2.2. New Generation of Metallized Film Capacitors Based on EPN for Solving Upcoming High Temperature and High Power Density Requirements

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ABSTRACT

The power electronic development trend is currently driven by the development on power semiconductors, mainly due to the package improvements and the implementation of Wide-bandgap (WBG) semiconductors. As a consequence, power electronic applications are improving its efficiency and power density, upgrading the operation conditions that power electronic components have to achieve.

This paper focuses on solving the challenges from the film capacitor technology point of view related to higher operation temperature and higher power density requirements. A new high power metallized film capacitor has been developed, based on its state-of-the-art modular design series, where the conventional polypropylene polymer has been upgraded to the new material EPN (Ethylene-Propylene-Norbornene), increasing its rated operation temperature from +80ºC to +105ºC, and consequently its power density, maintaining reliability, lifetime, energy density and electromagnetic performance. Research is based on both empirical tests and electromagnetic and thermal simulations based on Finite Element Analysis.

The second part of the paper will focus on DC-Link application solutions, being compared to conventional polypropylene film capacitors, reducing its volume and analysing cost differences.

INTRODUCTION

The main drivers of power electronics technology evolution are the semiconductors and their capability to improve efficiency, power density and size reduction of the converter. Consequently, improvements on semiconductors performance allows the upgrade of power converters operation, leading to more aggressive requirements for the rest of converter components as briefly summarized in Fig. 1.

The trend of new semiconductors development is based not only on the implementation of new WBG materials (such as SiC or GaN) but also on the optimization of power modules packaging design, compared to traditional power modules, they achieve:

- Faster switching speeds
- Lower power losses
- Higher operation temperatures (higher junction temperature and lower thermal resistance)

As a consequence, focusing on power DC-Link film capacitors, new requirements are demanded to the capacitors:

- Lower size (high electric field)
- Lower ESL, for faster transient responses, being compatible with high dV/dt and di/dt minimizing voltage overshoots in semiconductors.
- Lower ESR and less increase of ESR versus frequency, leading to wider frequency operation bandwidth. Requiring advanced internal constructions for minimizing undesired high frequency effects: internal resonances, skin effect and negative electromagnetic interactions, that create non-homogeneous internal current distributions and increase ESR.
- Higher operation temperature, leading:
    - Closer connection to semiconductors, in order to reduce loop inductance, handling heat injected from the semiconductor through the busbar.
    - Softer cooling systems, based on higher junction temperatures on semiconductors and/or converter design requirements
    - Facing the increase of capacitor losses when increasing frequency operation, even with optimized designs.
    - Higher current density, achieving high power density converters

Nevertheless, reliability in terms of robustness and aging must be maintained.

The present paper is focused on the new requirements of higher operation temperature and higher power density on high power film capacitors, analysing how it has been addressed on capacitors development leading to the creation of the new ModCap UHP series.

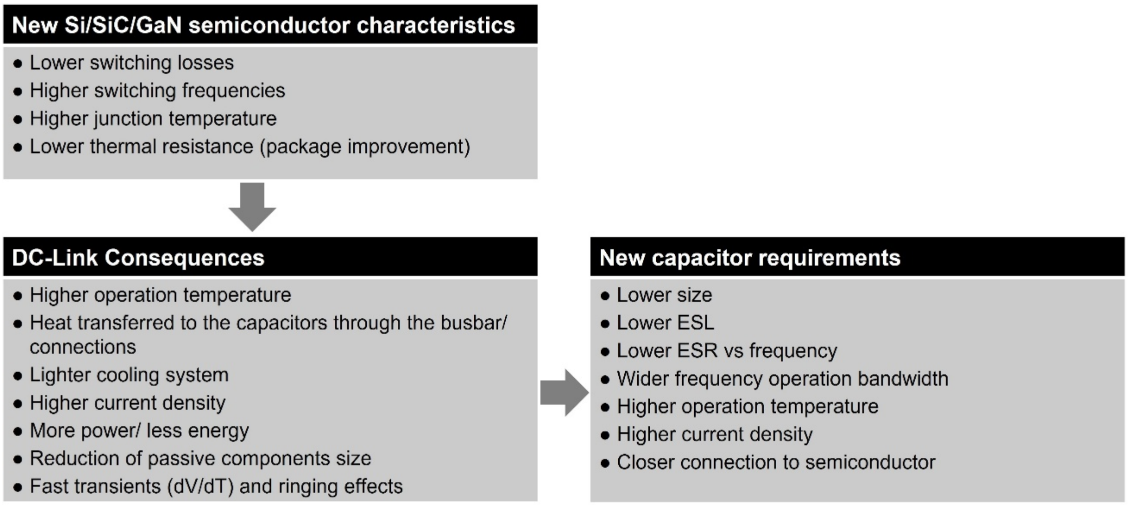

Fig.1. New capacitor requirements based on new semiconductor characteristics. Source: Own elaboration.

references [1], [2]

NEW POLYMER FOR HIGH TEMPERATURE METALLIZED FILM CAPACITORS: EPN

In order to face higher operation temperature on metallized film capacitors:

TDK has collaborated for years with other partners in the industry to develop PP-COC blends into capacitor films [3]. Based on that experience, Borealis and TOPAS Advanced Polymers have developed Stelora^{TM} EPN (Ethylene-Propylene-Norbornene) [4].

EPN is a polymer resin made from a blend of:

- Polypropylene (PP): State of the art polymer dielectric
- Cyclic Olefin Copolymer of Ethylene and Norbornene (COC): High temperature dielectric

COC alone cannot be stretched into a film, but a blend with PP is stretchable, joining the best advantage of each material: processability into films (PP) and high temperature operation (COC).

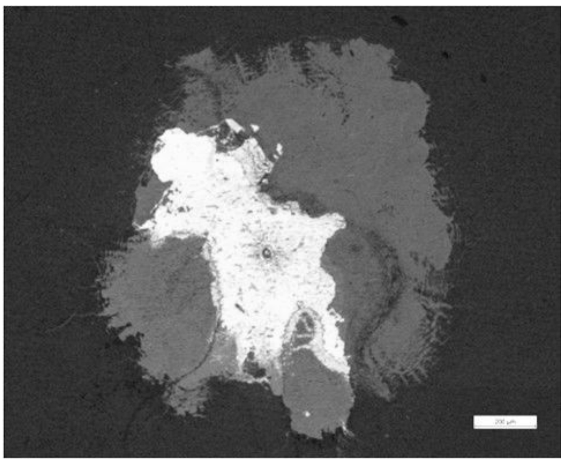

Fig.2. Views of two overlapping BOEPN films extracted from a capacitor after a 2.500- hour LET at 130ºC. Detail view of a self-healing. Source: [4]

On the one hand, at medium temperatures, Biaxially Oriented EPN (BOEPN) dielectric film offers an excellent self-healing performance, equivalent to Biaxially Oriented Polypropylene (BOPP), achieving the same level of voltage strength and consequently capacitance density.

On the other hand, at high operation temperature, BOEPN film has better performance than BOPP. Providing a good self-healing performance even at high temperatures, as seen in Fig. 2. Showing the analysis of films extracted from capacitors after a Long Endurance Test (LET).

At high temperatures, BOEPN offers lower electrical conductivity (lower leakage current) and higher breakdown strength than BOPP. The combination of both advantages allows to control breakdown under DC voltage, which may lead to a thermal runaway process, obtaining an excellent robustness even at high operation temperatures.

Implementing BOEPN on metallized film capacitors, allows to obtain excellent ageing performance and reliability at high temperatures compared to capacitors based on BOPP. A comparative test is shown in Fig. 3. at 125ºC, where capacitors based on BOPP suffered a much higher ageing on capacitance decrease, increase of tanδ (losses) and decrease of insulation resistance (increase of leakage current, risking a thermal runaway failure). Whereas the capacitors based on BOEPN only faced a gradual increase of tanδ that can be attributed to electrode oxidation.

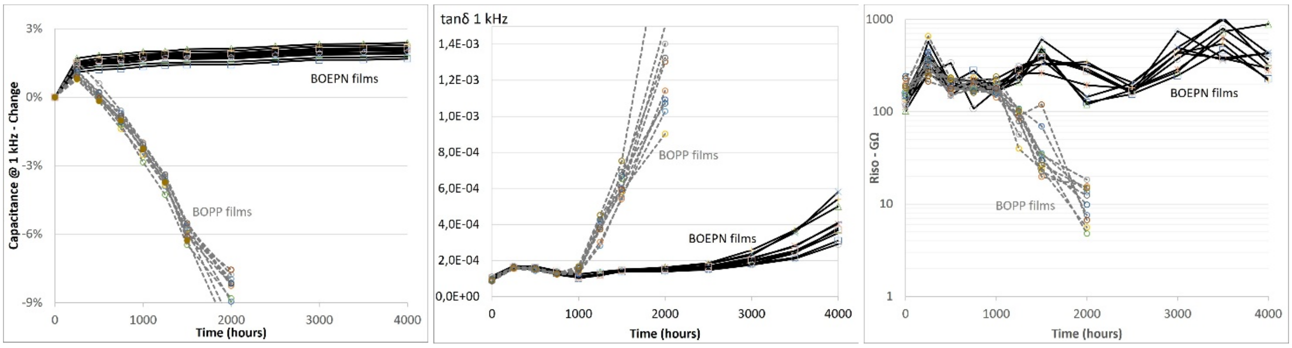

Fig. 3. Evolution of electrical characteristics of BOEPN-based and BOPP-based capacitors (1 µF, 10 pcs./group) during a LET at 125ºC: Left: change of capacitance at 1kHz, Middle: tanδ at 1 kHz, Right: insulation resistance after 10" at 500V. Source: [4]

Based on a substantial number of DC LETs, as the one showed in Fig. 3., the rating graph showed in Fig. 4 has been done [3], plotting rated DC voltage field versus operation temperature, comparing capacitors based on BOEPN and BOPP. Above 85ºC, BOEPN achieves higher voltage field, being able to increase capacitance density at high operation temperature without lifetime reduction.

Optimizing the film capacitor design, rated voltage field showed in Fig. 4. can be even increased, as is exposed in the next point when implementing BOEPN in ModCap technology.

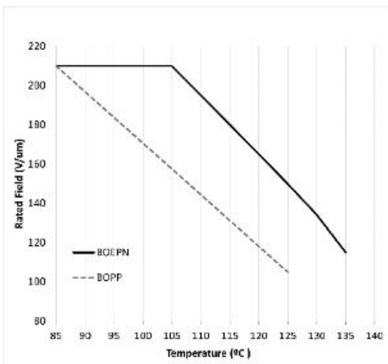

Fig. 4. Curves of DC field derating vs temperature for the BOEPN capacitors vs BOPP capacitors. Source: [4]

references [1], [2], [3], [4], [5], [6]

NEW METALLIZED FILM CAPACITOR FOR HIGH TEMPERATURE OPERATION: MODCAP UHP

State-of-the-art ModCap HF TDK series (B25647), based on BOPP dielectric film, was the most optimized series for new requirements on DC-Link based on advanced semiconductor implementation listed in Fig. 1. By implementing BOEPN dielectric film on it, TDK has developed a new product series called ModCap UHP (B25648), achieving even higher operation temperature and current density than ModCap HF. ModCap UHP is able to handle the most aggressive applications in terms of power density, cooling system and operation temperature, where the reference ModCapHF could be limited.

The main applications that could take advantage of this new ModCap UHP series would be Energy Storage Systems, Solar Central Inverter, hydrolyzers, DC/DC converters and auxiliary drives based on SiC semiconductors.

Since the main difference between ModCap UHP and ModCap HF is its film dielectric material, both series have in common the following features:

- Modular concept, being able to be parallelized and compatible with power modules dimensions.
- Terminals layout, being compatible with the same external busbar connection. External drawing and layout connections showed in Fig. 5.
- Main external dimensions, being able to be upgraded in case temperature or current increase is required.
- Electromagnetic and thermal performance, having the same equivalent electrical circuit (C, ESR, ESL, |Z|) and equivalent thermal circuit (Rth). Both series have a very low Equivalent Series Inductance (ESL) of 8nH, being ready for fast transients reducing overvoltage on power modules. Moreover, both achieve a low Equivalent Series Resistance (ESR) with very good performance versus frequency, being able to handle high frequency harmonics even without requiring snubber capacitors avoiding undesired resonances with them.
- ISCC certified 100% bio circular PP (Mass-balance approach) implemented in both series.
- High voltage strength, and consequently same capacitance values for the same rated voltage. Offering both a high energy density.
- High reliability and robustness, controlling thermal runaway processes, based on its self-healing capability achieved in both series thank to its dielectric film based on PP and its optimized internal construction and process parameters.
- Lifetime, offering both 200kh at rated voltage and rated temperature.

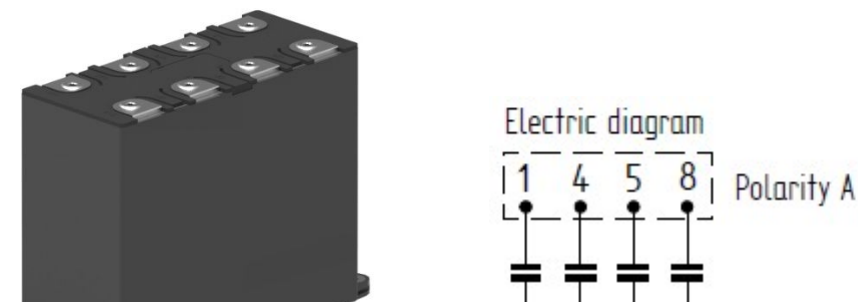

Fig. 5. ModCapUHP drawing. Source: [7]

However, ModCap UHP achieves an upgrade of:

- Rated current, increasing current density up to +21% and consequently converter power density up to +45%. Being a solution when is required to increase converter power keeping the same DC-Link volume.
- Rated temperature, increased + 25ºC (from +80ºC to +105ºC) without any voltage or lifetime derating. Offering the same capacitance and DC-link volume but allowing much higher operation temperature. Being an advantage not only when high current density is required but also when thermal boundary conditions are more aggressive due to softer cooling systems or due to heat transferred from advanced power modules to capacitor terminals

A comparative of ageing performance between ModCap UHP and ModCap HF is observed in Fig. 6. Showing the results of a Long Endurance Test (LET) under DC voltage plotting capacitance evolution during test. In both, same voltage strength was applied 1.3xU_n (acc. to IEC 61071:2017 and IEC 61881-1:2010). ModCap UHP at +105ºC had similar performance, low ageing due to low self-healing activity, than ModCap HF at +80ºC but increasing the test temperature +25ºC (from rated +80ºC to rated +105ºC). However, in ModCap HF, when increasing test temperature up to +90ºC, self-healing activity increases in a safe way, accelerating capacitor ageing and reducing its lifetime. It has to be considered that, in order to evaluate its reliability, test parameters where more aggressive than IEC 61071:2017 and IEC 61881-1:2010 requirements, where test temperature are defined as max case temperature whereas that test showed in Fig. 6., it was done at rated operation temperature.

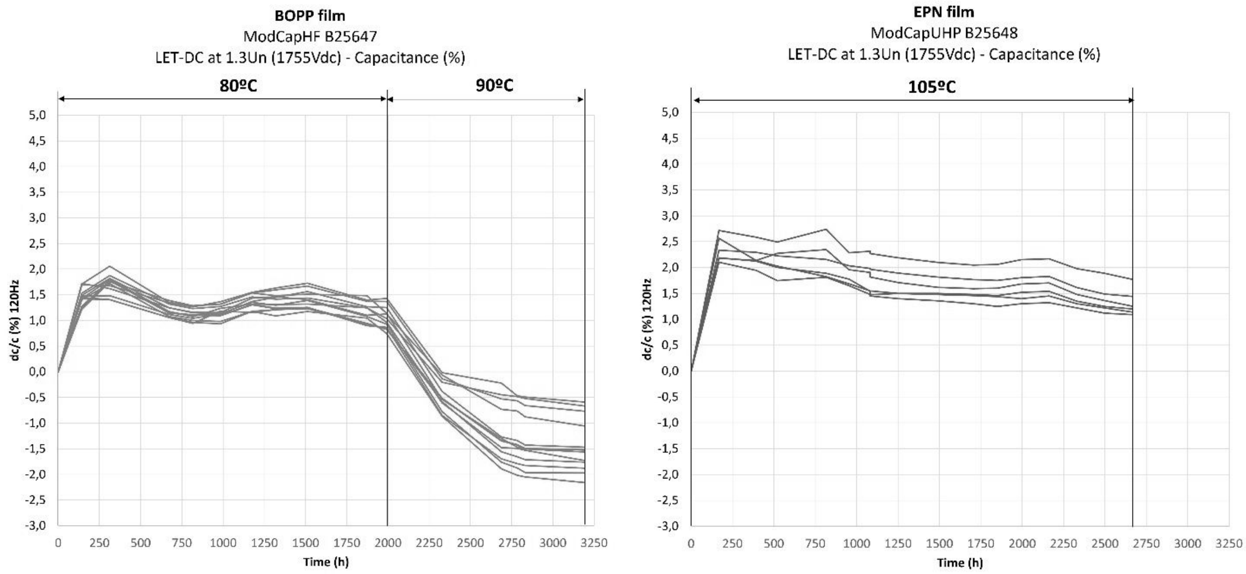

Fig. 6. ModCap HF Vs ModCap UHP LET performance. Source: [2]

Consequently, as showed in Fig. 7., at rated voltage and rated temperature, ModCap UHP has the same lifetime (200kh) than ModCap HF but having increased its rated operation temperature from +80ºC to +105ºC. Overvoltages up to +25% are allowed, although due to the higher self-healing activity, lifetime is directly reduced.

ModCap UHP is already released and available to the market, being actually offered in a rated voltage range from 1350 to 1800Vdc, its main electrical parameters are shown in Table 1. Series scope extension down to 900Vdc and up to 2000Vdc is under development.

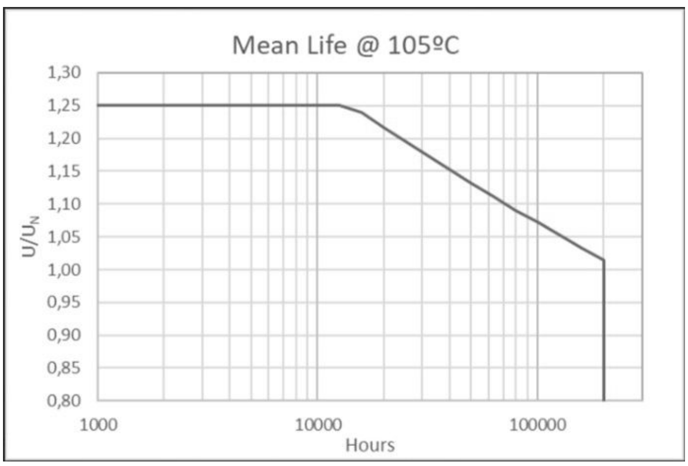

Fig. 7. ModCapUHP mean lifetime. Source: [7]

U_N V DC	C_R µF	I_N Tamb=+75 ºC[4)] A_{RMS}	I_S kA	Î kA	Dimensions LxWxH mm	Design / PU	Ordering code
1350	880	205	205	5	205x90x170	C / 4pcs	B25648A1887K003
1600	640	190	175	5	205x90x170	C / 4pcs	B25648A1647K003
1800	470	180	150	5	205x90x170	C / 4pcs	B25648A1477K003

[4)] Max. ripple current I_{RMS} at T_{amb} = +75 °C at 3 kHz for a ΔTHS-Amb ≤30 °C when ESR = ESR_{max}, considering increase of ESR due to temperature, and not-aged capacitors. Considering natural convection (h = 12 W/m²K) and no transfer of heat through the terminals.

For further information about simulation capabilities and support on specific projects, please contact CAPSimulations@tdk.com

Table 1. ModCapUHP electrical characteristics and ordering codes. Source: [7]

DC-LINK APPLICATION SOLUTIONS: FROM BOPP TO BOEPN BASED METALLIZED FILM CAPACITOR

Based on the benefits of upgrading dielectric film on metallized film capacitors from BOPP (ModCap HF series) to BOEPN (ModCap UHP series) described in the previous chapter (higher current density up to +21% and higher rated temperature +25ºC), the upgrade of DC-Link applications from ModCap HF to ModCap UHP has been analysed.

A typical high current density application has been analysed where key requirements are listed below:

- DC-Link voltage: 1600V
- DC-Link capacitance: ≥ 1850uF
- DC-Link current: 570Arms
- Ambient temperature: +75ºC
- Power module terminals: +95ºC
- DC-Link lifetime: ≥ 200000h

Based on those requirements, a DC-Link solutions based on series ModCap HF (B25647) and ModCap UHP (B25648) has been analysed.

ModCap HF – BOPP (B25647) DC-Link solution

Based on DC-Link voltage, analysing DS [8], solution could be based on B25647A1647K003 (1600V 640uF 160Arms), requiring 3 capacitors in parallel for reaching DC-Link capacitance requirement (3x640uF > 1850uF), however rated current would be below requirement (3x160Arms < 570Arms). Consequently, at least 4 ModCap HF capacitors in parallel are required due to current density requirement, not been limited by capacitance density.

As a consequence, as showed in Fig. 8. Left, it is proposed a solution based on higher rated voltage capacitor B25647A11477K003 (1800V 470uF 150Arms), offering higher voltage above rated temperature (+80ºC) being beneficial when handling power module terminals at +95ºC, and not being limited by capacitance density requirement. Based on B25647A11477K003 rated parameters, considering 4 capacitors in parallel, DC-Link capacitance-current-voltage requirements could be fulfilled:

- DC-Link voltage: 1800V > 1600V
- DC-Link capacitance: 1880uF > 1850uF
- DC-Link current: 600Arms > 570Arms

DC-Link volume based on ModCapHF (BOPP) would have a volume of 15.4dm^3.

In order to confirm temperature and lifetime requirements, an electromagnetic and thermal simulation based on Finite Element Method (FEM) has been performed, considering not only thermal boundary conditions (ambient temperature, cooling conditions and heat transferred from power modules) but also the complete current-frequency spectrum and its electromagnetic effect on internal capacitor construction.

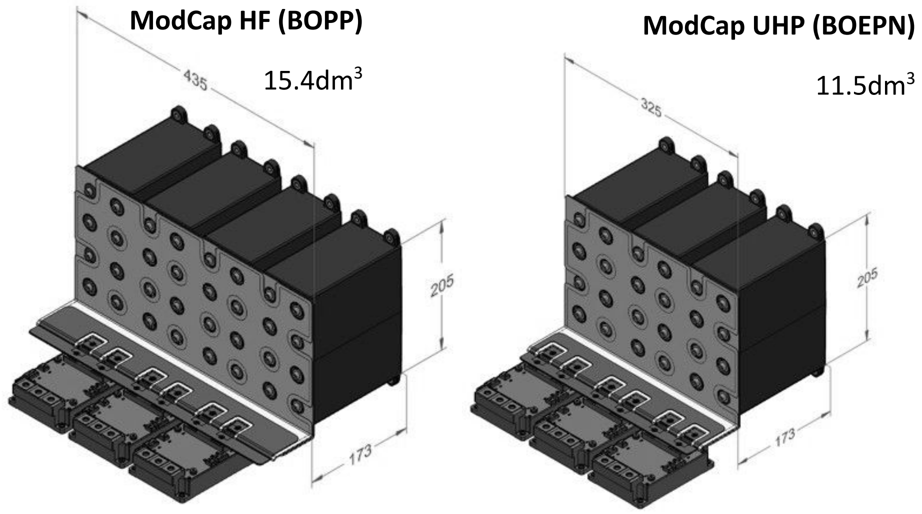

Fig. 8. DC-Link solution same capacitance, voltage and current requirements. ModCap HF (Left), ModCap UHP (Right). Source: [2]

Thermal results of FEM simulation are shown in Fig. 9. Left, showing a max internal operation temperature up to +96ºC due to capacitors self-heating and heat transferred from power module terminals. Consequently, since operation temperature is above rated one (+80ºC), based on DS [8], capacitors lifetime would be reduced not fulfilling the requirement of 200000h.

ModCap HF (BOPP) solution based on capacitors in parallel, fulfils capacitance, voltage and current requirements, but not thermal-lifetime requirement. As a consequence, an increase to 5 capacitors in parallel would be required (Fig. 10. Left) or to ModCap UHP (BOPEPN) parallel (Fig. 10. Right).

ModCap HF (BOPP) solution based on 5 paralleled B25647A11477K003 capacitors would fulfil complete DC-Link requirements with a DC-Link volume of 19.3dm^3, with DC-Link capacitance-current-voltage requirements as follows.

- DC-Link voltage: 1800V > 1600V
- DC-Link capacitance: 2350uF > 1850uF
- DC-Link current: 750Arms > 570Arms

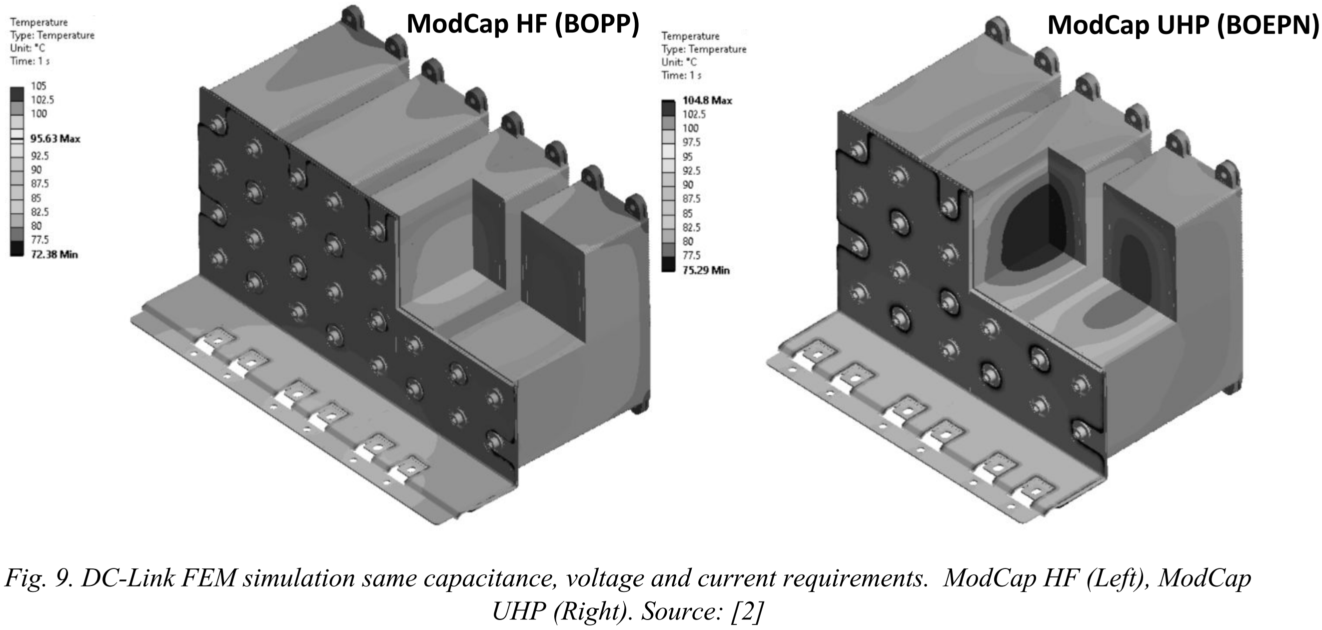

Fig. 9. DC-Link FEM simulation same capacitance, voltage and current requirements. ModCap HF (Left), ModCap UHP (Right). Source: [2]

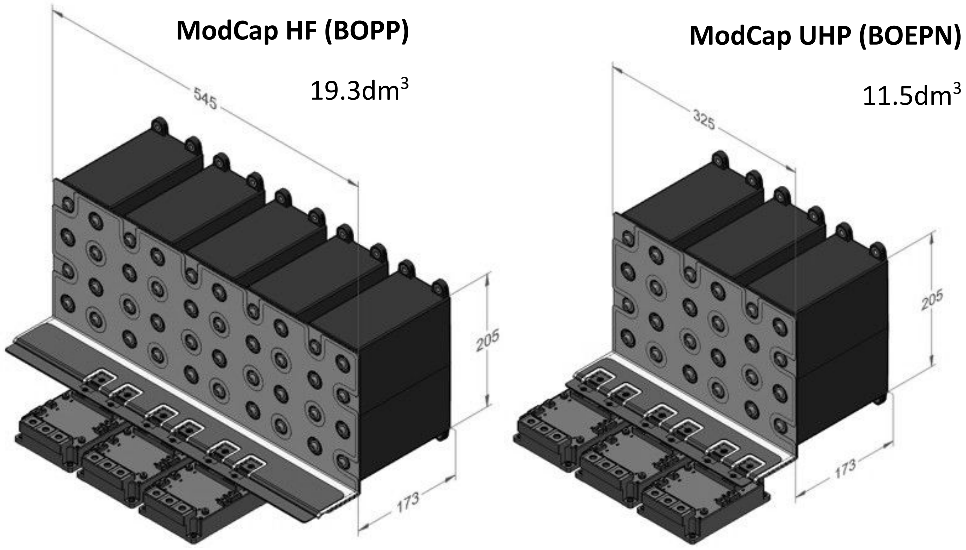

Fig. 10. DC-Link solution same capacitance, voltage, current and thermal-lifetime requirements. ModCap HF (Left), ModCap UHP (Right). Source: [2]

ModCap UHP– BOEPN(B25648) DC-Link solution

Based on DC-Link voltage, analysing DS [7]. Solution could be based on B25648A1647K003 (1600V 640uF 190Arms), having same capacitance, voltage and volume than reference ModCap HF but with +19% current density and +25ºC rated temperature. Requiring 3 capacitors in parallel for reaching DC-Link capacitance requirement (3x640uF > 1850uF), DC-Link capacitance-current-voltage requirements could be fulfilled:

- DC-Link voltage: 1600V = 1600V
- DC-Link capacitance: 1880uF > 1850uF
- DC-Link current: 570Arms = 570Arms

DC-Link volume based on ModCapUHP (BOEPN) would have a volume of 11.5dm^3.

Thermal results of FEM simulation are shown in Fig. 9. Right, showing a max internal operation temperature up to +104.8ºC. Consequently, since operation temperature is below rated one (+105ºC), based on DS [7], capacitors lifetime is not derated, fulfilling the requirement of 200000h.

ModCap HF – BOPP (B25647) Vs ModCap UHP– BOEPN(B25648) DC-Link solution

As a conclusion, comparing a high current density DC-Link solution with capacitors based on BOPP dielectric film (ModCap HF B25647) or based on BOEPN dielectric film (ModCap UHP B25648) for the application under study, a ratio of 3 capacitors (BOEPN) versus 5 capacitors (BOPP) is obtained, thanks to the higher current density (power density) and rated temperature of ModCap UHP. Drawings of both DC-Link solutions are shown in Fig.10.

Table 2. summarizes the key difference between both solutions, comparing BOEPN (ModCap UHP) with BOPP (ModCap HF):

- Lower DC-Link volume (-40%) due to the higher current density (+19%) and higher rated temperature (+25ºC).
- Lower DC-Link capacitors cost (-25%). Not being considered the extra cost reduction due to external busbar size reduction.

In conclusion, in high current density applications, as the ones based on advanced power modules, when DC-link current, lifetime and thermal requirements are critical, BOEPN capacitors provide optimized solution in terms of volume and cost compared to BOPP ones.

	Dielectric	BOPP	BOEPN	BOEPN Vs BOPP
	Product	ModCap HF	ModCap UHP	ModCap UHP Vs HF
DC-Link	Capacitors (pcs)	5	3	-40
	Capacitors volume (dm^3)	19,3	11,5	-40
	Capacitors cost (%)	Confidential	Confidential	-25

Table 2. DC-Link solution ModCap HF Vs UHP (Right). Source: Own elaboration.

references [2], [5], [6], [7], [8]

SUMMARY AND CONCLUSIONS

Due to the development of new semiconductors, mainly WBG, and the requirement of higher efficiency and power density in power converters, there is a trend on increasing current density and thermal requirements on DC-Link capacitors.

The development of the new dielectric film BOEPN, compared to conventional BOPP, allows the increasing of operation temperatures in metallized film capacitors without neither voltage nor lifetime derating. BOEPN has been implemented in the most optimized high power modular film metallized capacitor for advanced power modules (ModCap HF), developed and released as the new series ModCap UHP, obtaining higher current density (up to +21%) and higher rated temperature (from +80ºC to +105ºC), but keeping the same capacitance density, reliability, dimensions and thermal-electromagnetic performance.

In high power density applications, as the one analysed, where key DC-Link parameters are current density, boundary thermal conditions and/or lifetime, ModCap UHP optimizes DC-Link in terms of volume, capacitance density, current density, lifetime and cost.

REFERENCES

[1] M. Gómez, "Innovative film capacitor technologies for wide band-gap semiconductors" IEEE PSMA Capacitor Committee Workshop 2020

[2] F. Rodríguez, "High Temperature Capacitors for Medium Voltage Applications With New WBG Semiconductors", ECPE Hybrid Workshop, Medium Voltage Power Electronics, Freiburg, Germany, 2025.

[3] C. Alba, D. Peláez and L. Cabo, "High-Temperature Metallized Polymer Film Capacitors Based on Blends of Polypropylene and Cyclic Olefin Copolymers," *2020 IEEE 3rd International Conference on Dielectrics (ICD)*, Valencia, Spain, 2020, pp. 669-672, doi: 10.1109/ICD46958.2020.9342006.

[4] U. Wahner and C. Alba, "Polymers in Film Capacitors - The Next Generation Material is available!," *PCIM Europe 2023; International Exhibition and Conference for Power Electronics, Intelligent Motion, Renewable Energy and Energy Management*, Nuremberg, Germany, 2023, pp. 1-8, doi: 10.30420/566091018.

[5] IEC 61071:2017 Capacitors for power electronics

[6] IEC 61881-1:2010 Railway applications - Rolling stock equipment - Capacitors for power electronics - Part 1: Paper/plastic film capacitors

[7] ModCap UHP DataSheet, 2025, https://www.tdk-electronics.tdk.com/inf/20/50/ds/ModCap_UHP_B25648.pdf

[8] ModCap HF DataSheet, 2025, https://www.tdk-electronics.tdk.com/inf/20/50/ds/B25647_ModCap_HF.pdf