Solid-State Polymer Dielectric Capacitors as an Alternative to Aluminum Electrolytics in 48V–120 V Power Electronics

Angelo Yializis Ph.D. and Akilavasan Jeganathan Ph.D.
PolyCharge America Inc
Tucson, Arizona
ayializis@polycharge.com

ABSTRACT

In mild hybrid automotive inverters and aerospace power processing units, operating in the 48-120 VDC range, hybrid polymer aluminum electrolytic capacitors are currently the preferred choice due to their favorable balance of capacitance density, ripple current handling, cost, and availability for DC-link and filter applications. This work presents an advanced solid-state polymer multilayer capacitor technology as a superior alternative for these demanding applications. Fabricated with nanothick dielectrics and tens of thousands of layers, these capacitors have excellent energy density, operating temperature up to 140ºC, and self-healing properties. Dielectric characterization and performance data are presented for capacitors rated at 60 VDC and 120 VDC with capacitance values of 800 µF and 400 µF, respectively. The results demonstrate low Equivalent Series Resistance (ESR), excellent ripple current capacity, lower dissipation factor, high capacitance stability and a significantly smaller footprint on the PCB, positioning this solid-state polymer technology as a promising solution for next-generation high-reliability power electronics in automotive and aerospace systems.

INTRODUCTION

Capacitors operating in the 48 V to 120 V range have become a strategically important and fast-growing segment of power electronics. Once confined to a handful of niche circuits, this voltage band now sits at the center of several converging trends: the electrification of conventional vehicles through 48 V mild-hybrid architectures, the migration of data-center and telecommunications power distribution to 48 V busses to curb resistive losses, and the long-standing use of 100–120 V busses in spacecraft power systems. The clearest driver of 48 V power electronics is the automotive mild-hybrid (MHEV) powertrain, in which a 48 V lithium-ion battery, an inverter, and a belt- or crankshaft-integrated starter-generator recover braking energy and provide torque assist, reducing fuel consumption and CO2 emissions on the order of 10–25% depending on the specific architecture [1]. Depending on the integration point in the drivetrain these systems range from a few kilowatts for auxiliary loads such as e-boosters, electric water pumps, and catalyst heaters, up to on the order of 35–50 kW for the highest-power belt- and driveline-integrated starter-generator implementations [1]. In the higher-power tier (15 kW and above), the DC-link capacitor bank is commonly required to handle on the order of 150 A_{rms} of continuous ripple current, with short-duration peaks near 300 A [2]. The same 48 V rail is increasingly extended into full battery-electric platforms as a secondary bus stepped down from 400/800 V packs, since a 48 V harness carries a given power at one quarter of the current, and roughly one-sixteenth of the resistive loss, of an equivalent 12 V system [1].

Other than vehicle, 48 VDC has been the standard power feed for wireline and wireless telecommunications infrastructure for decades, favored in part because it causes less corrosion in metal hardware than an equivalent positive supply [3]. More recently, the same 48 V level has been adopted for data-center and AI-server power distribution: at typical rack power levels, resistive distribution losses at 48 V can be an order of magnitude lower than at legacy 12 V, one published example shows a roughly 16x reduction in distribution loss for the same delivered power — a factor that has become especially significant as AI-accelerator racks push per-rack power demand sharply higher [4].

Voltages in the range of 120VDC-160VDC is best established as a primary spacecraft power-distribution voltage. The International Space Station regulates its solar-array output at 160 VDC and distributes power to the U.S. segment at a nominal 120 VDC, and NASA has continued to develop follow-on 120 VDC power architectures for future missions [5]. A related, though distinct, trend is underway in more-electric aircraft, where primary DC distribution has moved from a legacy 28 V standard to 270 V specifically to cut distribution weight, with 540 V and 800 V under study for future platforms [6]; while 270 V rather than 120 V is the aircraft main-bus standard, the same weight-versus-voltage argument that pushes aircraft busses upward is what has kept spacecraft architectures at 120 V rather than the still-lower voltages used on early, lower-power satellites. As in the 48 V case, aerospace 120 V busses must be served by DC-link capacitors that combine high ripple-current capability with tolerance of extreme temperature excursions, radiation exposure, and

multi-year, often unserviceable, mission life — a combination considerably more demanding than commercial terrestrial power electronics.

Unless a long-term, high level of reliability is required, hybrid polymer aluminum electrolytic capacitors are today's default answer for serving DC-link applications especially in environments where operating temperatures are in the range of 125ºC to 140ºC. Capacitors with a rating of 60V-63V are typically used for most 48V applications. Hybrid electrolytics from most major manufacturers are limited to voltages of about 100V, above which conventional wet aluminum electrolytics are used. At these voltage levels aluminum capacitors retain a significant volumetric energy-density advantage, which in most applications is several times higher than that of film and multilayer ceramic capacitors, for a given case volume, at a correspondingly lower cost per unit of stored energy.

SOLID STATE POLYMER NANOLAMINATE CAPACITORS

NanoLam solid-state polymer nanolaminate capacitors are built on a fundamentally different platform than either wound film or wet/hybrid electrolytic technology. Rather than winding a pre-extruded polymer film, or assembling foil, paper, and liquid electrolyte, the NanoLam dielectric and its metal electrodes are built up together, layer by layer, on a single deposition line, giving direct control over dielectric chemistry, layer thickness, and electrode structure at the same time. That process control is what enables the two properties emphasized in this section: breakdown strength that increases, rather than degrades, as the dielectric is thinned toward the 200 nm range, and dielectric and electrode stability at temperatures beyond the reach of most conventional film or electrolytic technology.

Manufacturing Process

NanoLam capacitors are produced by a one-step, vacuum deposition process unlike any other commercial capacitor technology. Alternating nanothick layers of polymer dielectric and metal electrode are deposited directly onto a rotating drum in vacuum, building up a large-area solid-state polymer/metal nanolaminate composite of roughly 4,000–6,000 individual layers before the composite is segmented into discrete capacitor elements [7]–[9]. Because the polymer is formed and cross-linked, via beta-radiation curing, in the same continuous process that defines each electrode layer, dielectric thickness, chemistry, and electrode geometry are all set directly by process parameters rather than by the properties of a pre-made film feedstock; the same platform reaches individual element thicknesses of roughly 1–2 mm and surface areas from tens of millimeters to tens of centimeters on a side. For higher-voltage parts, multiple nanolaminate sections are built up in internal series inside a single element, a construction used to reach ratings up to 10 kVDC without changing the underlying dielectric [7]–[9]; the 60 V and 120 V DC-link parts addressed later in this paper use the same platform at the opposite end of that voltage range, prioritizing electrode count and layer thickness for ESR and ripple current rather than for series voltage withstand.

Dielectric Thickness and Breakdown Strength

Perhaps the most consequential property of this construction is that breakdown strength increases as the individual dielectric layers are made thinner, down to layer thicknesses of approximately 200 nm. This runs against bulk-material intuition, but it is well documented in the polymer dielectrics literature: as film thickness is reduced through the submicron range, breakdown strength transitions from a thickness-independent "intrinsic" regime into a thickness-dependent regime in which thinner, more uniform layers withstand higher fields [7-9], an effect reported to be further enhanced by multilayer, multi-interface polymer film construction [11], [12].

This inverse relationship between dielectric thickness and breakdown strength is most commonly expressed as a power law, $E_b \propto d^{-n}$, a form that traces back to Forlani and Minnaja's classical electron-avalanche model of breakdown in thin dielectric films [13]. The exponent n, however, is not a single universal constant: it varies with material, construction, and test conditions across a fairly wide range. A recent study of ultrathin poly(methyl) methacrylate entangled glassy polymer cast films show a sharp increase in dielectric strength with the decreasing film thickness in the submicron thickness region. This study also showed that this property is universal in glassy thin polymer layers by testing a range of polymer films including polysulphone, Poly(2 vinylpyridine) and polyimide [10]. Direct-current breakdown measurements on polyimide films report a comparable exponent of about 0.32 [14], underscoring that the same power-law framework spans multiple polymer chemistries even as the specific exponent shifts.

The physical explanation is consistent across this literature and with NanoLam's own construction: a thinner, more uniform dielectric layer gives charge carriers a shorter path to travel before contributing to a breakdown event, and a well-controlled deposition process minimizes the local electric-field enhancement that impurities, particulates, and surface roughness otherwise cause in thicker, cast or extruded films. This is also why the benefit is conditional on process control rather than automatic, ultrathin films with uncontrolled surface roughness or defect density can show reduced, not enhanced, breakdown strength [11], and why a vacuum deposition process that builds every layer under the same controlled conditions, rather than casting or biaxially orienting a pre-made film, is a prerequisite for realizing the effect rather than an incidental feature of it. In NanoLam capacitors this translates into intrinsic breakdown strengths as high as 1000 V/μm [7]–[9]. Thickness cannot be reduced indefinitely, however: below roughly 100 nm, Poole-Frenkel emission begins to raise leakage current in most polymer dielectrics, which sets a practical floor beneath the operating range used in NanoLam parts [15].

High-Temperature Performance

The same deposition and cross-linking process that sets dielectric thickness also determines the polymer's thermal behavior. The NanoLam dielectric is formulated and beta-radiation cross-linked to a glass transition temperature of 200°C, and shows no melting point and no significant mass loss by thermogravimetric analysis to at least 350°C, behaving as a thermoset rather than a conventional thermoplastic film dielectric [7]–[9]. That distinction is why NanoLam capacitors can be rated for continuous operation above 160°C, well past the roughly 85°C ceiling of standard biaxially oriented polypropylene and the 125–140°C range typical of hybrid polymer aluminum electrolytic technology. Commercially available higher-Tg engineering polymers such as polyphenylene sulfide, polyetherimide, and polyimide can reach or exceed these temperatures as well, but they do so using aromatic, benzene-ring backbone chemistry, which is intrinsically less favorable for both breakdown strength and self-healing than an aliphatic structure; published intrinsic breakdown strengths for these aromatic high-temperature films fall well below what NanoLam's submicron, non-aromatic dielectric achieves [7]–[9]. NanoLam's high O:C and H:C ratios are instead formulated specifically to preserve efficient self-healing at temperature, avoiding the thermal-runaway failure mode that can occur in thermoplastic metallized film capacitors after repeated overvoltage self-healing events. This combination, a thermoset, high-Tg, non-aromatic dielectric built as a submicron multilayer structure, is consistent with the broader direction of the polymer-dielectrics literature, where nanoconfinement and multilayer, multi-interface structures have independently been shown to raise both glass transition temperature and breakdown strength together relative to a single thicker film of the same base polymer [11]. In DC-link service, this is what matters most for the 60 V and 120 V ratings addressed later in this paper: capacitance and ESR that remain stable, rather than drifting or requiring derating, as ambient and self-heating temperatures rise toward the top of the automotive- and aerospace-relevant range.

60V/800μF NANOLAM CAPACITORS

To minimize ESR and maximize current-carrying capacity, a rectangular capacitor element was selected, measuring 10 mm wide by 55 mm long. Actual capacitor elements are illustrated in Fig.1 with a packaged capacitor. Both the 60V and the 120V capacitors that are described below, have elements with the same XY dimensions and are packaged in the same size capacitor case. Each capacitor element is comprised of 2,000 active dielectric layers with additional protective layers on the top and bottom surface. Using a dielectric thickness of approximately 300 nm, 60 μF capacitor elements were produced. All capacitor elements are fully tested for capacitance, dissipation factor, ESR at different frequencies, overvoltage based on target application requirements, leakage current and voltage at which self-healing effects are detected.

60V/120V Packaged Capacitor and Capacitor Elements



Fig. 1. Individual capacitor elements are tested, connected in parallel to form a capacitor block, lead attached and packaged in a high temperature polymer case.

Test Results

Basic Dielectric Properties of 60V Capacitors

The table in Fig.2a summarizes typical key dielectric parameters of several capacitor elements. As shown, the 60 μF capacitor elements exhibited a dissipation factor below 0.01 and ESR below 10 mohm at both 10 kHz and 20 kHz. Full-size capacitor blocks were assembled using thirteen capacitor elements per capacitor block. The blocks were tested using a 4-point test fixture as shown in Fig. 2b. The table in Figure 2c shows typical capacitance, dissipation factor, and ESR

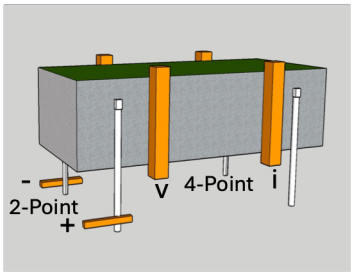
measurements at 10 kHz and 20 kHz. The block ESR values are below 1 mohm and as expected the ESR values at both frequencies are approximately proportional to the ESRs of the thirteen capacitor elements connected in parallel.

Both the capacitor elements and capacitor blocks were measured using a four-point contact fixture with the electrodes located approximately as shown in Fig. 2b. After packaging, a two-point measurement fixture was used (see Fig.2b), which resulted in higher dissipation factor and ESR, as illustrated in the table of Fig. 2d. In addition to contact resistance, the wire leads introduced measurable resistance, and the charging of the capacitor blocks from two points located on one side of the packaged capacitor added significant series resistance. Although all reported measurements on packaged parts were made using this arrangement, the capacitors were soldered to a PCB for hot-spot and surface-temperature measurements so that current entered the capacitor through all four leads. Leakage current of all elements is typically less than 5 µA, often less than 1 µA, although at times some elements may have a leakage current of 10-20 µA which drops below 5 µA after a short time on voltage.

a) 4-Point Capacitor Element Measurements

Cap 1kHz (µF)	DF 1kHz	ESR 10kHz (mohm)	ESR 20kHz (mohm)
59.375	0.007	8	7
59.944	0.0071	8.2	7.2
60.362	0.0072	8.2	7.2
60.817	0.0071	8.2	7.2
60.952	0.0072	8.2	7.2
59.486	0.0071	8.2	7.3
60.093	0.0071	8.3	7.3

b) Capacitor Block Unpackaged



c) 4-Point Capacitor Block Measurements (13 capacitor elements per block)

CAP 1kHz (µF)	DF 1kHz	ESR 10kHz (mohm)	ESR 20kHz (m0hm)
799.739	0.0077	0.6	0.6
814.185	0.0081	0.7	0.7
809.384	0.0088	0.9	0.8
799.845	0.0076	0.6	0.5
809.56	0.0078	0.7	0.6
815.619	0.0082	0.7	0.7
806.51	0.0089	0.9	0.8

d) 2-Point DF and ESR of Packaged Parts

DF 1kHz	ESR 10kHz (mohm)	ESR 20kHz (m0hm)
0.0114	1.5	1.4
0.0125	1.6	1.6
0.0128	1.7	1.6
0.0114	1.4	1.4
0.0117	1.5	1.5
0.0126	1.6	1.6
0.0128	1.7	1.7

Fig. 2. a) Typical values of key dielectric parameters of 60V capacitor elements; b) schematic illustrating how the capacitor elements and capacitor blocks were measured using a 4-point fixture, while packaged parts were measured using only two leads with a 2-point fixture; c) typical values of key dielectric parameters of 60V capacitor blocks; d) dissipation factor and ESR of packaged parts measure using a 2-point test fixture.

Self-healing Initiation Voltage and Life Test

An important test to determine if the chosen dielectric thickness is adequate for the selected voltage rating is the self-healing initiation voltage. That is the voltage at which multiple self-healing events are first detected. The results of this test are illustrated in Fig. 3. As shown, elements with the target ESR (Fig. 2a), have a self-healing initiation voltage higher than double the rated voltage. If this voltage level is in the form of an overvoltage that does not last for more than one or two seconds, the capacitor does not lose any significant amount of capacitance. This is confirmed by using a multichannel analyzer with 1000-4000 energy channels. The clearings are counted and plotted as a function of energy. A sub-second overvoltage pulse that exceeds 150V and generates 10-100 clearing events does not result in any significant or even measurable loss of capacitance.

Fig. 3 also shows a life test of packaged 800µF/60V capacitors fabricated using elements that have the "Target ESR." Although this is a relatively short and "mild" test for these capacitors, the capacitance and ESR remain stable over the test period.

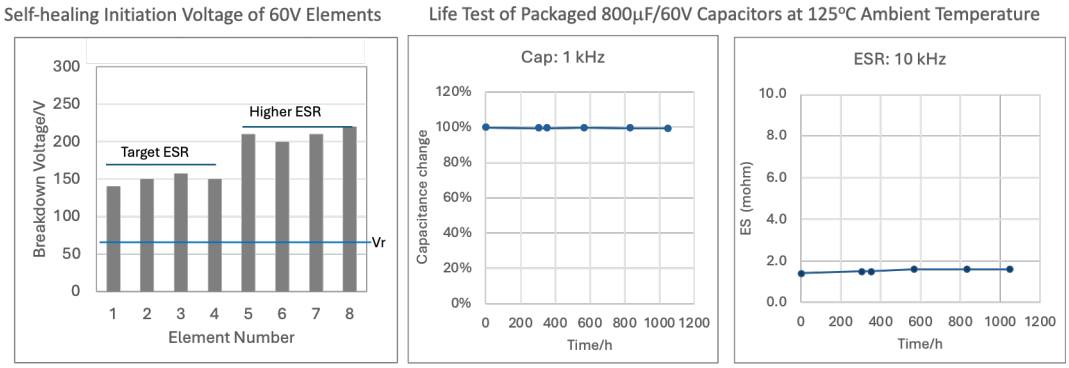


Fig. 3. Left: Self-healing initiation voltage of 60V capacitor elements with different levels of ESR. Right: Typical life test performance of capacitance and ESR of packaged 800µF/60V capacitors at 125ºC

Ripple Current Capacity

Higher voltage (400V-850V) NanoLam capacitors when tested at 140ºC under static conditions have been shown to have a life of approximately 10,000hrs with less than 10% capacitance loss. When testing for ripple current capacity at given ambient temperature the target average temperature between hot spot and package surface temperature is approximately 140ºC to assure 10,000hr life. The new lower voltage 60V-120V capacitor designs have not been tested long enough to determine if the same life law applies, although the field stress (V/t t=dielectric thickness) is significantly lower than that of the higher voltage capacitors, which can lead to longer life under the same voltage and temperature conditions.

The ripple current test was performed by drilling a hole at the center of the packaged capacitor and inserting a thermocouple to measure the hot-spot temperature. A second thermocouple was attached to the top surface of the capacitor. The capacitor was soldered to a PCB consisting of two separate conductive electrodes separated by a 5 mm gap, with high-current terminals bolted to the electrodes (see Fig. 5). The assembly was placed in an oven with minimal air movement to maintain a uniform ambient temperature without significantly cooling the capacitor surface. Capacitors were typically tested over a range of ambient temperatures and frequencies. As shown in Fig. 4, the current at 125°C is limited to 40 A_{rms} to meet the 10,000-hour life target with no more than 10% capacitance loss.

Ambient Temperature ºC	Test Frequency kHz	Ripple Current Arms	Surface Temperature ºC	Hot-Spot Temperature ºC
85	10	60	116	135
125	10	40	137	145

Fig. 4. Ripple current capacity based on hot spot and surface temperature of packaged capacitors at different ambient temperatures.

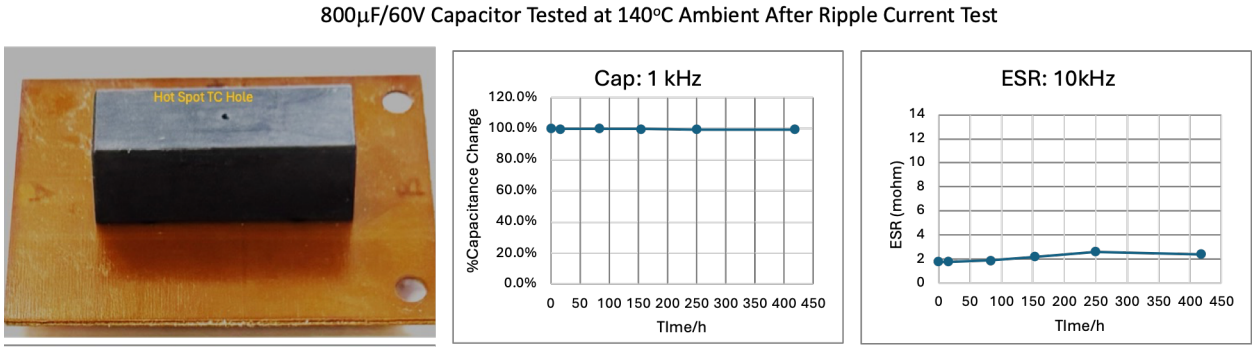


Fig. 5. Left: Typical capacitor setup to perform ripple current capacity tests. Right: Life test results at 60V/140ºC for a few hundred hours to determine if the drilled hole influenced the capacitor self- healing properties.

Following the high current test although the drilled capacitor was environmentally compromised, it was placed on a life test at 140ºC for a few hundred hours to see if the drilled hole affects the self-healing properties of the capacitor.

Capacitance and ESR stability, shown in Fig. 5, indicate that, as expected, the NanoLam capacitors even at such low voltage have excellent self-healing properties.

120V/400µF NANOLAM CAPACITORS

Basic Dielectric Properties of 120V Capacitors and Self-healing Initiation Voltage

Capacitors for 120V applications comprise capacitor elements with the same dimensions as the 60V capacitors and are encapsulated in the same size polymer box. The dielectric thickness is increased resulting in 40 µF capacitor elements. A smaller number of elements is also used to form a capacitor block. The test procedure used to evaluate capacitor properties is the same as that described for the 60V parts. The thicker dielectric results in a lower dissipation factor as shown in Fig.6. The leakage current is typically lower than 5 µA per element and it drops to about 1 µA or less with time on voltage.

The self-healing initiation voltage of typical elements is also illustrated in Fig.6. The level of overvoltage required to initiate self-healing events varies between $1.7V_{rated}$ to $2.0V_{rated}$. As noted above this level of overvoltage is well above that of electrolytic capacitors that serve applications with this level of applied voltage.

Cap 1kHz (µF)	DF 1kHz	ESR 10kHz (mohm)	ESR 100kHz (mohm)	Leakage Current (µA)
41.016	0.0062	8.2	5.1	4.1
38.124	0.0063	9	5.7	2.2
39.82	0.0063	9	5.9	3.5
39.911	0.0064	9.2	6	3.8
39.135	0.0063	9.3	6.2	3
39.702	0.0065	9.5	6.1	1.9
39.187	0.0069	11	7.8	3.7

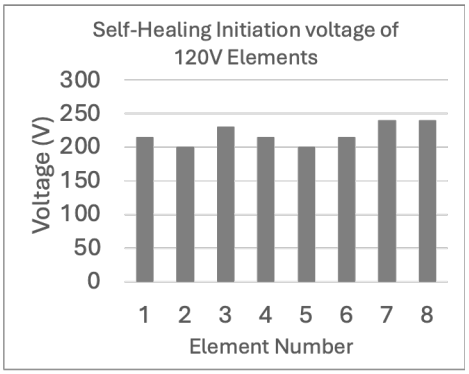


Fig. 6. Left: Typical values of capacitance, dissipation factor, ESR and leakage current of 120V capacitor elements. Right: Self-healing initiation voltage of 120V capacitor elements.

Ripple Current Capacity and Preliminary Life Test

The ripple current capacity, tested using packaged capacitors as described above, is presented in the table of Fig. 7. Measurements of ripple current at an ambient temperature of 125°C show that in order to achieve a 10,000 hr life with less than 10% capacitance loss the current capacity is limited to $30A_{rms}$. At 140°C ambient condition and $20A_{rms}$ the average capacitor temperature increases to about 146°C. Extensive life test data is not available at this point in time to predict life 140°C ambient with $20A_{rms}$. A preliminary test at 140°C ambient static test which is approximately equivalent to an ambient temperature of 125°C with a ripple current of $30A_{rms}$ is presented in Fig. 8.

Ambient Temperature °C	Test Frequency kHz	Ripple Current Arms	Surface Temperature °C	Hot-Spot Temperature °C
85	20	40	107	116
105	20	40	128	136
125	20	30	137	142
140	20	20	145	147

Fig. 7. 20KHz ripple current capacity of 400µF/120V packaged capacitors, showing hot spot and surface temperature at different ambient temperatures.

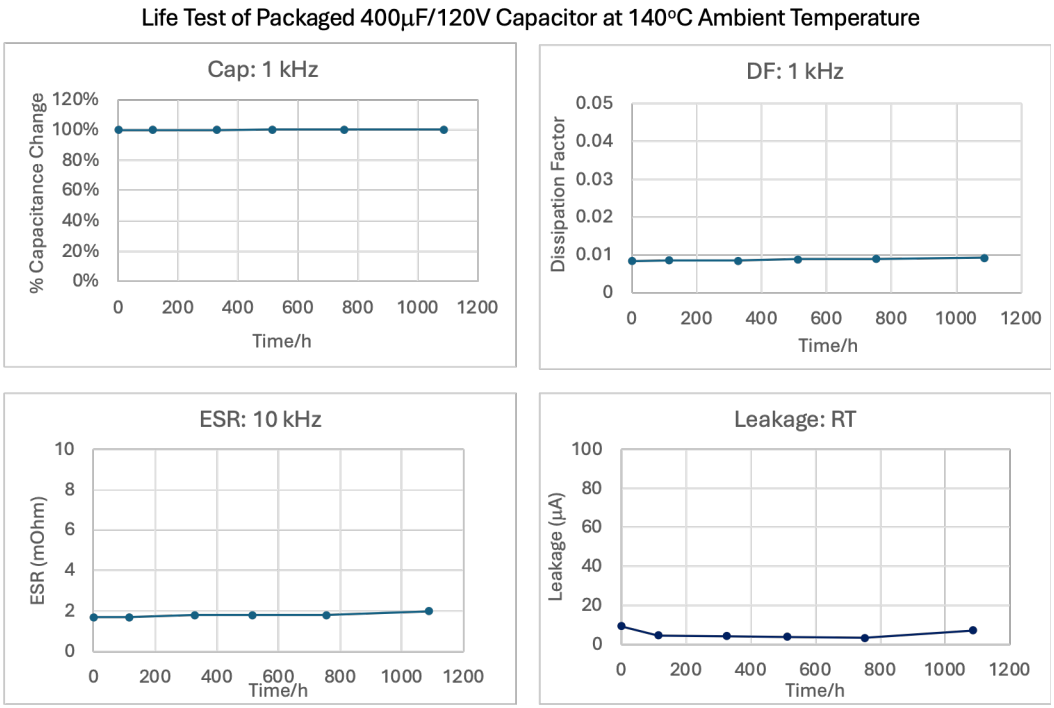


Fig. 8. Typical test results of packaged 400µF/120V capacitors tested at an ambient temperature of 140°C

Fig. 8 shows that, as anticipated, in 1000 hours of static test that corresponds to dynamic conditions of 125°C ambient temperature and 30A_{rms}, there is virtually no change in capacitance, dissipation factor and ESR. The leakage current is also lower than the cumulative leakage of the individual capacitor elements.

COMPARISON WITH STATE-OF-THE-ART ALUMINUM ELECTROLYTIC CAPACITORS

State of the art aluminum hybrid capacitors produced by Panasonic (new ZL series) [16], at 220µF/63V at 125°C have a ripple current capacity of 5.0A_{rms} and an ESR of 12 mohm at 100KHz. The ripple current is reduced to 75% of this value at frequencies in the range of 10KHz< f <20KHz. The leakage current is typically <0.01CV. For four capacitors in parallel with a rating of 880µF/63V, this translates to 20A_{rms} or 15A_{rms} in the frequency range of 10 KHz to 20KHz, and a cumulative current of 550µA. Life at 125°C after 4000hr is defined by less than 30% drop in capacitance and 200% of the original ESR. As shown above, in addition to having no polarity restriction and a high overvoltage withstand, the performance of the 800µF/60V NanoLam capacitor is superior in every respect.

For 100V applications Panasonic SVX series solid aluminum electrolytics 30µF/100V have an ESR of 30 mohm, with 3A_{rms} current carrying capacity at frequencies >100KHz adjusted to 70% or 2.1 A_{rms} of this value between 10KHz< f <100Khz. Leakage current <195 µA [21]. Life, defined as less than 20% drop in capacitance, is 1000hr at 125°C. The data presented above for the 400µF/120V NanoLam capacitors indicate that it will take approximately ten Panasonic SVX 30µF/100V with a leakage current <1.95mA_{rms}, to match the current capacity at an ambient temperature of 125°C. However, there is little comparison that can be made on the cumulative leakage current and the capacitor life after 1000 hours at 125°C of SVX 30µF/100V capacitors versus a single 400µF/120V capacitor.

Polymer electrolytic capacitors with voltages in the range 125V-160V typically have much lower capacitance and when operated at a frequency of 10 KHz or higher, the maximum ambient temperature is reduced to 105C. For example, Nichicon PVC solid electrolytic series 15µF/125V capacitors have an ESR of 48 mohm at 2A current carrying capacity at 100KHz, with a leakage current of 375 µA [22]. The performance of this higher voltage electrolytic capacitors is such that it does not even warrant a comparison with the 400µF/120V NanoLam capacitors.

An alternative to polymer electrolytic capacitors for high voltage and high current DC-link applications are wet electrolytic capacitors. For example, state of the art liquid electrolyte capacitors manufactured by TDK series B43693–B43793 targeted for DC-link inverters at 125VDC [23]. The capacitance can be as high as 650µF with an ESR of 79 mohm and a current carrying capacity of 7.5A at an ambient temperature of 125°C. Life is defined by less than 30%

drop in capacitance at >2500hr at 125ºC and an ESR change ≤ 3X original (≤ 237mohm). Although larger than polymer aluminum capacitors, these are higher energy density parts available in axial or surface mount packages. Although three such parts can match the current carrying capacity of a single 120V NanoLam capacitor, the life stability is in comparison relatively poor.

DISCUSSION

The 60 V and 120 V NanoLam capacitors characterized above demonstrate the combination of properties this paper set out to demonstrate is unavailable from any single incumbent technology in this voltage range. Both designs combine element-level ESR below 10 mΩ (block-level ESR below 1 mΩ) with a self-healing initiation voltage of at least 1.7 times rated voltage, rising above 2.0 times rated voltage for the 60 V design, and stable capacitance, dissipation factor, and ESR through preliminary elevated-temperature life testing, a few hundred hours for the 60 V design and 1,000 hours for the 120 V design, all in a footprint set by a single rectangular prismatic element rather than a wound cylindrical can. For the DC-link and filter applications, this is a materially different starting point than the hybrid polymer aluminum electrolytic capacitors that currently serve most of this voltage range.

Matching the ripple-current capacity of a single 60 V or 120 V NanoLam capacitor requires multiple parallel electrolytic parts in every case: on the order of ten for the 100 V solid aluminum benchmark and three for the 125 V wet-electrolytic benchmark, while for the 125 V solid polymer benchmark the available capacitance and current are low enough, relative to the NanoLam part, that a meaningful comparison does not apply. This pattern is consistent with the broader aluminum electrolytic literature: volumetric energy density remains a genuine electrolytic strength, but ripple-current capability, voltage headroom, and operating life are all achieved by trading against capacitance density, cost, or both [17], [18]. The self-healing initiation voltage margin is the more consequential difference for reliability: none of the four benchmarked electrolytic technologies is specified for any meaningful overvoltage margin, and the failure mode of an overstressed electrolytic capacitor is a wear-out process, gradual capacitance loss and ESR growth, rather than a self-clearing event.

Matching current-carrying capacity with several parallel electrolytic capacitors, as the comparison above requires, carries a cost beyond parts count and board area: parasitic loop inductance. Each additional capacitor in a parallel bank adds its own lead and via inductance, and unless every part is laid out with identical interconnect impedance, current sharing across the bank becomes uneven, concentrating ripple-current stress on whichever capacitor sits electrically closest to the switching node. In practice, a DC-link bank built from several parallel wound or cylindrical electrolytic capacitors rarely reaches the loop inductance of a single compact element, and the resulting voltage overshoot and ringing at switching transitions become a limiting factor for switching frequency and device stress well before the semiconductor itself is the bottleneck. A single small prismatic NanoLam capacitor placed close to the switching devices avoids this multiplication of parallel current loops by construction; PolyCharge's own integration work with SiC power modules has shown this class of low-inductance, high-temperature prismatic capacitor enabling total switching-loss reductions on the order of 30–60% when co-designed tightly with the power module, compared with a conventional busbar-connected capacitor bank of similar capacitance [19]. For the 15 kW-and-above 48 V inverters and multi-kilowatt 120 V power processing units where switching frequency and di/dt continue to increase, this inductance advantage is likely to matter as much as the ripple-current and life advantages demonstrated directly in this work.

There are two limitations of the present results. First, the 10,000-hour, under-10%-capacitance-loss life criterion referenced in this paper has been established for NanoLam capacitors at 400–850 V, not yet for the 60 V and 120 V designs reported here; the lower field stress (V/t) of the lower-voltage designs is a favorable indicator, since it can be expected to lead to longer life under comparable voltage and temperature conditions, but it remains an inference rather than a demonstrated result until longer-duration testing at 60V–120 V is complete. Second, the 120 V ripple-current life data presented here is limited to a 1,000-hour static test at 140°C, approximately equivalent to the target 125°C/30 A_{rms} dynamic condition, and the 60 V drilled-capacitor life check covers only a few hundred hours at 140°C, though a separate, undrilled 60 V sample held at 125°C ambient shows no significant change in capacitance or ESR through 1,000 hours. Future work will extend these data sets so that adequate data is available to apply a life-law to calculate long term performance.

None of these limitations changes the competitive picture established in this paper: at 60–120 V, the combination of ripple-current capacity, overvoltage margin, low loop inductance, and operating-temperature headroom demonstrated here is not simultaneously available from hybrid polymer, solid polymer, or wet aluminum electrolytic technology. With the 48 V automotive segment alone projected to grow at a compound rate near 24% through the early 2030s [20], and with

120 V remaining the baseline spacecraft distribution voltage for the next generation of higher-power satellite and power-processing platforms, the DC-link position in this voltage range is becoming more demanding rather than less, in exactly the dimensions where solid-state polymer nanolaminate technology carries the largest margin over incumbent electrolytic alternatives.

REFERENCES

[1] N. Flaherty, "48 V systems," *E-Mobility Engineering*, 2022 (updated 2023). [Online]. Available: https://www.emobility-engineering.com/48-v-systems/

[2] TDK Corporation, "High power density solution for DC link on 48 V inverter application with Hybrid Aluminum Electrolytic Capacitors," Application Note, Aug. 2022. [Online]. Available: https://product.tdk.com/en/techlibrary/applicationnote/dc-link-on-48V-inverter.html

[3] Analog Devices, "Building a Better – 48 VDC Power Supply for 5G and Next-Generation Telecom Equipment," *Analog Dialogue*. [Online]. Available: https://www.analog.com/en/resources/analog-dialogue/articles/building-a-better--48-vdc-power-supply-for-5g-and-next-generation-telecom.html

[4] Panasonic Industry, "Why is a 48-V power supply required for a data center?," Technical Note, 2021. [Online]. Available: https://industrial.panasonic.com/ww/ds/ss/technical/p6

[5] NASA, "Spacecraft Bus Voltage Selection," 2015 NASA Space Power Workshop. [Online]. Available: https://ntrs.nasa.gov/api/citations/20150019744/downloads/20150019744.pdf

[6] TT Electronics, "Smart DC-DC Strategies," 2022. [Online]. Available: https://www.ttelectronics.com/news/smart-dc-dc-strategies/

[7] A. Yializis, "A Disruptive DC-Link Capacitor Technology for Use in Electric Drive Inverters," European Passive Components Institute, Bucharest, Romania, Sept. 10–13, 2019.

[8] A. Yializis, P. Roop, and A. Teverovsky, "High Energy Density NanoLam™ Capacitors for Use in Spacecraft Power Processing Units," PCNS, Sonderborg, Denmark, Sept. 14, 2023.

[9] A. Yializis, "High Energy Density Solid State Polymer Capacitors for Space Applications," 4th Space Passive Components Days, ESA/ESTEC, Noordwijk, Netherlands, Oct. 11–14, 2022.

[10] M. Singh, S. K. Tiwary, R. Nejat, and J. F. Douglas, "Anomalously High Dielectric Strength and Capacitive Energy Density of Thin Entangled Glassy Polymer Films," *JACS Au*, vol. 5, no. 1, pp. 121–135, 2025.

[11] X. Li et al., "High-temperature capacitive energy storage in polymer nanocomposites through nanoconfinement," *Nature Communications*, vol. 15, Art. 6655, Aug. 2024.

[12] C. Neusel and G. A. Schneider, "Size-dependence of the dielectric breakdown strength from nano- to millimeter scale," *Journal of the Mechanics and Physics of Solids*, vol. 63, pp. 201–213, 2014. [Online]. Available: https://www.sciencedirect.com/science/article/abs/pii/S0022509613001841

[13] F. Forlani and N. Minnaja, "Thickness Influence in Breakdown Phenomena of Thin Dielectric Films," Physica Status Solidi (b), vol. 4, pp. 311–324, 1964.

[14] D. Min, Y. Li, C. Yan, D. Xie, S. Li, Q. Wu, and Z. Xing, "Thickness-Dependent DC Electrical Breakdown of Polyimide Modulated by Charge Transport and Molecular Displacement," *Polymers*, vol. 10, no. 9, Art. 1012, 2018.

[15] S. G. John, "Poole–Frenkel Effect and Schottky Effect in Metal-Insulator-Metal Systems," Physical Review, vol. 155, no. 3, pp. 657–660, March 1967.

[16] Panasonic Industry, "Conductive Polymer Hybrid Aluminum Electrolytic Capacitors – ZL Series," Product Datasheet. [Online]. Available: https://industrial.panasonic.com/ww/ds/products-cap/polymer-capacitors/hybrid-aluminum/ZLseries-pr

[17] Nippon Chemi-Con Corporation, "Lifetime of Aluminum Electrolytic Capacitors," Technical FAQ. [Online]. Available: https://www.chemi-con.co.jp/en/faq/detail.php?id=alLifetime

[18] A. Albertsen, "Aluminum Electrolytic Capacitors vs. Film Capacitors," Jianghai Europe Electronic Components GmbH. [Online]. Available: https://www.heynen.com/products/aluminum-electrolytic-capacitors-vs-film-capacitors/

[19] PolyCharge America Inc., "Unlocking SiC Performance Through Integrated DC-Link and Power Module Design," PolyCharge Publications. [Online]. Available: https://www.polycharge.com/publications/unlocking-sic-performance-through-integrated-dc-link-and-power-module-design

[20] The Business Research Company, "Automotive 48V System Global Market Report," 2026. [Online]. Available: https://www.thebusinessresearchcompany.com/report/automotive-48v-system-global-market-report

[21] Panasonic Industry Co., Ltd., "Conductive Polymer Aluminum Solid Capacitors—SXV Series, 100SXV22M," Product Datasheet, Sept. 2, 2025. [Online]. Available: https://industrial.panasonic.com/ww/products/pt/os-con/models/100SXV22M

[22] Nichicon Corporation, "Conductive Polymer Aluminum Solid Electrolytic Capacitors—PCV Series," Product Datasheet, CAT.8100M. [Online]. Available: https://www.nichicon.co.jp/english/series_items/catalog_pdf/e-pcv.pdf

[23] TDK Electronics AG, “Axial-Lead and Soldering-Star Capacitors B43693, B43793: High Ripple Current—Up to 140 °C,” Product Datasheet, 2026. [Online]. Available: https://www.tdk-electronics.tdk.com/inf/20/30/db/aec/B43693_B43793.pdf