White Paper

Familiar Jobs, Harder Conditions: How Electrification Is Redefining the Capacitor's Role

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Capacitors are fundamental to moving and managing electrical power, performing functions such as storing energy, smoothing voltages, and filtering the byproducts of switching in power converters. But as electrification transforms how electricity is generated, converted, and consumed, the demands placed on those familiar functions are changing.

For example, as rotating generators give way to inverter-based resources and mechanical and electromechanical systems are rebuilt around power electronics, grid stability and equipment reliability increasingly depend on components that have historically operated behind the scenes. As a result, capacitor selection is becoming more complex as engineers need to match the right technology to increasingly demanding electrical functions.

Rather than viewing electrification through the lens of power systems or grid infrastructure, this paper explores it from the capacitor outward, showing how familiar electrical functions are being performed in increasingly demanding environments.

The Fundamental Jobs Capacitors Do

Every capacitor used in power electronics performs one or more of the following four fundamental electrical functions:

- **Electrostatic energy storage** – The capacitor stores energy in its electric field, governed by $E = \frac{1}{2}CV^2$, and releases it on demand.
- **Impedance-based filtering** – Because a capacitor's impedance decreases as frequency increases, it can attenuate unwanted frequencies while allowing the desired electrical signal or power to pass.
- **Resonant energy exchange** – Energy oscillates between a capacitor and an inductor at a defined resonant frequency, enabling resonant power conversion.
- **Signal coupling and transfer function shaping** – A capacitor passes or blocks portions of an electrical signal to shape a signal path or control loop response.

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While these four functions remain fundamental to power electronics, electrification is placing new demands on two in particular: filtering and energy storage. As power conversion stages increase and operate at higher voltages, switching frequencies, and power densities, these familiar functions become even more critical to system performance and reliability.

In modern power conversion systems, these functions are primarily performed by two capacitor technologies: the film DC link capacitor and the supercapacitor. Let's take a closer look at each one.

The Film DC Link Capacitor: Filtering and Storage in One Component

In nearly every modern power converter, inverter, motor drive, and onboard charger, there is a DC bus: an internal rail of direct current sitting between the power source (a battery, grid connection, or solar string) and the electronic switches that convert that power into the form the load needs. The capacitor connected across that bus is the DC link capacitor, and it performs both energy storage and filtering.

On the storage side, the DC link capacitor supplies the rapidly changing currents demanded by the switching bridge. The switches draw power in sharp pulses, far faster than the source behind them can respond, so the capacitor acts as a local energy reservoir, delivering power when needed while decoupling the switching bridge from the relatively slow, high-impedance source.

On the filtering side, the switching action generates ripple: rapid, repetitive fluctuations in current and voltage superimposed on the DC bus. This ripple stresses, and can damage, semiconductors and other components sharing the bus. It also heats the capacitor itself because ripple current flowing through the capacitor's internal resistance dissipates power as heat ($P = I^2 \times ESR$). Capacitor life is halved for roughly every 10 °C rise in operating temperature, making ripple current handling one of the primary specifications that determines how large the DC link capacitor must be.

Figure 1. Power film capacitors for DC applications provide stable, low-loss energy storage and filtering for high-voltage systems

This combination of duties at the intersection of high voltage, high ripple current, and long-life requirements, is why the DC link capacitor is often in the most demanding capacitor role in a power converter. For example, DC link capacitors in an 800 V electric vehicle traction inverter may be required to carry more than 100 A of continuous ripple current over a 15-year service life.

For decades, aluminum electrolytic capacitors served this role because they were inexpensive and stored a great deal of energy in a small space. However, their relatively high ESR increases self-heating, their liquid electrolyte gradually dries out, and their service life is typically limited to 3,000 to 5,000 hours at rated temperature. They also cannot recover from internal dielectric faults.

Film capacitors, built on a thin metallized polypropylene dielectric rather than a liquid electrolyte, resolve these problems. They handle far more ripple current without overheating, operate across a wider temperature range, and self-heal, which means if a microscopic weak spot in the film breaks down, the capacitor essentially seals off that spot on its own and keeps working.

Film DC link capacitors can exceed 100,000 working hours, which is 20 to 30 times the typical electrolytic capacitor service life. The difference in size can also be substantial. In a representative 10 kW DC-DC converter, a film-based DC link solution can occupy less than 150 cm^3 while dissipating roughly one watt of power, whereas a functionally equivalent electrolytic solution can exceed 1,000 – 2,000 cm^3 and dissipate several watts.

The Supercapacitor: Storage Between the Capacitor and the Battery

A supercapacitor, also called an electric double-layer capacitor (EDLC), is designed to store large amounts of energy and release it almost instantly. It bridges the gap between a conventional capacitor and a battery, storing orders of magnitude more energy than a standard capacitor while delivering and absorbing that energy far faster than any battery chemistry can.

Supercapacitors complement batteries rather than compete with them. A battery stores energy in chemical reactions, which gives it high energy density and long runtime for its size, but limits how fast it can deliver or absorb power and how many times it can be cycled before the chemistry degrades.

Figure 2. Supercapacitors are designed to store large amounts of energy and release it almost instantly

A supercapacitor stores energy directly in an electric field at the surface of high-area carbon electrodes. Because no chemical reaction is involved in storing or releasing energy, it responds in milliseconds and can sustain more than 500,000 full charge-discharge cycles with only minimal degradation, compared with roughly 2,000 to 5,000 cycles for a typical lithium-ion battery. The two technologies pair naturally, with the battery providing endurance and the supercapacitor providing speed and exceptional cycle life.

Supercapacitors are used in applications that take advantage of these characteristics, including holdup and ride-through energy in uninterruptible power supplies, regenerative braking capture in vehicles, backup power for wind turbine blade pitch systems, and burst-power buffering in drones.

Electrification as the Driving Force

The familiar capacitor functions have not changed, but the number of places they are performed, and the conditions under which they are performed, have.

Electrification is commonly understood as replacing technologies powered by fossil fuels with technologies powered by electricity. While that definition is accurate, it's also incomplete. The broader shift underway is the replacement of mechanical and electromechanical systems with power electronic ones: a synchronous generator gives way to an inverter-based resource, a fixed-speed motor to a variable frequency drive (VFD), a conventional transformer to a solid-state transformer (SST). This is what is referred to as technology densification.

This broader perspective explains why capacitors are central to the story. Every power conversion stage that electrification adds is built around fast-switching semiconductors, and each stage relies on capacitors to hold its DC bus steady, filter switching noise, and store and release energy fast enough to keep the surrounding system stable. As electrification multiplies conversion stages, it also multiplies the places where capacitor performance influences system reliability, efficiency, and stability. The familiar capacitor functions have not changed, but the number of places they are performed, and the conditions under which they are performed, have.

Applying Familiar Capacitor Functions in Emerging Power Systems

Let's look at three emerging applications to see how familiar capacitor functions are being applied in new ways as electrification reshapes modern power systems.

The Solid-State Transformer

An SST is a power-electronics-based replacement for the conventional transformer. It performs the same voltage-changing job, but instead of a passive magnetic core at 50/60 Hz, it converts incoming AC to DC, processes it through fast-switching converter stages, passes it through a compact high-frequency transformer, and converts it back to the form the load requires.

Because transformer size is inversely proportional to operating frequency, the high-frequency stage makes the SST dramatically smaller and lighter for the same power. And because power now flows through controllable electronics rather than passive iron, the SST can regulate voltage, correct power factor, and control power flow bidirectionally, functions that previously required separate equipment alongside the transformer.

For capacitors, the significance is architectural rather than functional. The filtering and energy storage functions have not changed, but an SST multiplies where those functions are performed. Every SST contains at least one internal DC link, and most contain several at different voltage levels — one on the medium-voltage side, one at the isolation stage, and one at the output. Each DC conversion stage requires a DC link capacitor performing the same energy storage and filtering functions discussed earlier.

The exposed DC bus also provides a convenient integration point for dedicated energy storage. The energy stored in the DC-link capacitors can sustain the output briefly through a disturbance, while a supercapacitor bank connected to the same bus can extend that ride-through capability substantially.

The E-STATCOM

A STATCOM (static synchronous compensator) is a grid-connected power electronics device that regulates voltage by exchanging reactive power with the electrical system. Built around a voltage-source converter, it relies on a DC link capacitor to stabilize its internal DC voltage. A conventional STATCOM, however, cannot exchange real power. It regulates voltage but has no meaningful energy reserve.

An E-STATCOM adds that energy reserve. By integrating energy storage, typically supercapacitors on the converter's DC side, the device gains a second capability: injecting or absorbing real power for the critical seconds after a disturbance, providing the ability to respond to frequency events as well as voltage events. The world's first E-STATCOM is now in operation in Mehrum, Germany. Siemens Energy's SVC PLUS FS® commissioned with transmission operator TenneT in December 2025 combines a 300 MVA modular multilevel converter with supercapacitor banks capable of delivering ±200 MW of active power within milliseconds, in roughly one-third the footprint of an equivalent battery installation.

Virtual Inertia

One of the clearest expressions of what electrification is asking energy storage to become, that is not a device but a function, is virtual inertia. In a traditional grid, stability in the first moments after a disturbance is provided naturally by physics. The spinning rotors of synchronous generators store kinetic energy. When a fault or sudden loss of generation pulls frequency down, that rotating mass resists the change, releasing stored energy instantly. This inertia buys the time slower control systems need to respond. Inverter-based resources, including solar, wind, and battery energy storage systems (BESSs), do not have a rotating mass, so as they displace synchronous generators, the grid's inherent inertia declines.

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The consequences of operating a low-inertia, inverter-dominated grid became visible in the Blue Cut fire event of August 2016, when brush fires in southern California caused faults on the 500 kV transmission system and nearly 1,200 MW of utility-scale solar generation abruptly ceased output. The plants were not damaged. Instead, their inverter controls misinterpreted the disturbance as frequency and voltage excursions, causing them to stop injecting current, some for several minutes. The event demonstrated how differently inverter-based resources behave during disturbances, and how much a modern grid needs fast-acting stabilization.

Virtual inertia instead combines a control system with a fast energy buffer, programmed to detect a frequency excursion and inject or absorb real power in much the same way a rotating mass would. The control algorithm supplies intelligence, but the energy buffer supplies the physics, and the buffer's requirements are exacting. It must deliver full power within milliseconds, cycle constantly as it tracks small frequency movements, and do so for years without degradation. These requirements are why supercapacitors have emerged as a preferred storage technology for many virtual inertia applications. The size of the buffer determines how long the emulated response can be sustained, and therefore the effective inertia the device contributes.

How Electrification is Reshaping Capacitor Functions

The three examples above illustrate a common pattern: whether inside an SST, an E-STATCOM, or a virtual inertia system, capacitors are still performing the familiar functions of filtering and energy storage. What has changed is the environment in which those functions must operate. Higher switching speeds, greater power densities, and longer-duration energy demands are reshaping the criteria engineers use to select capacitor technologies.

Filtering: From Capacitance to Impedance

In general, filtering is moving up in frequency. In conventional power systems, capacitor behavior was often evaluated primarily at the 50/60 Hz fundamental and lower-order harmonics. Today's converters switch at tens to hundreds of kilohertz, and wide-bandgap (WBG) silicon carbide (SiC) and gallium nitride (GaN) semiconductors drive voltage transitions that commonly exceed 50 volts per nanosecond, with some devices surpassing 100 V/ns.

At these speeds, a capacitor's nominal capacitance alone is no longer sufficient to predict behavior. Equivalent series inductance (ESL) contributes directly to voltage overshoot during switching events ($\Delta V = ESL \times di/dt$), so even 15 nanohenries of parasitic inductance can generate significant transients. ESR drives self-heating under increased ripple current and therefore influences capacitor life.

Meanwhile, the traditional remedy of simply adding more capacitance is becoming less effective. Modern converter architectures operating at much higher switching frequencies demand more sophisticated filtering strategies. For example, research on SST converter stages has found that doubling DC link capacitance produced only slight improvement in harmonic current suppression.

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Filtering can no longer scale up; it has to become more precise. The emerging best practice is a hybrid, frequency-banded approach: film capacitors handle bulk storage and most of the ripple current, while ultra-low-ESL ceramics placed within millimeters of the switching devices handle the highest-frequency transients where film inductance becomes limiting. The goal is to maintain a low-impedance profile from DC through several megahertz, a multiband approach long used for IC decoupling, now applied at power-converter and grid-equipment scale.

Energy Storage: From Burst to Sustained Delivery

Energy storage is stretching in duration. Many traditional supercapacitor applications were measured in milliseconds or fractions of a second. But newer electrification applications extend that demand into seconds. They may require storage to ride equipment through interruptions or sustain an emulated inertial response until slower reserves take over. In these cases, total delivered energy matters as much as response speed. Buffer sizing has become a first-order design decision as it sets how long a system can stand on its own, and in inertia applications, how much stability the device contributes.

That pull toward longer duration is reshaping storage design at the component and system levels. Designers are now using solutions such as:

- Larger series-parallel supercapacitor banks with module-level cell balancing
- Hybrid architectures that pair supercapacitors with batteries so each technology serves its natural timescale
- Hybrid lithium-ion capacitors that trade some cycle life for several times the energy density of a standard EDLC when runtime matters more than maximum cycle count

The result is that energy storage is no longer defined simply by how quickly it can respond, but by how long it can sustain system performance once that response begins.

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Taken together, these changes in filtering and energy storage illustrate how electrification is reshaping capacitor selection. Engineers must now optimize not only capacitance, but also impedance, thermal performance, lifetime, and the duration of energy support required by increasingly demanding power conversion systems.

Capacitor Selection for the Electrified Future

As discussed, electrification is not inventing new capacitor functions. Filtering and energy storage remain the same fundamental electrical jobs they have always been. What is changing is the environment in which those functions must operate. Higher switching frequencies elevate ESR and ESL from secondary considerations to primary design constraints. Increasing ripple currents make thermal performance inseparable from reliability. Energy storage is extending from millisecond transients to sustained, seconds-long support that enables grid stability. In short, across applications, the underlying physics remain familiar, but engineering requirements continue to intensify.

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For design engineers, this shift is changing how capacitors are selected as engineers must place more emphasis on considerations such as impedance across frequency, ripple current capability, thermal performance, operating lifetime, and the role each capacitor plays within the broader power conversion architecture. For decades, Knowles has supported these evolving requirements by supplying capacitors for renewable energy systems, battery energy storage, transportation electrification, industrial power conversion, and grid-support applications.

Our portfolio of film capacitors, supercapacitors, and hybrid capacitor technologies is intentionally designed for the higher voltages, faster switching speeds, and longer operating lifetimes demanded by modern SiC- and GaN-based power electronics. Whether you need a standard component or a custom solution, our applications engineers can help optimize capacitor selection for your topology, balancing electrical performance, thermal management, and long-term reliability.

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Explore Knowles' portfolio of film capacitors and supercapacitors as well as our custom capacitor solutions for grid and power conversion applications. Or, to discuss your next power electronics design, contact our engineering team.

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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.