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Supercapacitors Support Miniature Energy Harvester ICs In Powering ULP Devices

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Several individual electronic trends have come together to create low-cost, easy-to implement energy management circuits capable of total power supply control of scavenged and harvested energy supplied to small loads. These circuits can significantly extend the life of a battery powering the load or entirely replace the battery. Among the trends propelling practical, low-cost scavenged energy modules are

- the development of ultra-low power (ULP) ICs
- the ability to create efficient ultra-low-power dc-dc converters with control logic, allowing intelligent energy measurement and management functions
- the introduction of high-capacitance storage devices in miniature sizes.

This article builds upon a previous work discussing the benefits of ULP IC technology.[1] Here, we will discuss the performance and characteristics of a scavenging/harvesting circuit in powering the equivalent of a ULP IC and document its performance using prismatic cell supercapacitors, radial-can supercapacitors, and extended-value tantalum capacitors.

The energy management circuit investigated is comprised of an energy management IC (the e-peas AEM10330) and four passive components—three capacitors and one inductor. We begin by describing the capabilities of the energy management IC and the associated application circuit.

We then discuss the electrical characteristics of the three previously mentioned capacitor types, each of which may be used to store the excess energy harvested by the chip and thereby extend operation of the energy harvesting circuit. As we explain, the different capacitor types are suited to different application requirements, and voltage derating is a key consideration for ensuring capacitor reliability. Finally, we present experimental results to illustrate the performance enabled by the supercaps and tantalum capacitors, followed by a summary of key takeaways from this discussion.

Moving Away From Batteries

Powering ULP loads with batteries has been successfully accomplished for some time. Though this method of powering loads is well documented and successful, U-Blox, a provider of chips and modules for positioning and communications, utilizes this technology in their SARA-N310 cellular module.[2] However, it still ultimately involves maintenance costs associated with changing a battery and the adverse effects of electronic waste associated with batteries at end of life. To overcome these limitations, an investigation was undertaken to identify a miniature, low-cost power management IC to convert power from scavenged sources and power ULP loads.

The e-peas AEM10330 solar energy harvester was selected for exclusive investigation because of its complex electrical capabilities, which are contained within a small 5- x 5- x 0.8-mm quad flat no-lead (QFN) package. The electrical capabilities are so significant that it is worth discussing before proceeding with the study.

This IC can provide 30 mA of current in low-power mode and 60 mA in high-power mode. Its programmable output voltage ranges from 1.2 V to 3.3 V. The AEM10330 offers an ultra-low startup budget with a cold-start input voltage of 275 mV and typically consumes 3 µW of input power demonstrating a very efficient energy extraction capability.

The IC has open-circuit voltage monitoring capability to create its version of maximum power point tracking (MPPT). The MPPT function has a programmable sense period, and an operational range of 100 mV to 4.5 V. Open-circuit voltage ratios are selectable from a 60%, 90%, or fixed-impedance level.

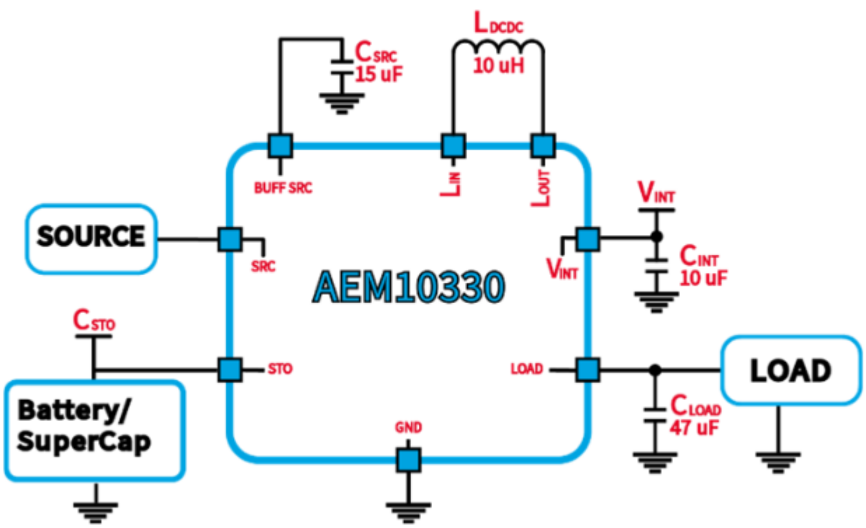
This IC has an adaptive and intelligent energy management approach that can provide a regulated output from a boost-buck converter. It can balance two supercapacitors as energy storage cells, manage multiple solar cell configurations, and transition power automatically or through preprogrammed levels.

The chip can automatically switch between boost, buck-boost, and buck operation to maximize energy transfer between the input and output. Also, for the input, the chip automatically selects between a source, a storage capacitor, and potentially an optional battery. Additionally, the chip can select the output to "toggle" or switch between the internal supply, the load, and the energy storage capacitor.

Further, the chip has several battery protection features: selectable overcharge and overdischarge protections for any chemistry of battery and supercapacitor, fast supercapacitor charge options, dual supercapacitor cell balancing, and also an option for rapid capacitor charging. Implementing the AEM10330 is simple since it only requires three capacitors, one inductor, and an optional Li-ion battery or supercapacitor at the storage (STO) pin.

A typical schematic configured for an output voltage of 1.8 V using a single supercapacitor charged to 2.0 V is shown below in Fig. 1. A list of peripheral passive components, also given in Fig. 1, illustrates just how simple and compact the energy harvesting circuit can be.

The end applications for miniature harvesting power management integrated circuits (PMICs) are widespread and growing. Traditional uses range from asset tracking and monitoring to smart buildings. Industrial uses cover machine condition monitoring to environmental and safety monitors. Aftermarket transportation applications continue to expand in consumer automotive to class 8 application sectors. (Class 8 encompasses commercial vehicles, and construction and farm equipment.) There are also several emerging applications, including electronic shelf labeling and smart sensors for constant monitoring of the flow of goods and real-time pricing.



Component location	Component description	KYOCERA AVX part number
C_{LOAD}	47 µF, 6.3 V, 20%, X5R, 0603	06036D476MAT-A
C_{INT}	10 µF, 6.3 V, 20%, X5R, 0402	04026D106MAT-A
C_{SRC}	22 µF, 6.3 V, 20%, X5R, 0402	04026D226MAT-A
L_{DCDC}	10 µH, >1 A	LMMN0605*101MTCS

Fig. 1. An application circuit for the e-peas AEM10330 energy harvester and a list of the support components. The source in this case is a solar cell. Given the small size of the IC and external passives, this circuit can be implemented in a very small footprint.

Energy Storage Capacitor Options

A key feature of the AEM10330 is converting energy from the scavenged source and supplying that to the load in an easy-to-implement, small circuit package. If excess energy is left over, a supercapacitor is charged with that power. This design feature boosts efficiency since no harvested power is wasted.

With this in mind, a quality energy storage capacitor is a crucial contributor to the performance and practicality of the harvesting circuit. Our investigations centered on supercapacitors and tantalum capacitors.

Supercapacitors

Supercapacitors are commonly chosen as energy storage capacitors because of their small size and ability to provide many hundreds of thousands of charge-discharge cycles. Low-value supercapacitors are widely available in two very different form factors—small radial cans and prismatic cells. Ultra-miniature devices were chosen for this study since these devices offer designers maximum flexibility through the availability of multiple product series, a wide array of voltage offerings, a multitude of case sizes, and the highest number of capacitance values available (relative to the non-miniature ones).

Radial can parts are commonly used in single configuration (as was the method for this study) for lower-voltage designs, or multiple cans can be configured to obtain the correct voltage/energy for higher-voltage loads. Multiple cans can be balanced via active or passive methods.

Small radial-can supercapacitors are attractive because of their minimal footprint. The radial device tested (KYOCERA AVX's SCCQ12B105PRB) occupies a PCB area of ~0.3 cm^2 and exhibits an energy density of ~1.56 Wh/kg. This capacitor has a height of 12 mm.

Radial supercapacitors are available in sizes as small as 6.3 mm in diameter and 12 mm in height for a 1-F capacitor. Multiple options exist for radial-can supercapacitors (see Table 1 comparisons) and the end device selected depends upon the desired application run time and package characteristics of the supercapacitor.

Table 1. Radial-can supercapacitor options.

Capacitor form factor	Capacitance (F)	Voltage (V)	Dimensions (mm)	Terminal options	Weight (g)
Radial can	1 to 3000	2.7 to 3.0	6.3 to 60, diameter 12 to 138, length	Solder in, snap in, cylindrical lug, and screw in	0.6 to 504
Radial module	0.33 to 15	5 to 9	6.3 to 14, diameter 13.6 to 32, width 14 to 33, length	Radial straight lead and radial bent lead	1.35 to 18
Custom module	100s to 1000	2.7 to ~200	Custom package	Custom options	Custom

Supercapacitors need to be properly derated to achieve long-term reliable operation regardless of the specific package configuration. Previous work[3] shows that supercapacitor reliability is a function of applied voltage and temperature.

Early on, tests were designed to show the reliability impacts of a variety of can chemistry supercapacitors (those offered in an aluminum can with the bottom sealed) when subjected to a matrix test where voltage, temperature, and humidity stress levels were varied while the DUTs' capacitance and ESR were measured to determine stress effects. A series of graphs that show MTTF in years versus applied voltage and applied temperature was developed from test data.

These graphs indicate that expected life more than doubles for every 10°C lower operating temperature (per the Arrhenius rule). Life doubles again for every reduction of 0.1-V lower operating voltage. Results are shown in Fig. 2.

When a lower-profile supercapacitor is needed than that of radial cans, a prismatic-packaged device can provide supercapacitors with heights as low as 0.8 mm.

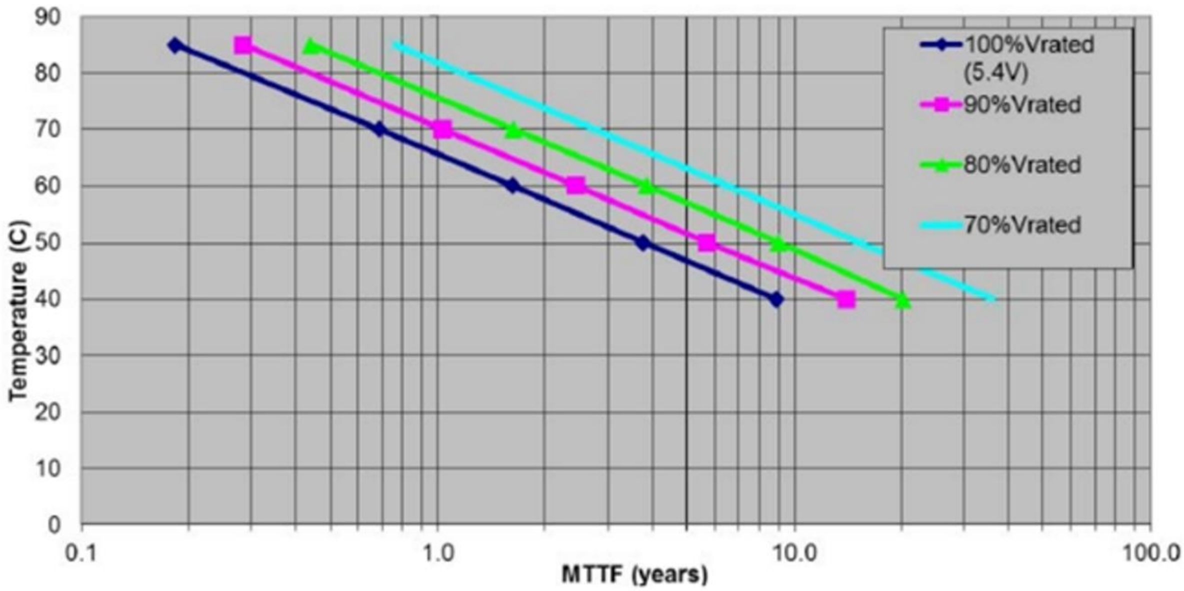


Fig. 2. MTTF in years at various voltages and temperatures for ACN (acetonitrile) material 5.4-V, 5.0-V rated supercapacitors.

PrizmaCap Supercapacitors

PrizmaCap supercapacitors are a family of prismatic supercapacitors that offer the highest energy density of any prismatic EDLC (electrochemical double layer capacitor). They operate over a wider temperature range and exhibit lower leakage currents than traditional supercapacitors.

PrizmaCap devices are a family of low-profile prismatic supercapacitors, which utilize a propylene-carbonate-based electrolyte. A unique electrochemical combination allows the supercapacitor to operate across a wide temperature range (-55°C to +90°C). Current technology dictates capacitance range limitations between 1 and 500 F with 3.5, 8.5 and 15 F being widely available capacitor values. These devices have a rated voltage of 2.1 V, when operating at ≤+65°C and must be derated to 1.1 V when operating at +66°C to +90°C.

PrizmaCap capacitors offer many electrical advantages when compared to similar capacitance radial-can supercapacitors. ESR values are uniformly lower and are as low as 30 mΩ. The devices have approximately twice the capacitance density and 50% higher energy density than traditional supercapacitors.

The package differs greatly from standard radial-can supercapacitors. PrizmaCaps come in two different case sizes with X and Y dimensions of 48 mm x 45 mm and heights of 0.8 mm to 2.3 mm. Further, the devices are ultralight with weights <2 grams. All PrizmaCaps are RoHS and REACH compliant.

The PrizmaCap device we tested was KYOCERA AVX's SCPB13A855SNA. This supercapacitor has a thickness of 1.3 mm and X and Y measurements of 44 mm long x 45 mm wide. It exhibits an energy density of 1.87 Wh/kg. A summary of supercapacitors and tantalum capacitors evaluated in this study is shown in Table 2.

Table 2. Test capacitor parameters.

Parameter	PrizmaCap	SCC radial	TLN PulseCap
Kyocera-AVX part number	SCPB13A855SNA	SCCQ12B105PRB	TLN6228M006R0055
Capacitance (F)	8.5	1	0.0022
Capacitance tolerance (%)	+30/-10	+100/0	±20
Standard temperature range & voltage	-55°C to +65°C at 2.1 V	-40°C to +65°C at 2.7 V	-55°C to +40°C at 6.3 V
Extended temperature range & voltage	-55°C to +90°C at 1.1 V	-40°C to +85°C at 2.3 V	-55°C to +125°C at 1.3 V
DCL (µA)	80	6	132
DC ESR max (mΩ)	80	1500	55
Peak current (A)	5.31	0.9	~7
Capacitance density (F/CC)	3.03	2.7	0.0095
Joules/CC	6.68	9.85	0.19
Power density (W/kg)	2380	2692	0.191
Energy density (Wh/kg)	1.87	1.56	41.3
Dimensions: L x W x thickness) (mm) or diameter by L	44 x 45 x 1.3	6.3 x 12	14.8 x 7.8 x 2.0

Tantalum Capacitors

Tantalum (solid electrolytic) capacitors are often employed in the storage of energy based on their small form factor, long life (they have virtually no wearout mechanisms), stability across temperature and voltage, and their ability to achieve very high capacitance per unit volume (CV). While they do not have the maximum capacitance values garnered from supercapacitors, there is virtually no change in functionality throughout their near-infinite lifespan.

Tantalum polymer capacitors are commonly chosen for dying-gasp applications in solid state drives (SSDs) because of their small size, adequate energy storage capability, high reliability and extreme ease-of-processing, high-volume manufacturing environments.

Tantalum capacitors offer another major advantage when it comes to energy scavenging/energy harvesting—the potential for ultra-low leakage currents. Though the leakage current for tantalum polymer capacitors is higher than supercapacitors, it can be exponentially reduced if the applied voltage is derated properly. This is visible in Fig. 3, a graph of leakage vs derated voltage.

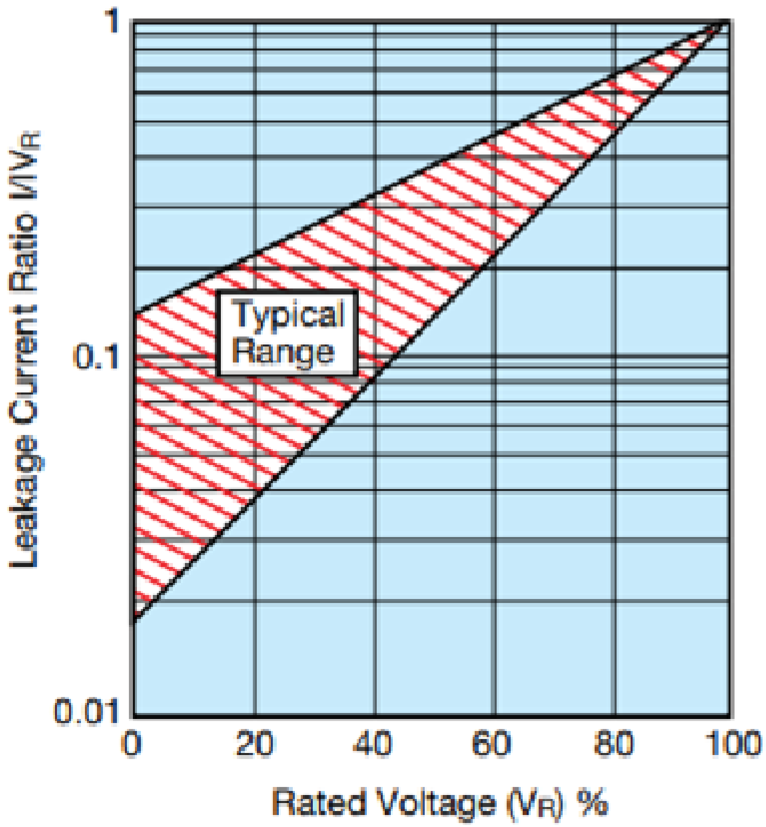


Fig. 3. Tantalum capacitor leakage current ratio vs. rated voltage. As the applied voltage on the cap is derated, the level of leakage current for this chemistry is generally reduced, lowering the associated losses.

The tantalum PulseCap component tested was KYOCERA AVX's TLN6228M006R0055. It has a thickness of 1.3 mm and X and Y measurements of 44 mm and 45 mm, respectively. The PulseCap has an energy density of 41.3 Wh/kg.

While any of the capacitors listed will achieve optimal usage, the energy storage capacitor chosen depends entirely upon the type of load and application the AEM10330 is ultimately intended for. The tests that were conducted will shed light on what each capacitor can bring to the table. All the pertinent data specific to each part tested can be found in Table 2.

Test Setup And Results

The e-peas AEM10330 module was driven with a solar cell using an artificial light source at a fixed distance to provide consistent power levels to the energy harvesting device. The load was attached and configured to draw approximately 1.82 V. The supercapacitors and tantalum capacitors were then separately affixed to the module.

A basic representation of the module setup can be seen in Fig. 4. Then, Figs. 5, 6, and 7 show the seamless power delivery of the AEM10330, which outputs 1.8 V to the load while simultaneously charging the capacitors. The results demonstrate how minimal power is wasted utilizing the capacitors in conjunction with the AEM10330. From the graphs, it is also easy to gather that the load output starts up as soon as the cap reaches 1 V of charge—so the module output starts up before the cap is fully charged.

The data illustrates how both the load and capacitors are supplied power as well as how the capacitors can deliver power to the load once the supply is removed. (In each case, the solar cell is removed once the cap is fully charged.) Essentially, the information validates how easily supercapacitors and tantalum capacitors are to implement with the AEM10330 and how efficient the system is.

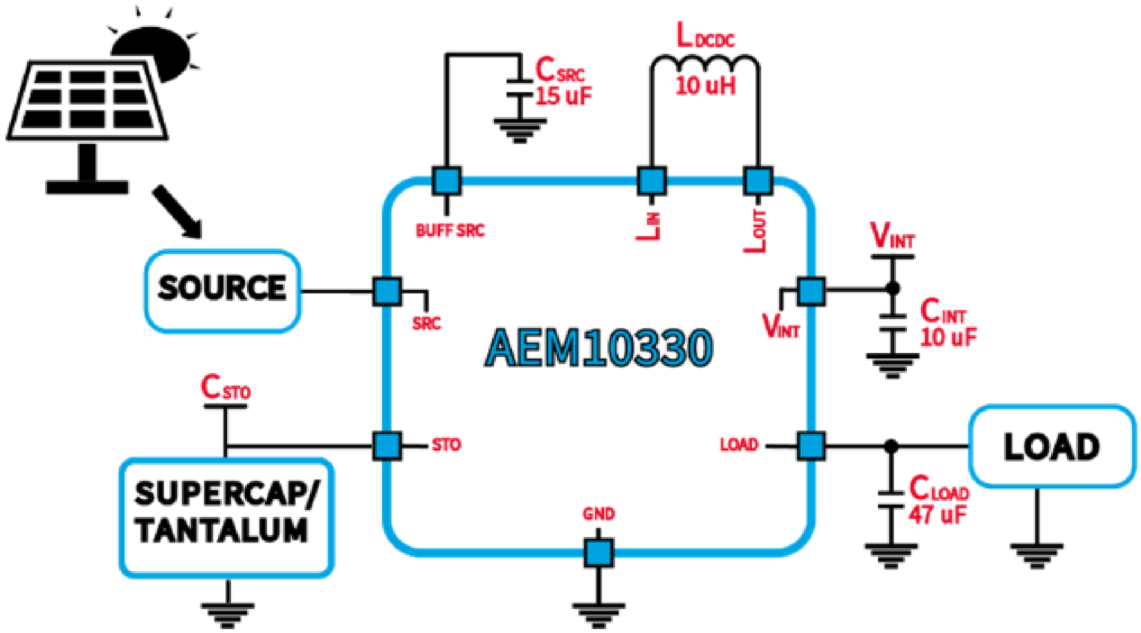


Fig. 4. The AEM10330 with solar cell and capacitor setup.

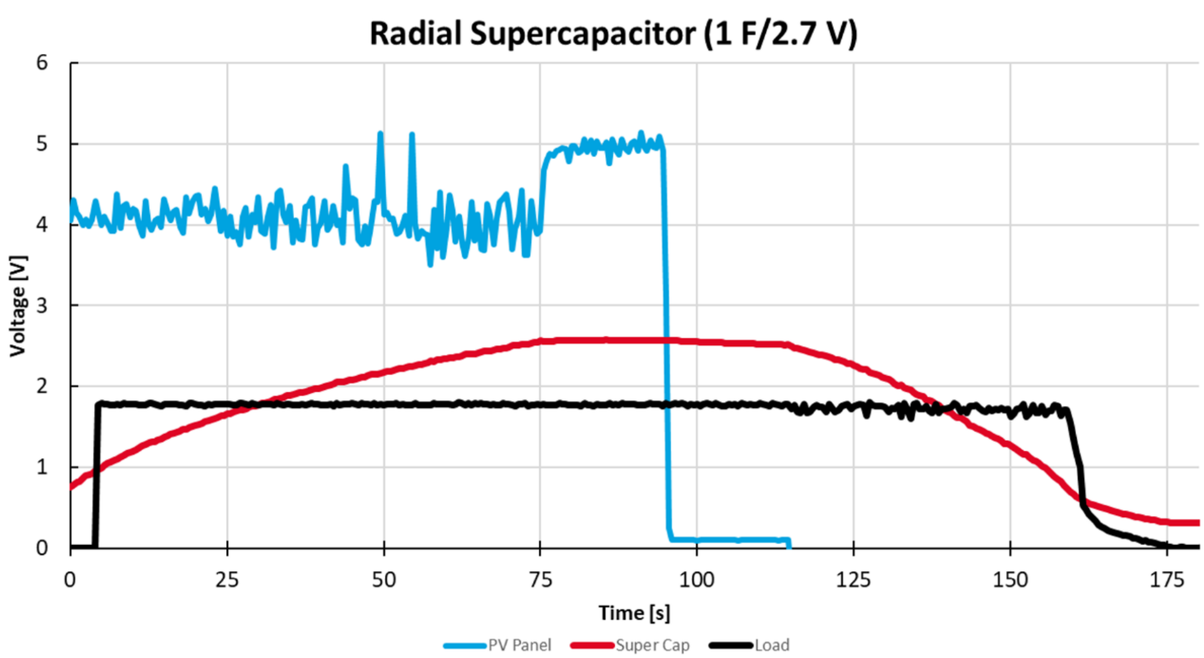


Fig. 5. Output voltage (black curve) produced by an AEM10330 solar energy harvester when powered by a small 10- x 8-cm solar cell and a 1-F radial supercapacitor. The load is 10 mA.

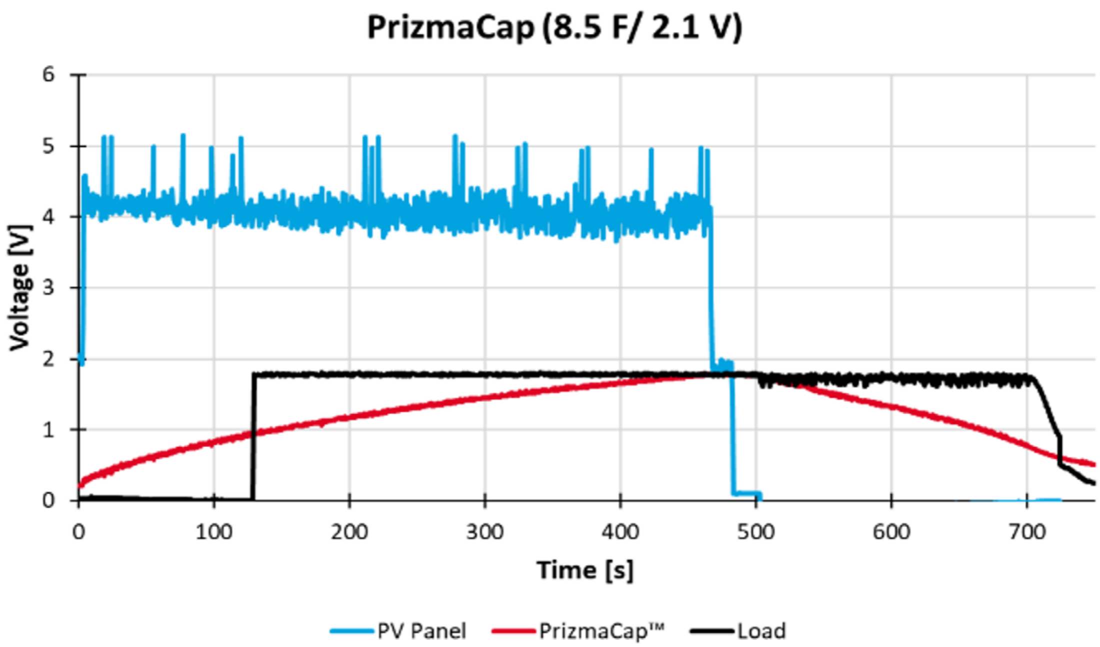


Fig. 6. Output voltage (black curve) produced by an AEM10330 solar energy harvester when powered by a small 10- x 8-cm solar cell and an 8.5-F PrizmaCap. The load is 10 mA.

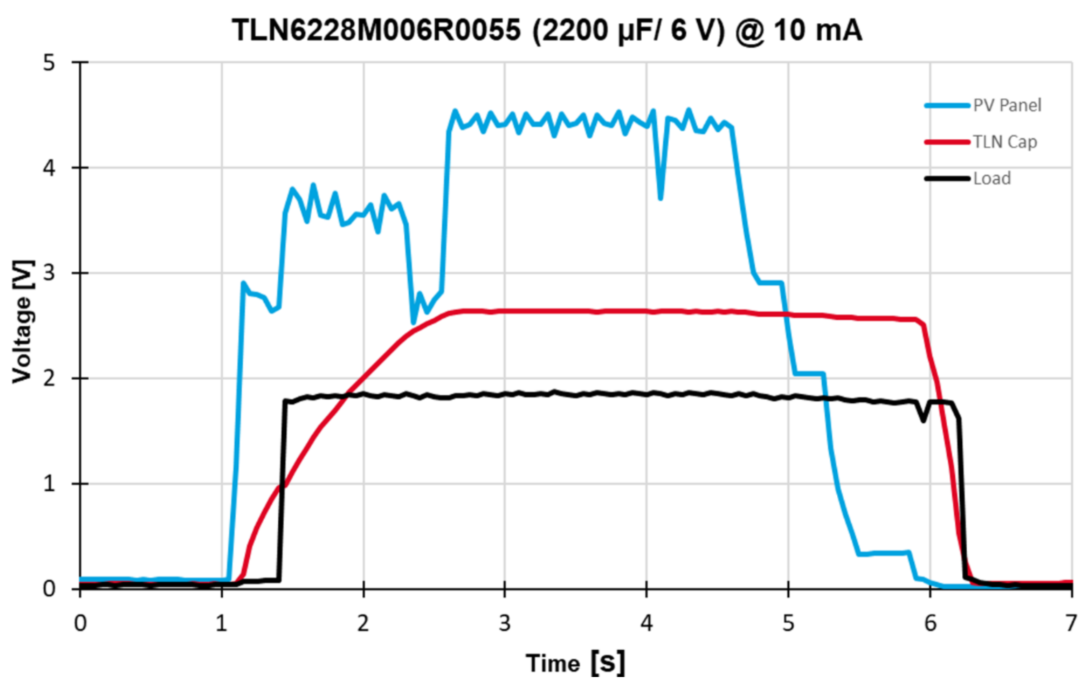


Fig. 7. Output voltage (black curve) produced by an AEM10330 solar energy harvester when powered by a small 10- x 8-cm solar cell and a 2200-µF tantalum PulseCap. The load is 10 mA.

Observing these results, we have a few takeaways. The smaller capacitance of the tantalum capacitor is ideal for quick-charge-up capacitor needs as in the case of startup capacitors. Also, the tantalum capacitors' smaller size, ease of automatic pick-and-place plus SMT IR reflow capability make these capacitors ideal for lower load holdup as required, for example, by solid-state drives (SSDs).

Prismacaps' use tends to be concentrated in miniature modules with extended time needs. The radial can supercapacitors occupy a larger height profile but also have reasonably large capacitance and power holdup characteristics. The holdup times can be very cost effectively increased by using larger supercapacitor values in a wide variety of packages.

Summary

ULP devices are becoming the norm as ICs become more efficient, making e-peas's energy harvesting solution attractive for powering these devices. According to KYOCERA AVX's research, the market size for energy harvesters sat at approximately $5.42 billion in 2020 with a projected growth rate of 25.3% from 2022 to 2027. As the data indicates, there is a serious market that e-peas can fill alongside high-quality KYOCERA AVX tantalum, tantalum polymer and supercapacitors.

The most common energy storage capacitor options trend toward supercapacitors. Easy-to-implement derating methods can be implemented which can greatly enhance the supercapacitor reliability.

Tantalum-based capacitors can be chosen with consideration of recharge frequency and power levels. This solution is typical of ultra-low-load applications in need of standard low-profile ECIA packages. PrizmaCaps can also provide low-profile capacitor options with associated increases in X-Y board area.

It is important to anticipate the operating temperatures of the device as these can be crucial criteria for determining what kind of storage capacitor to use. For higher operating temperatures (>85°C), tantalum is the appropriate choice. It is also important to reiterate the need for derating voltage for both the supercapacitors and tantalums to maximize efficiency, achieve max capacitance, and extend the part's length of operating life.

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2. "U-Blox SARA-N3 For Periodic IoT Sensing From a Small Battery" by Kersten Heins, U-blox.com, April 28, 2022.

3. "Powering IoT Modules Using Solar Panels, Supercapacitors, and an Automatic Buck/Boost Controller IC" by Ron Demcko, Ashley Stanziola and Daniel West, Kyocera-AVX technical paper.

About The Authors

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Prior to joining AVX, Ron worked as a product engineer and, later, a product engineering manager in the electronics division at Corning Glass Works. In these roles, he supported the development, production, and sale of pulse-resistant capacitors, high-temperature capacitors, and radiation-resistant capacitors, developed high-frequency test methods, and co-developed high-temperature test systems. Ron earned his BSEE from Clarkson College of Technology (now Clarkson University). He can be reached at ron.demcko@kyocera-avx.com.

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Previously, Ryan served five years as an Infantry Squad Leader in the United States Marine Corps. He resides in Greenville, SC, with his wife, and they are currently expecting their first child. Ryan graduated from Clemson with a B.S. in electrical engineering. He can be reached at ryan.messina@kyocera-avx.com.

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Prior to this role, Ashley earned her bachelor's degree in electrical engineering at Clemson University. She can be reached at ashley.stanziola@kyocera-avx.com.

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He has published various papers from connectors to capacitors among other passive electronic components. Daniel is a combat veteran of the 82nd Airborne, and resides in Greenville, S.C. with his wife and two children. He received his BSEE from Mercer University. Daniel can be reached at daniel.west@kyocera-avx.com.

For more on power design for energy harvesting, see How2Power's Design Guide, and do a keyword search on "energy harvesting". Also search "supercapacitors" or see the "Component" category and select "Capacitors".