White paper

How supercapacitors address modern electrical supply challenges

Executive summary

The diversification and decentralization of electrical energy sources for utility power have been a necessity for critical infrastructure, military, and government installation for nearly a century. Recent energy sources, such as renewable energy systems, have introduced a beneficial source of grid (or standalone) energy, but this comes at the expense of increasing the transient nature of the grid supply[1]. To overcome reduced grid inertia and meet the reliability demands of critical loads, enhanced short term energy storage systems have become increasingly deployed. A new energy storage solution, supercapacitors (also known as electric double-layer capacitors, EDLCs or ultracapacitors), offers extremely reliable short-term energy storage that can be used to reduce power ramp rates and help provide frequency regulation services during highly transient events while minimizing capital and/or operational expenditure (CapEx and OpEx) impacts.

The goal of this white paper is to illustrate the benefits that supercapacitors can offer for modern electrical supply infrastructure with the increase in grid-tied distributed energy resources (DERs).

Powering Business Worldwide

Grid supply and demand challenges & distributed energy resource trends

Ensuring a reliable and resilient supply of electrical energy is a top concern of energy providers servicing large regions, or for islanded local systems. Though providing a stable and regulated energy supply has always been a challenge for electrical utilities, this challenge is only increasing with the accelerated adoption of distributed energy resources (DER)-based microgrids and renewable energy generation technologies. Due to the transient nature of DER supply, such as with photovoltaics (PV) or wind turbines, situations can occur when the supply and demand of energy are unequal, leading to power outages or costly, and potentially hazardous, conditions to the electric utility's generation assets.

For instance, if the demand exceeds the supply, either due to the activation of additional loads or a sudden drop in generation, the frequency of the supply voltage may drop. In these cases, utilities may need to begin load shedding to mitigate the stress on generation sources. If load shedding is inadequate, whole generation plants may need to be shut down for protection, which can lead to a substantial cost to utilities. Traditional generation sources, such as fossil fuel burning, nuclear, or hydroelectric plants, typically have a significant amount of inertia, which can help to provide some frequency regulation in cases of high demand and supply imbalances. However, with DERs replacing retired traditional generation technologies, the inertia of sources is far less than in the past.

On the other hand, if supply availability exceeds the demand, a frequency increase could occur, which may also damage downstream loads, generation assets or elements connected to the grid. In this instance, the additional supply must be shed, being dissipated in condensers as heat or discarded to load banks. Otherwise, generation sources may need to be temporarily shut off or run at a much less efficient, low-power state. Not only is this energy wasted at cost, but it could also lead to instances where the instantaneous demand exceeds the adjusted supply, causing further challenges such as voltage spikes that can damage downstream equipment.

In the case of isolated, or islanded, electric power systems (isolated microgrids) dependant on DERs, responding to the demand in real-time by ramping up or down the renewable energy supply is essential. Even minor cloud cover or rapidly changing wind patterns can lead to massive drops and spikes of renewable energy for microgrids, which can lead to highly unstable supply conditions and damage connected elements. Short-term and peak power support for critical loads is another concern, as backup generators, such as diesel generations, can take tens of seconds or up to minutes to yield optimum power.

Energy storage assets can be used to reduce the stresses on generation sources during transient conditions and help to ensure supply frequency regulation. If an energy storage system is optimized for a particular grid's supply profile, both capital expenditures and operational expenditures can be reduced for the utility while providing a much more efficient and stable service for consumers.

Key supercapacitor features for the modern energy infrastructure

Though there are a variety of energy storage solutions that can be used to augment electric utility generation sources, supercapacitors (supercaps) fill a unique niche, providing substantial value compared to other energy storage solutions[2,3]. Some of the benefits supercapacitors provide come as a product of their unique passive operation and method of electrical energy storage. Supercapacitors store energy in an electric field, as opposed to energy storage in chemical bonds or kinetically. The electrostatic storing of charge allows supercapacitors to discharge their energy nearly instantaneously with substantially higher power densities due to the lower equivalent series resistance (ESR).

These features of supercapacitors allow for energy storage systems that are able to store and respond to large supply needs within a fraction of a second, which is beneficial for evenly balancing instantaneous demand or supply fluctuations. The rapid response time of supercapacitor energy storage can also be used to aid in the black startup of some energy generation sources. Moreover, the extremely high power density of supercapacitors means that a relatively small footprint system could provide much higher instantaneous power over a short period compared to lithium-ion batteries or kinetic (flywheel) energy storage. Often, traditional battery technologies have to be drastically oversized to meet the power delivery needs of the application. In cases where power density is the main requirement for an energy storage system, supercapacitor-based storage systems will be a fraction of the size of other storage technologies.

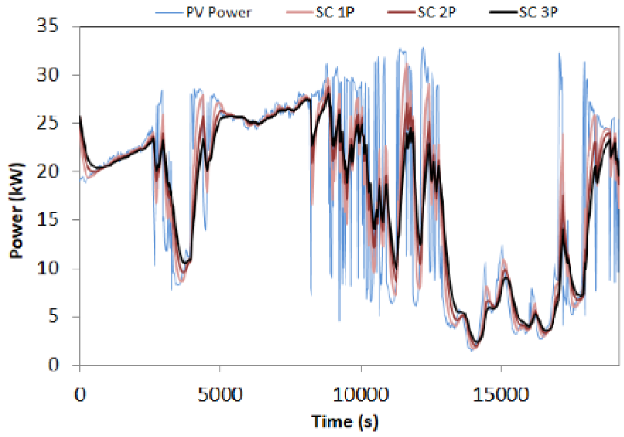
Additionally, unlike other volatile chemical or mechanically intensive energy storage systems, supercapacitors provide long operation life and inherent reliability without the need for extensive maintenance or monitoring. Supercapacitors are also extremely environmentally rugged and can provide high discharge/charge rates through a wide operating temperature range. Supercapacitors are passive devices that can be charged and discharged, to virtually any degree, over millions of cycles for a potential operation lifetime of 20 years. With such reliability, this means that the upfront cost of a supercapacitor energy storage system is often the only expense necessary, and the supercapacitor system can continue to provide energy generation cost savings or transmission and distribution capital deferment for decades. This provides end users a very low total cost of ownership for their energy storage system.

Supercapacitors & generation sources

Supercapacitors can be used alongside energy generation sources to help dampen transient supply behavior from microgrids, address rapid changes in demand, and provide bridging power during rapid rates of demand change or supply drop out for backup situations. These features lead to supercapacitors pairing well with modern microgrid and macrogrid energy source technologies.

Solar PV & wind power firming

Supercapacitors can be used alongside Solar PV and Wind to aid in power firming during transient conditions. As a greater percentage of energy is generated by renewable sources with intermittent energy generation, the need to smooth rapid variation in the power supply is necessary. As Solar PV systems produce DC power, supercapacitors can even be used in parallel to the PV arrays to provide smoothing prior to AC conversion.



Supercapacitor strings integrated with PV array output to assist in ramp rate control. 1P, 2P and 3P are additional strings placed in parallel to reduce power output rate of change.

Fuel cell microgrids

Fuel cells have steadily been gaining adoption in microgrid installations, as the electrochemical process of converting hydrogen-rich fuels into electrical energy with fuel cells is more environmentally friendly than fossil fuel generation. While a traditional battery needs to be recharged, a fuel cell will provide electrical energy as long as fuel is supplied. In cases of peak demand or rapid spikes in demand, fuel cells may struggle to ramp up quickly enough to provide the power required by the load, which can cause voltage instability. A supercapacitor energy storage solution can be used to augment a fuel cell generator by smoothing out the spikes and dips from transient loads and also provide generator bridging while the fuel cell ramps up to meet peak demand.

Combined heat and power (CHP) plant

Cogeneration plants use electrical energy generation processes that also produce usable heat to enhance overall efficiency. Typically, these types of plants use heat generation to produce high-pressure steam that powers turbines. Hence, CHP energy generation tends to have a moderate amount of inertia, which aids in maintaining adequate voltage and frequency regulation. However, these plants aren't generally able to respond rapidly to changes in demand and take a significant amount of time to cold start. Therefore, cogeneration plants can benefit from supercapacitor energy storage for highly transient load conditions and additional energy storage for cases where the supply is degraded for long periods of time.

Supercapacitors & other energy storage systems

As energy storage technologies are not one-size-fits-all in their performance, there is often a benefit to pairing energy storage solutions in order to optimize storage perftormance. In these cases, the rapid charge/discharge profile of supercapacitors can be extremely beneficial when paired with most other energy storage technologies, as other technologies tend to have a much slower response

Lithium-ion batteries

While lithium-ion batteries also have a higher energy density than supercapacitors, lithium-ion batteries exhibit a lower power density. Hence, to build a lithium-ion battery energy storage system that can meet the same peak power discharge capability as a supercapacitor system, the lithium-ion battery version would necessarily be much larger, heavier, and more expensive. However, supercapacitors don't provide near as much energy density, making a hybrid supercapacitor/lithium-ion battery energy storage solution viable for many applications. For example, a hybrid energy storage solution can be used in a generator-bridging application where the generator may take several minutes to reach optimal output. In this instance, the supercapacitor portion of the hybrid solution could be used for the extremely high initial power demands and eventually transition over to lithium-ion battery storage as the generator ramps up.

Cell level comparison

Key characteristics	Units	Supercapacitor	Li-ion batteries
Voltage per base unit	V	2.5 - 3.0	3.6 - 4.2
Cold operating temp	°C	-40	-20
Hot temperature	°C	+85	+45
Cycle life		> 1,000,000	10,000
Calendar life	years	5 - 20	3 - 10
Energy density	Wh/L	1 - 10	250 - 650
Power density	W/L	1,000 - 22,500	800 - 3,000
Efficiency	%	> 98	80 - 90
Charge rate	C/x	> 1,500	< 40
Optimal discharge time		seconds or minutes	hours

Flow batteries

Flow batteries are a modular energy storage solution that relies on electrochemical energy from stored chemical liquids. Unlike a traditional battery, and similar to a fuel cell, a flow battery can readily be recharged by the addition of energy storage chemicals, and the power density and energy density of a flow battery are modular, based on the number of flow battery cells and the total volume of chemical liquid used for energy storage. However, flow batteries typically require pumps and take some time to ramp up to a peak power state. Therefore, supercapacitors in a hybrid system with flow batteries can be used to handle both highly transient/intermittent load conditions as well as very long-term energy storage and generation.

Flywheel

Flywheels are a form of mechanical energy storage that rely on the rotational energy stored in a mass wheel. Flywheel technologies have been used for decades to store energy in vehicle applications and have been adapted for electrical energy storage with mechanical to electrical energy conversion methods. Though flywheel technologies can be made highly efficient, they are far less energy dense and power dense than Li-ion batteries or supercapacitors. Moreover, flywheels tend to charge at a much slower rate than both Li-ion and supercapacitors, and this greatly asymmetric charge/discharge profile limits the use of flywheels. Where supercapacitors can rapidly charge and discharge, allowing their use in ramp rate and high transient control, Flywheels are most typically useful for filling in gaps of energy sources.

System level comparison

Specification	(24) XLM - 62 Supercapacitors	Grid/Regen Flywheels
Operating voltage	Up to 1450 Vdc	750 Vdc/1500 Vdc
Temperature range	-40 to +65 °C	0 to +50 °C
Input/output power	450 kW+	125 kW (normal)
Energy storage	4362 kW-sec*	1875 kW-sec
Design lifetimes	Up to 20 years**	15 - 20 years***
Footprint (W x D)	31.2 x 33.5	30 x 30"
Weight	730 kg	998 kg

* Assumes a 1450 - 700 V operating range

** Dependent on ambient temperature and charge voltage

*** Annual maintenance and component replacements required to meet these estimated lifetimes

Conclusion

Amidst the changes in the energy infrastructure of most modernized countries, DERs and renewable energy sources are able to provide more resilient and ecologically sustainable energy solutions than traditional fossil fuel based energy sources. Though viable for other means, the new microgrid aspects of the energy infrastructure and renewable energy sources typically are not the most reliable sources, and they suffer from intermittent demand and supply instabilities. Even most modern energy storage technologies would benefit from additional high power-density and high-reliability energy storage. This is why supercapacitors have become an increasingly viable and adopted technology to solve short term power needs to enhance grid resilience and stability, as well as providing power firming and ramp rate reduction for renewable and DER energy sources.

References

1. https://ourworldindata.org/energy-production-and-changing-energy-sources
2. https://www.eaton.com/content/dam/eaton/products/electronic-components/resources/brochure/eaton-providing-grid-resiliency-with-supercapacitors.pdf
3. https://www.eaton.com/content/dam/eaton/products/electronic-components/resources/brochure/eaton-supercapacitors-strengthen-renewable-energy-utilization.pdf

Eaton
Electronics Division
1000 Eaton Boulevard
Cleveland, OH 44122
United States
Eaton.com/electronics

Printed in USA
Publication No. 10992 BU-MC19119
September 2019

EATON
Powering Business Worldwide