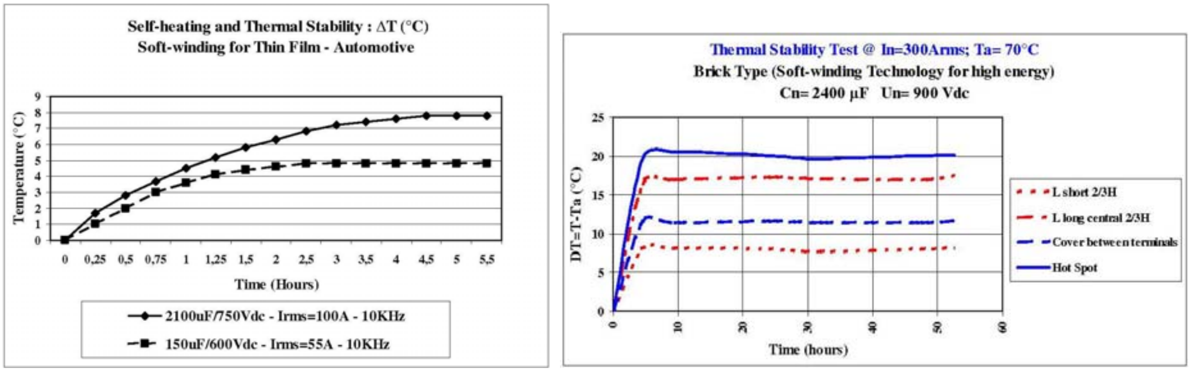


Figure 7 : Self-heating and Thermal Stability - Soft-winding Technology

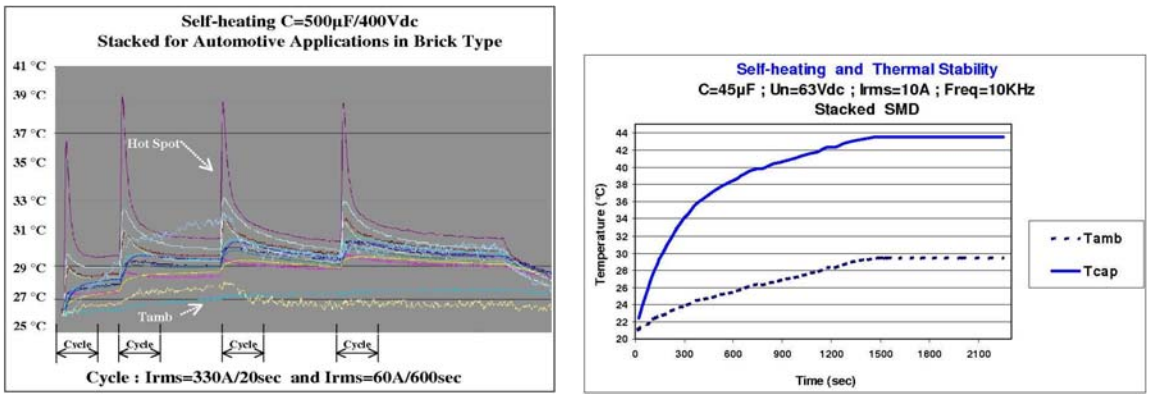


Figure 8 : Self-heating and Thermal Stability - Stacked Technology in Brick and Stacked SMD

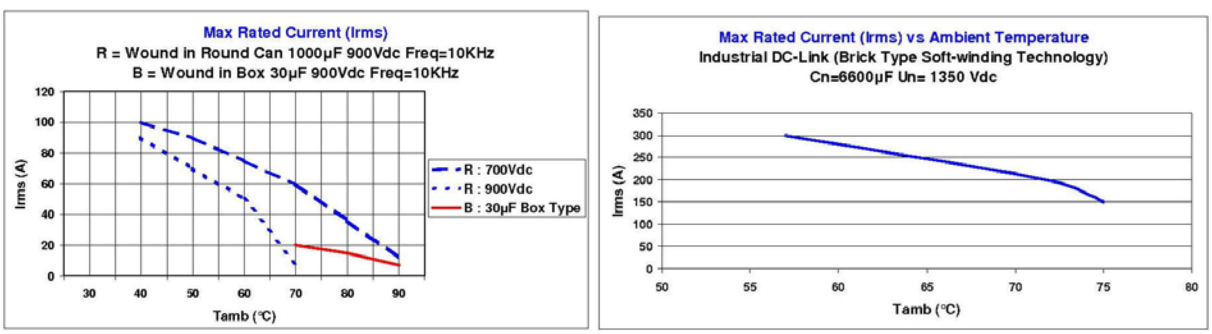


Figure 9 : Max Rated Current (Irms) – Wound in Round Can and in Box – Soft-winding

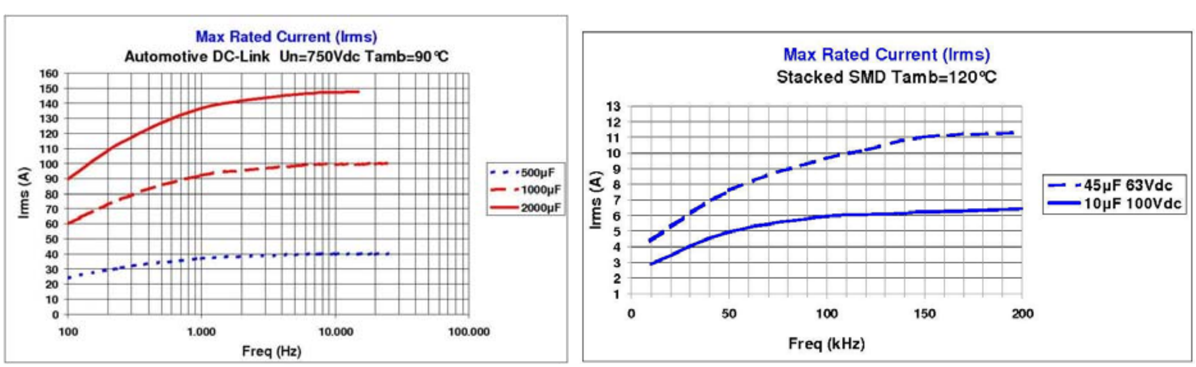


Figure 10 : Max Rated Current (Irms) – Soft-winding Technology for Thin Film and Stacked SMD

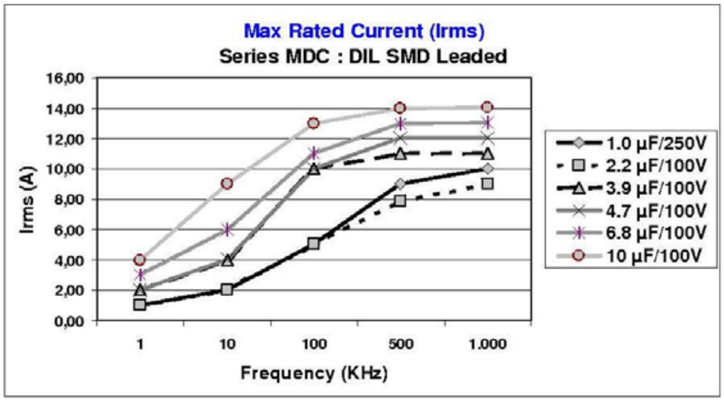


Figure 11 : Max Rated Current (Irms) – Wound in DIL (MDC series)

Life Time

Automotive and Industrial Applications require a long life time. This can be accomplished by utilizing a new metallization configuration of the film, a plastic or metallic housing, sealed by epoxy or polyurethane resins, and a new production process for the thermal treatment.

Figure 12 shows working life time at rated voltage (Un) vs. hot spot temperature for a capacitors fabricated using soft-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.

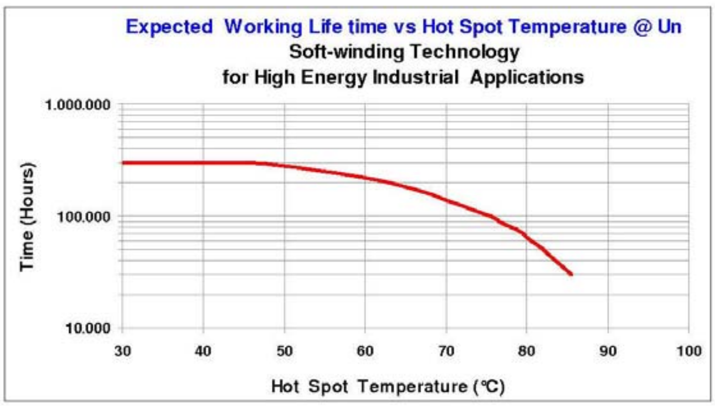


Figure 12 : Working Life Time – Soft-winding Technology for High Energy.

Figure 13 shows life time vs. ambient temperature at rated voltage for a capacitor fabricated with soft-winding for thin film technology. At ambient temperatures up to about 90°C, over 20,000 hours of lifetime can be obtained.

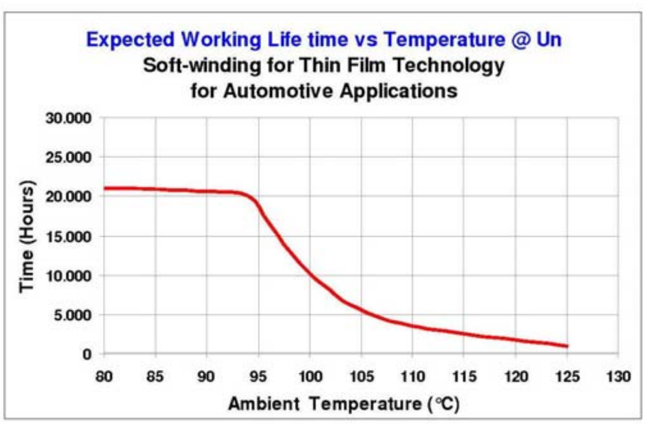


Figure 13 : Working Life Time – Soft-winding Technology for Thin Film (Automotive).

COMPARISON OF FILM AND ELECTROLYTIC TECHNOLOGIES

Due to these enhanced performances of the film capacitors, the competition (particularly for higher voltages) in the DC-Link field between Film and Electrolytic technologies has lately become more pronounced.
The choice of either type in a specific project can be the result of different considerations:
- max operating voltage in order to increase the inverter's power
- min inductance to limit the surge current
- max working temperature, whose value is higher and higher due to the miniaturization process
- weight & available real estate
- mechanical strength
- global cost of the system.

PROJECT EXAMPLE : 3 PHASE AC MOTOR DRIVE

Table 3 : Design Conditions of DC-Link Capacitor for 3 phase AC Motor Drive

Design Conditions : 3 phase AC Motor	
Output V	690Vac
DC-Link Voltage	1000Vdc
Max Ripple Voltage allowed	100V
Frequency	50Hz
Min Capacitance	500µF
Ripple Current	30A
DC-Link Frequency	300Hz
Ambient Temperature	75°C

Table 4 : Design of DC-Link Capacitor for 3 phase AC Motor Drive in Electrolytic and Film Technologies

	Comparison	
Characteristic	**Electrolytic**	**Film**
Capacitance (µF)	1500	250
Voltage (Vdc)	400	1100
Diameter (mm)	63	85mm
Length (mm)	105	140mm
Volume (litre)	0,327	0,794
Series (Nr.)	3	1
Parallel (Nr.)	3	2
Ripple Current / Branch (A)	10	15
Capacitor (Nr.)	9	2
Total Volume (litre)	2,94	1,59
Total Capacitance (µF)	1500	500
Voltage Ripple (V)	33	100

As the example highlights, due to the huge differences between the two technologies, the comparison must not only be done by considering the same equivalent capacitance, but rather on the final result that the design "demands" for the capacitor's bank.
In the example, the target was to carry a specified amount of ripple current at a specified frequency and in a specified DC voltage condition, with a limitation for the max allowed ripple voltage and minimum allowed capacitance.
In conclusion the advantages of the film technology vs. the electrolytic technology can be summarized as follows:
- much longer expected life
- lower dissipation / higher ripple current
- higher rated voltages with no need of series connections and balancing resistors
- better stability vs. time of Capacitance value and lower ESR
- lower losses and better conversion efficiency

Configuration flexibility

The KEMET's Technologies for AC Filtering and DC-Link 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 5).
The available shape, size and connections of the customer application can be met by the high flexibility of the Technologies.

Table 5 : Terminals solutions

Technology	Terminals Connections
Wound in Round Can	Male and Female Screws
Wound in Box	Trough-hole Wires ; Lugs
Wound in DIL	SMD ; Trough-hole Leads
Soft-winding in Brick	Bus-bar ; Male and Female Screws
Stacked in Brick	Bus-bar
Stacked	SMD

SUMMARY

The KEMET's film capacitors for Automotive and 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 Filter and DC-Link Capacitors with high operating characteristics :

- High Voltage
- High Ripple Current
- Low Dissipation Factor and low ESR → low self-heating
- Low ESL → low switching transient voltages
- High frequency
- Long Life Time
- Large range of Working Temperature
- Low volume and weight → high Capacitance Density
- High mechanical strength
- Maximum flexibility of adaptation to the shape of the available space
- Customized termination technology
- Low total cost

The most important applications are :
AC Filtering : to reduce the harmonic components overlapped to the fundamental frequency
DC-Link : To support a DC network by supplying periodically high currents for DC and AC motor drives. We can divide the DC-Link applications in three main fields :

1. **Industrial** : AC and DC Motor Drives, Windmill and Solar Cell Converters, Welders, UPS
2. **Automotive** : Inverters for Hybrid and Electric Vehicles
3. **Train** : Inverters for auxiliary equipments

Figure 14 shows a summary of the power density (C x Un x Irms/Volume) vs. different technologies.

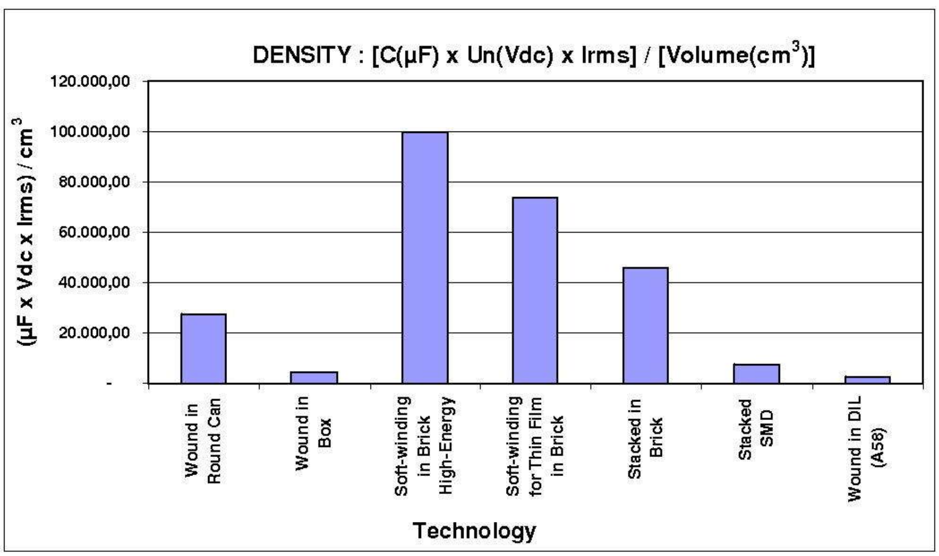


Figure 14 : Density [C(µF) x Un(Vdc) x Irms]/Volume(cm^3) of KEMET's Film Technologies

Table 6 : Guidance for the applications of the different technologies

TECHNOLOGY	APPLICATION				
	ENERGY	**INDUSTRIAL INVERTERS**	**AUTOMOTIVE INVERTERS**	**TRAIN**	**DC/DC and SMPS**
Wound in Round Alu Can	Medium - High	**X**		**X**	
Wound in Box Type with 4 wires and lugs terminals	Low	**X**	**X**	**X**	**X**
Soft-winding in Brick Type	High	**X**	**X**	**X**	
Soft-winding for Thin Film in Brick Type	Medium		**X**		
Stacked with bus-bar in Brick Type	Medium		**X**		
Stacked SMD	Low		**X**		**X**
Wound DIL (Dual In-Line)	Low		**X**		**X**