

The Role of Capacitors Across Modern Energy Systems



AUTHOR: PETER MATTHEWS

Today, electrification is transforming systems, processes, and applications that have historically depended on fossil fuels to operate on electricity, particularly electricity derived from clean and renewable sources. As a result, renewable energy generation is scaling rapidly, and power systems are becoming more distributed, dynamic, and interconnected.

These systems also must operate at higher voltages, perform switching at faster frequencies, and perform reliably over longer lifetimes and in more demanding environments. It's also important to understand that these changes are not isolated and instead propagate across the entire energy ecosystem, influencing everything from grid infrastructure and transmission to backup power and end-use applications.

At each stage, from generation to conversion to transmission, storage, and distribution, capacitors play a critical role in performing tasks such as stabilizing voltage, filtering electrical noise, supporting high-frequency switching, and enabling both long-duration energy storage and instantaneous power delivery. While small in size, their impact is foundational to system performance, efficiency, and reliability.

This ebook examines how modern energy systems are evolving and where capacitors fit within that evolution. It explores key trends in renewable generation, power conversion architectures, EMI and reliability challenges, grid-scale storage and transmission, and fast-response power systems. Together, these sections provide a system-level view of how capacitors enable the performance and resilience required in today's energy infrastructure.



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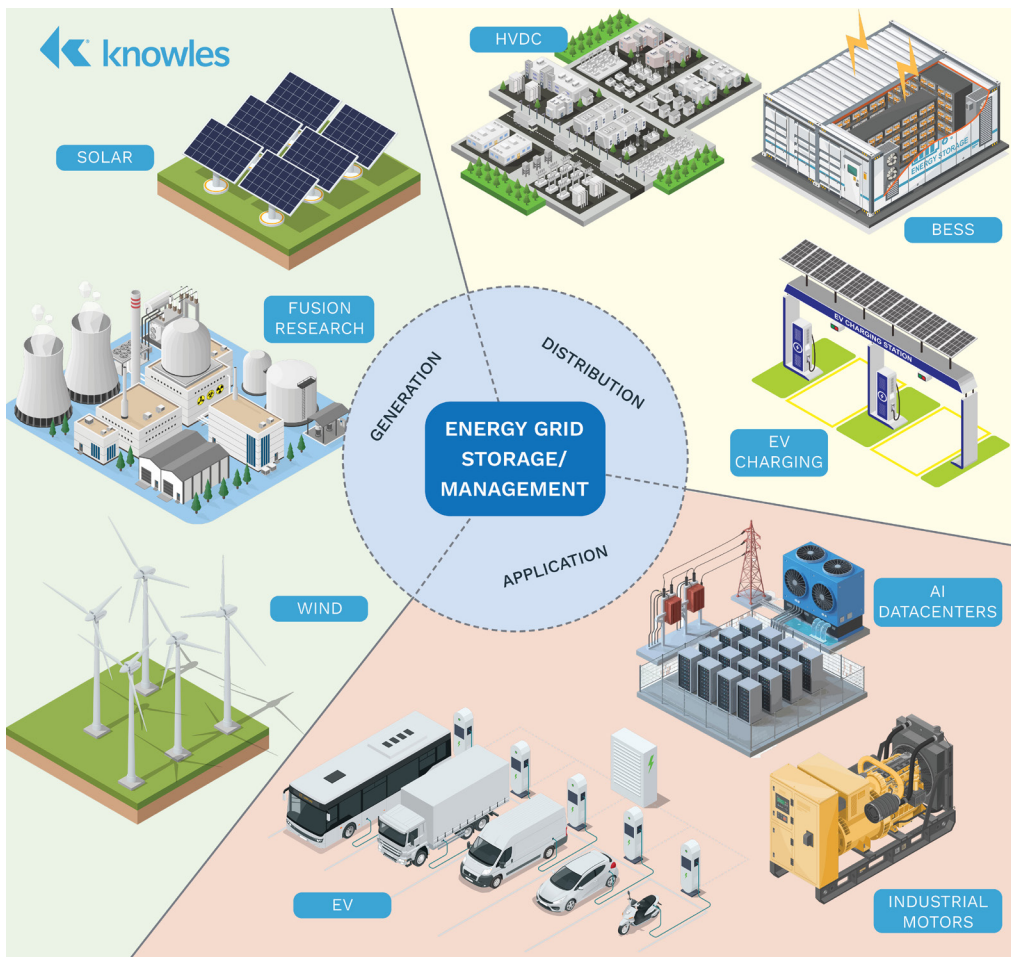
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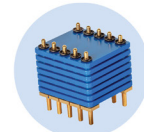
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Energy Generation Is Scaling in Power and Complexity



Capacitors are fundamental to every component of the modern energy system.



Energy generation is rapidly evolving as renewable sources expand and system demands increase. Solar and wind installations are scaling in capacity, operating at higher voltages, and moving into more complex and distributed environments.

The developmental trajectory of many modern power electronics systems is driven by evolving carbon dioxide (CO₂) regulations. By maintaining compliance, green energy production, like photovoltaics (PV) and wind, and high-efficiency distribution systems, like high-voltage direct current (HVDC) and battery energy storage systems (BESS), support the transition to a more sustainable future.



Across power electronics systems, a wider variety of applications now require high-voltage, high-temperature operation, driving new circuit design approaches.

Solar Power: Higher Voltages and Evolving Inverter Architectures

PV cells generate direct current (DC) electricity as they convert sunlight into electrical energy. For this energy to be fed into the electrical grid and used for commercial and residential power, DC must be converted to AC using inverters.

To improve efficiency and reduce transmission losses, solar inverters are evolving toward higher maximum input and output voltages. Today, inverter input voltages have increased from 500V to 1500V. This is possible because of two key developments: lower component costs and the increased adoption of wide band gap (WBG) devices capable of operating at higher voltages.

Across power electronics systems, a wider variety of applications now require high-voltage, high-temperature operation, driving new circuit design approaches. While the cost of silicon carbide (SiC) components still limits adoption in some PV systems, their advantages are enabling lighter, higher-power inverters in the 100 kW range.

At the system level, inverter architectures are also evolving. Traditional centralized inverter designs, which treat an entire PV array as a single voltage source, are being supplemented or replaced by string, multi-string, and microinverter architectures. These distributed approaches improve maximum power point tracking (MPPT), reduce single points of failure, and allow for more flexible system expansion.

Wind Energy: Larger Turbines, Offshore Expansion, and Reliability Demands

Global demand for wind power is surging, driven by increased investment in renewable energy technologies. Over the past decade, technological advancements and operational improvements have decreased the levelized cost of energy (LCOE) for wind. At the same time, turbine output has increased dramatically, with onshore converters reaching 8.5 MW and offshore systems approaching 18 MW.

Offshore wind, in particular, is expanding rapidly. Since 2013, global offshore wind capacity has grown nearly ninefold, with **projections** indicating continued acceleration. Larger turbines can be deployed offshore to take advantage of stronger, more consistent wind conditions. However, these environments introduce new challenges. Harsh operating conditions and remote installations make maintenance difficult, placing a premium on long-term reliability and uptime for all system components.

Fusion Energy: High-Energy Pulses and Extreme Operating Conditions

Beyond established renewable technologies, fusion energy represents a potential source of nearly limitless power. In 2022, the **National Ignition Facility** (NIF) achieved **fusion ignition**, producing more energy than was used to initiate the reaction. This marked a major milestone in fusion research. Fusion experiments require overcoming the intense repulsion between two light nuclei (i.e., the Coulomb Barrier), typically through extreme heat. Under these conditions, it's challenging to keep high-energy plasma in one place (confinement).

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Capacitors play a key role in these systems due to their ability to store and rapidly discharge energy. In NIF's design, large capacitor banks supply energy to nearly 200 pulsed laser beams, delivering high-energy bursts to a target capsule.

Arrays of capacitors, called Marx generators, are used to generate extremely high voltages, while pulse forming networks shape energy delivery to meet precise experimental requirements.

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Power Conversion Is the Control Point of the System

Across renewable energy systems, power conversion is essential to making generated energy usable. In solar applications, this process begins with converting DC electricity into AC power through inverter systems. Capacitors play a key role in these power conversion systems as they smooth and regulate power flow, protect against voltage surges, and filter unwanted signals.

From Centralized to Distributed Architectures

In traditional PV systems, centralized inverter architectures combine multiple panels into a single DC input, presenting the inverter with one aggregated voltage source. While this approach is economical at scale, it doesn't account for real-world operating conditions.

Each PV panel operates at a different optimal point depending on irradiance and temperature. Since the inverter assesses the string of PV panels as a single voltage source, power can't be optimized on a panel-by-panel basis. While a centralized inverter (Figure 1) is an economical choice at scale, it's susceptible to the drawbacks of non-optimal maximum power point tracking (MPPT), where the MPPT algorithm doesn't perfectly align with the actual maximum power point (MPP) of the solar panel array.

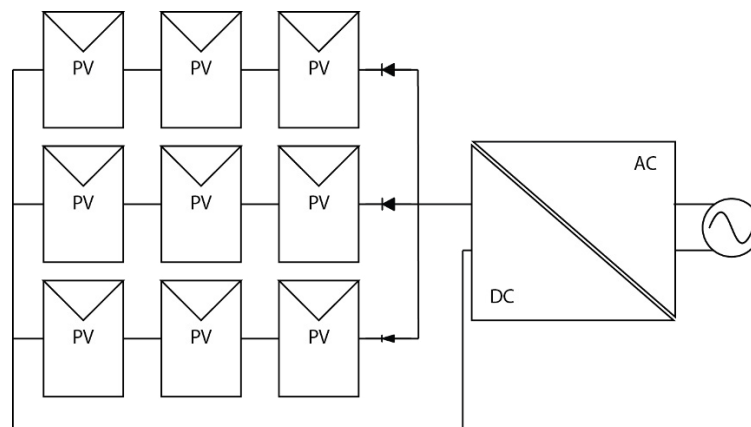


Figure 1: Central inverter PV power plant architecture example.

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To address these limitations, more distributed architectures have emerged.

String inverter architectures connect smaller strings of panels and provide each string with an inverter, so the MPP of each string can be optimized. This presents a scenario with a single point of failure; however, each panel can't be optimized individually. If a string fails to create a high enough DC voltage for its inverter, there are additional inefficiencies to consider. With this string inverter configuration (Figure 2), it's easier to expand the PV system by adding strings.

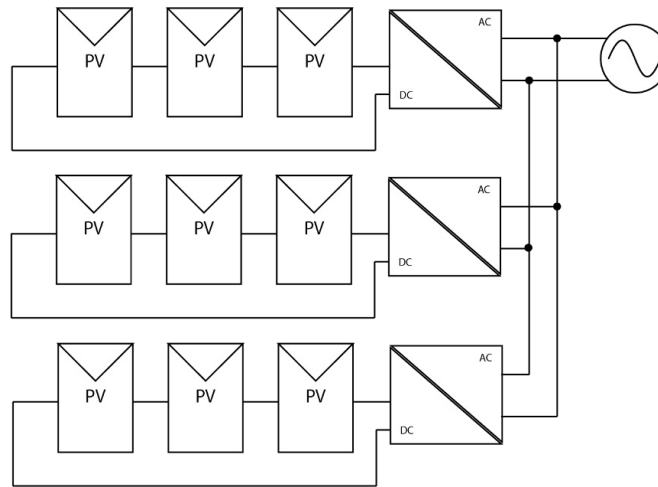


Figure 2: String inverter PV power plant architecture example.

Multi-string inverter architectures (Figure 3) build on this approach by connecting multiple panel strings to a shared DC bus via DC/DC converters. A DC/AC converter exports the energy that was aggregated at the DC bus to the AC system. This configuration retains both the optimal MPP of each string (also achieved by a string inverter) and the added flexibility in string design. As a result, this approach is becoming more popular in large-scale solar plants.

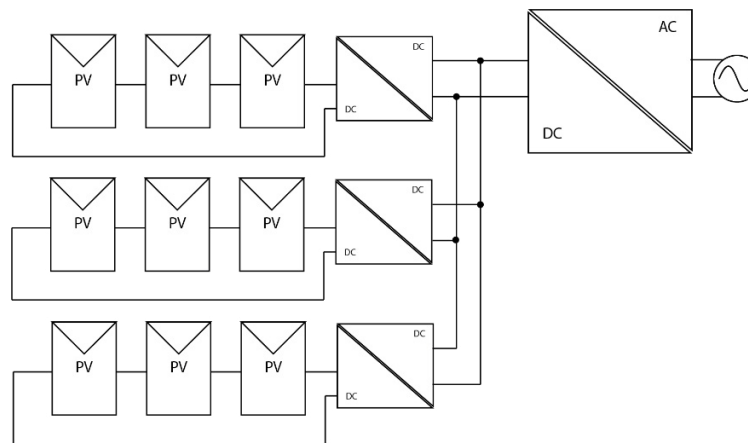


Figure 3: Multi-string inverter PV power plant architecture example.

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Microinverter architectures embrace a modular system configuration through an inverter-per-panel design to minimize single-point failures (Figure 4). While microinverters are a poor choice for near-ideal conditions (e.g., shading-free solar farms), installations are becoming more complex. There are multi-angled roofs, installation costs to consider and lifetime restraints that limit the effectiveness of central inverter installations in residential and commercial settings. Under these conditions, microinverters are growing in popularity.

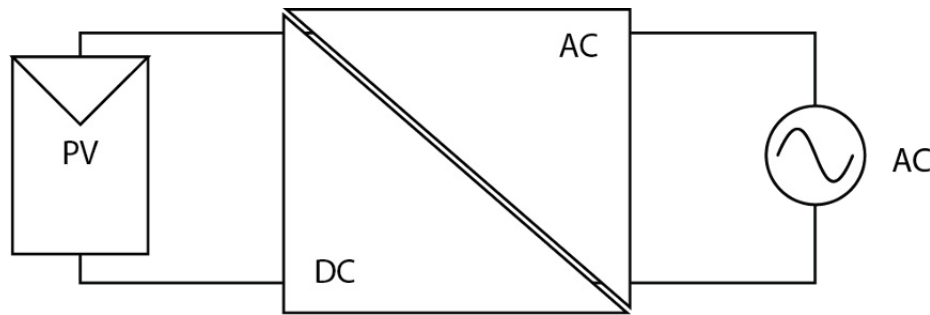


Figure 4: Microinverter PV power plant architecture example.

The industry is moving toward more distributed, flexible designs that improve performance under real-world conditions while reducing system-level risk.

Increasing Voltage and Switching Frequency Trends

To improve efficiency and reduce system losses, modern power conversion systems are moving toward higher maximum input and output voltages. In solar inverters, DC voltages now commonly reach up to 1100V, with commercial and industrial systems exceeding 110 kW. In addition to improving efficiency, higher system voltages can reduce overall component count and system cost, as fewer components may be required in high-voltage designs.

At the same time, switching frequencies are increasing, often exceeding 10–20 kHz and moving into the 100 kHz range with wide band gap semiconductors such as SiC and gallium nitride (GaN).

WBG devices enable operation at both higher voltages and higher switching frequencies, while improving power density and reducing system size. These capabilities are driving the development of lighter, more compact, and more efficient power conversion systems.

However, these advances introduce new challenges. Higher voltages increase electrical and thermal stress on components, while faster switching introduces more complex electromagnetic interference (EMI) behavior that's more difficult to suppress. Additional switching events and complex power flow patterns further complicate system-level noise and stability.

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Within these evolving architectures, capacitors perform several critical functions:

- **DC Link Capacitors** smooth voltage ripple, store energy, and suppress surges
- **AC Harmonic Filter Capacitors** improve power quality by filtering inverter output
- **Snubber Capacitors** protect switching devices from overvoltage during high-speed operation
- **Input/Output Filter Capacitors** stabilize voltage on both supply and load sides

Together, these components enable stable, efficient operation despite increasing system complexity.

Increased electrical stress, faster switching transients, and more complex system interactions introduce new risks that must be managed through careful design and component selection.

Managing Power Quality, EMI, and System Reliability

Increased electrical stress, faster switching transients, and more complex system interactions introduce new risks that must be managed through careful design and component selection.

EMI Challenges in High-Performance Power Electronics

There are multiple interacting factors that impact EMI. For example, differential-mode noise appears between conductors, while common-mode noise propagates through parasitic capacitances to ground. Both must be addressed through careful filter design to maintain system performance and compliance with global standards.

Safety Capacitors in Filtering and Protection Circuits

Safety capacitors are essential components in EMI filtering circuits, designed to mitigate the risks associated with transient voltages and electrical interference. These capacitors are typically classified as Class X (line-to-line) or Class Y (line-to-ground), depending on their function within the system.

In solar inverter applications, safety capacitors (Figure 5) must withstand continuous operating voltages as well as transient over voltages caused by grid disturbances or environmental factors like lightning strikes. They're also responsible for maintaining stable electrical performance across wide temperature and humidity ranges, particularly in outdoor installations.

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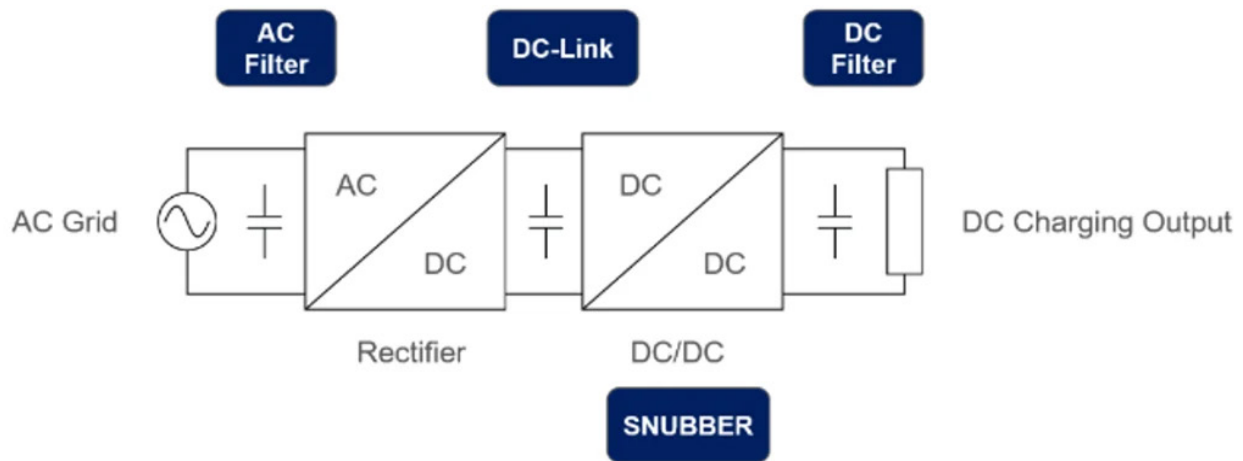


Figure 5: Safety capacitors play key roles in both the DC Filter and AC Filter sections.

High ripple currents demand low equivalent series resistance (ESR) to minimize self-heating and extend capacitor life. Further, compliance with international standards like IEC 61000, CISPR 11, and IEC 62109-1 requires filters that perform reliably across all environmental conditions.

To ensure safe operation over long service lifetimes, these components are designed with self-healing behavior and fail-safe modes. For example, Class Y capacitors are engineered to fail open-circuit to prevent shock hazards, while Class X capacitors may fail short to trigger protective mechanisms like fuses.

Designing for Long-Term Reliability Under Harsh Conditions

Modern power electronics systems are expected to operate reliably for decades, often in demanding environmental conditions. Solar inverters, for example, are typically required to maintain performance for 20 to 25 years while exposed to temperature fluctuations, humidity, and electrical stress.

To meet these requirements, capacitors must maintain stable electrical performance across wide operating ranges, typically from $-40\text{ }^{\circ}\text{C}$ to $+105\text{ }^{\circ}\text{C}$, and withstand prolonged exposure to high humidity conditions, such as biased testing at 85°C and 85% relative humidity for 1,000 hours. As system voltages increase and switching speeds rise, components must also handle higher ripple currents and sustained electrical stress without degradation.



Energy Storage and Grid Stability

Even with optimized conversion and filtering, renewable energy systems introduce variability in both generation and demand. Maintaining consistent, reliable power requires systems that can store energy, stabilize the grid, and respond dynamically to changing conditions.

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Battery Energy Storage Systems and Grid Integration

Battery energy storage systems (BESS) capture, accumulate, and store energy to be discharged when needed, supporting applications ranging from grid stabilization to backup power and operational efficiency.

While systems have different monitoring and control units depending on the application and operating conditions, the main components of a BESS include:

- **Battery System:** Contains battery cells arranged into battery packs; responsible for converting chemical energy into electrical energy
- **Battery Management System (BMS):** Monitors, balances and protects the battery system to ensure its longevity, safety, and efficiency
- **Inverter or Power Conversion System (PCS):** Converts the DC produced by batteries into AC to power homes and facilities; bi-directional inverters accommodate both charging and discharging
- **Energy Management System (EMS):** Monitors and controls the energy flow in the battery storage system by coordinating the work of the BMS, PCS, and other BESS components to manage power resources effectively

Supporting Renewable Integration and Load Balancing

As solar and wind generation expand, their intermittent nature introduces fluctuations in power supply. BESS help balance these fluctuations by storing excess energy during periods of high generation and releasing it when demand increases or generation decreases.

These systems also provide essential grid services, including frequency stabilization, voltage support, and black-start capability, allowing systems to recover quickly from outages and maintain stable operation.

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HVDC Transmission and Long-Distance Efficiency

As renewable generation shifts to remote locations, efficient long-distance transmission becomes increasingly important. High-voltage direct current (HVDC) systems enable electricity to be transmitted over long distances with reduced energy loss, supporting large-scale grid interconnection and improving overall system efficiency.

Modern HVDC systems operate at higher voltages and switching frequencies, enabling efficient power transfer from generation sites to high-demand regions while minimizing transmission losses.

Capacitors in Storage and Distribution Systems

At the component level, capacitors enable reliable operation across both storage and transmission systems as these systems scale in voltage, size, and complexity.

In BESS, capacitors within power conversion stages must support high-voltage operation, often approaching 1.5 kV, while maintaining performance over long service lifetimes. These systems depend on high-reliability capacitors to ensure efficient operation, maximize uptime, and support modular, scalable architectures (Figure 6).



Figure 6. An example BESS.

In HVDC transmission systems, capacitors operate under similarly demanding conditions, supporting high-voltage, high-frequency conversion required for long-distance power transfer. As renewable generation sites move further from demand centers, these systems rely on capacitors to maintain stable operation while minimizing transmission losses.

Fast Response Power for Critical Systems

While grid-scale storage supports long-duration energy needs, many systems require immediate power delivery during faults, interruptions, or transient events. In these scenarios, even short delays between power loss and backup generation can result in system failure, equipment damage, or safety risks.



The Limitations of Batteries in High-Power, Short-Duration Events

Batteries are widely used for backup power, but they present limitations in applications that require rapid, high-power response. With limited power surge capabilities, capacity degradation over time, and a finite number of charge and discharge cycles, batteries are not designed to deliver the immediate bursts of energy needed in short-duration events. Compared to supercapacitors, which can withstand hundreds of thousands to millions of cycles, batteries typically support only a few thousand charge and discharge cycles before performance degrades.

Environmental conditions further impact battery performance. Exposure to extreme temperatures can accelerate degradation, reducing reliability and increasing maintenance requirements, particularly in remote or hard-to-access installations.

Unlike batteries, supercapacitors store energy electrostatically rather than chemically, resulting in significantly longer lifespans and the ability to handle hundreds of thousands to millions of charge and discharge cycles with minimal degradation.

Supercapacitors for Rapid Response

Supercapacitors, or ultracapacitors, are energy storage devices designed for high-power, rapid-response applications. With capacitance values millions of times greater than traditional capacitors, they can deliver quick bursts of energy with minimal delay.

Unlike batteries, supercapacitors store energy electrostatically rather than chemically, resulting in significantly longer lifespans and the ability to handle hundreds of thousands to millions of charge and discharge cycles with minimal degradation.

They also operate across a wider temperature range, maintaining performance in environments from -40°C to 70°C, and exhibit high efficiency with minimal energy loss during charging and discharging cycles.

In many systems, supercapacitors are used to bridge the gap between an initial power interruption and the activation of long-term backup power sources (e.g., generators or battery systems). Facilities like data centers and hospitals rely on immediate power availability to maintain continuous operation of essential systems. In industrial and building systems, backup power ensures that actuators, valves, and control systems can return to safe states during outages.

In electrical grids, supercapacitors are increasingly used in reclosers, which automatically isolate and restore power following faults. These systems require a temporary power source to operate during low-voltage conditions or outages. While batteries have traditionally been used for this purpose, their limited lifespan and maintenance requirements present challenges, particularly in remote deployments. Supercapacitors offer an alternative solution with high power density, long service life, and reliable performance across a wide range of environmental conditions.

That said, supercapacitors do not replace BESS; they complement them. While batteries are designed for sustained energy delivery over longer periods, supercapacitors excel in delivering immediate, high-power responses.



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Together, these technologies enable a more resilient energy system, combining long-duration storage with fast-response capability to support both grid stability and system reliability.

The Critical Role of Capacitors in an Electrified Future

Capacitors serve as a critical enabling component in the energy ecosystem. They support efficient power conversion, help maintain stable operation under demanding conditions, and enable both sustained and rapid energy delivery where it's needed most. As energy systems scale and diversify, the role of capacitors will remain central to meeting performance requirements and ensuring the reliability and resilience of modern power infrastructure.



ABOUT THE AUTHOR

Peter Matthews

Peter Matthews is Director of Technical Marketing at Knowles, a market leader and global provider of high-performance capacitors, RF filtering products, and advanced micro-acoustic microphones and balanced armature speakers for MedTech, defense, electrification, and industrial markets. Peter has more than 20 years' experience in technology sales, marketing, and product management.