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The Role of Capacitors in High-Energy Pulsed Power Systems

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Like a thunderclap captured in a circuit, high-energy pulsed power systems deliver rapid, precisely controlled energy. They are foundational to technologies across defense, medical, scientific, and renewable energy sectors as they power everything from electromagnetic launch systems and particle accelerators to defibrillators, pulsed lasers, and experimental fusion research.

At the core of these systems are capacitors. Their ability to charge gradually and release energy almost instantaneously makes them uniquely suited for pulsed power environments; however, delivering energy is only part of the challenge. Engineers must also control pulse shape, duration, repetition rate, and thermal behavior, all of which are influenced by capacitor characteristics and how they integrate into the broader system.

With decades of experience in pulse discharge capacitor design and manufacturing, Cornell Dubilier and Knowles bring deep application knowledge and proven component reliability to pulsed power systems. Here we'll cover the key principles and components behind pulsed power systems with a focus on how capacitors are selected, configured, and applied to meet the demanding requirements of modern high-energy applications.

RLC Circuits in Pulsed Power Applications

RLC circuits, composed of a resistor (R), inductor (L), and capacitor (C), are common in many pulsed power systems because of their natural ability to store and transfer energy for fast, controlled energy bursts (Figure 1). The behavior of an RLC circuit, particularly during rapid energy discharge, determines the shape and characteristics of the resulting pulse.

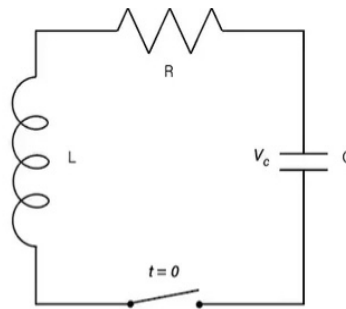


Figure 1. Series RLC circuit.

When a switch closes in a series RLC circuit, the current response depends on the damping ratio, ζ , which reflects how quickly the energy oscillates and dissipates. Two RLC circuit parameters can be used to understand a system's damping ratio: neper frequency and resonant angular frequency.

Find the neper frequency, α , using:

$$\alpha = \frac{R}{2L}$$

The resonant angular frequency, ω_0 , indicates what frequency a system will oscillate at:

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

In combination, these parameters can be used to calculate the damping factor and identify which mathematical model would best represent the system's behavior.

The value for ζ places the system into one of three categories:

Case 1: Overdamped: $\zeta > 1$

Case 2: Critically Damped: $\zeta = 1$

Case 3: Under Damped: $\zeta < 1$

Where:

$$\zeta = \frac{\alpha}{\omega_0}$$

When $\zeta > 1$, apply the following equation:

$$i(t) = \frac{V}{L(s_1 - s_2)} e^{s_1 t} - \frac{V}{L(s_1 - s_2)} e^{s_2 t}$$

Where:

$$s_{1,2} = -\alpha \pm \sqrt{\alpha^2 - \omega_0^2}$$

When $\zeta = 1$, apply the following equation:

$$i(t) = \frac{V}{L} t e^{-\alpha t}$$

When $\zeta < 1$, apply the following equation:

$$i(t) = \frac{V}{L\sqrt{\omega_0^2 - \alpha^2}} e^{-\alpha t} \sin\left(\sqrt{\omega_0^2 - \alpha^2} t\right)$$

See [Foundations of Pulsed Power Technology](#) by Jane Lehr and Pralhad Ron for detailed derivations.

These expressions help us understand the system's time-domain response. Underdamped systems exhibit oscillations that gradually decay as energy transfers between the capacitor and inductor before dissipating. Critically damped systems return to zero current as quickly as possible without oscillating, offering the fastest non-oscillatory response. Overdamped systems also avoid oscillation, but the current decays more slowly, making the response more sluggish than in the critically damped case.

Figure 2 illustrates these three behaviors, showing how current evolves over time for different damping ratios.

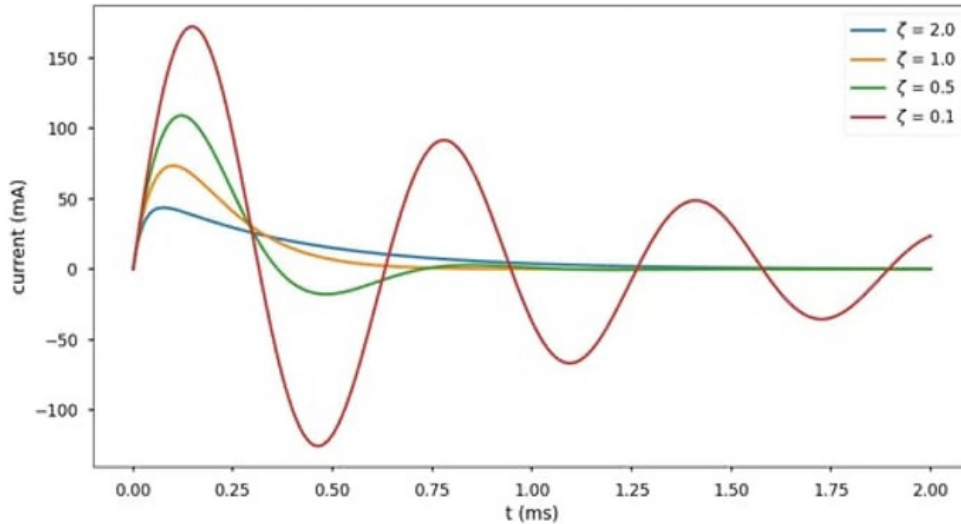


Figure 2. Current over time for various damping ratios in an RLC circuit.

Understanding these dynamics is key when designing pulsed systems that require precise control over pulse shape, duration, and peak current.

Specifying Capacitors for High-Energy Pulse Applications

With their role in storing and releasing energy in mind, capacitors selection is an important consideration for RLC circuits within pulsed power systems.

Selecting the right capacitor starts with understanding the required capacitance, which determines how much energy the system can store based on the relationship:

$$\frac{1}{2}CV^2$$

where C is capacitance (F) and V is the charging voltage (V).

However, the capacitor's performance in a pulsed power application depends on more than just energy storage. It's critical to evaluate how the capacitor interacts with the overall RLC network. The values of resistance, inductance, and capacitance collectively shape the system's response, including ringing frequency, voltage reversal, and pulse width. These parameters are directly tied to the damping behavior and are influenced by how quickly the capacitor must charge and discharge.

Capacitor selection also accounts for parameters like equivalent series resistance (ESR) and equivalent series inductance (ESL), which affect how efficiently energy is delivered and how much the component heats during operation. In high-energy applications, even small inefficiencies can lead to significant thermal stress and reduced reliability.

Different capacitor technologies offer trade-offs in terms of ESR, ESL, voltage rating, and form factor. For instance, ceramic capacitors typically have low inductance and fast response times but may have lower capacitance values compared to film or electrolytic options. Engineers need to balance electrical performance with physical constraints and reliability under repeated pulse conditions in the selection process.

Energy and Power Density in Capacitor Selection

In pulsed power systems, choosing the right capacitor often means working within tight physical and thermal constraints. That's why it's essential to understand how energy storage and delivery relate to both size limitations and electrical performance. Two concepts that become especially relevant in this context are energy density and power density.

Energy density refers to how much energy a capacitor can store relative to its volume. This metric becomes particularly important when physical space is limited, as it often is in high-energy systems. A higher energy density allows for greater energy storage in a smaller footprint.

Power density, on the other hand, describes how quickly the stored energy can be discharged into the load. While power output is tied to voltage and capacitance, it's heavily influenced by the capacitor's ESR. Lower ESR allows for faster discharge and higher peak currents, making it a key factor in maximizing power delivery.

Energy and Power Density Math

Calculate the energy stored in a capacitor using:

$$E_r = \frac{1}{2} C V_r^2$$

where C is capacitance and V_r is the voltage rating of the capacitor.

To find the volumetric energy density of a capacitor, divide E_r by volume:

$$\gamma_v = \frac{E_r}{Vol}$$

The power rating of a capacitor can be estimated from the rated voltage and current as:

$$P_r = V_r I_r$$

Power density is P_r divided by volume:

$$\rho_v = \frac{P_r}{Vol}$$

Alternatively, another approach to determining power density is to examine the impedance-matched condition, where the load matches the source impedance (i.e., the capacitor's ESR). Under these conditions, we find:

$$P_{im} = \frac{V_r^2}{4 \times ESR}$$

Then, power density is calculated as:

$$\rho_{Vim} = \frac{P_{im}}{Vol}$$

In general, ceramic capacitors offer excellent power density due to their inherently low ESR, enabling them to deliver sharp, high-current pulses with minimal internal losses. Film capacitors, on the other hand, often provide higher energy density, making them well-suited for applications where total energy storage is more critical than discharge speed.

Additionally, since ESR contributes to heating during discharge, power density is often thermally limited. In high-repetition-rate systems, thermal stress can lead to elevated temperatures, affecting both short-term performance and long-term reliability.

Understanding and balancing energy density, power density, ESR, and thermal behavior ensures capacitors can meet both electrical and environmental requirements of the system without compromise.

High-Energy Capacitor Banks in Pulsed Power Applications

Since total energy stored is directly related to capacitance, individual capacitors often can't meet the demands of high-energy applications on their own. Engineers leverage capacitor banks to scale up capacitance and energy storage for applications in fields like plasma research, where extremely high voltages and currents must be released in precise, controlled bursts.

In a capacitor bank, shown in Figure 3, engineers combine multiple capacitors in series, parallel, or hybrid configurations to meet specific electrical and physical requirements.

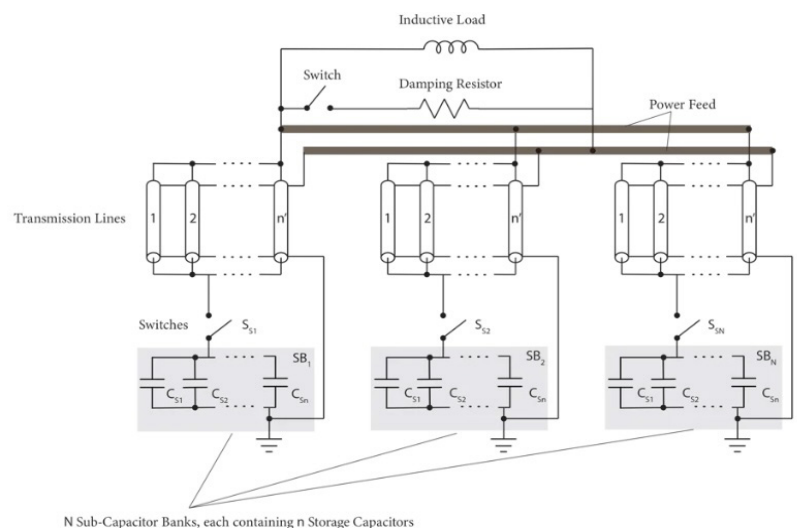


Figure 3. This high-energy capacitor bank system is composed of N sub-capacitor banks, each containing n energy storage capacitors. C represents the capacitance of each energy storage capacitor. The result is a total equivalent capacitance of nNC .

In a parallel configuration, capacitors are added together to increase total capacitance, allowing for greater energy storage. In series configurations, voltage rating is increased for applications operating at very high voltages. Engineers must also account for balancing resistors, discharge circuits, and safety considerations when working with large capacitor banks.

Because each capacitor in the bank contributes to the overall energy delivery, the selection of capacitance value, ESR, ESL, and physical form factor still matters. ESR affects individual capacitor performance, but it also determines how uniformly current is shared across the bank. That uniformity ensures system reliability and pulse fidelity.

By scaling energy storage through capacitor banks, engineers can meet the demanding energy and power requirements of advanced pulsed systems while tailoring performance to application-specific constraints.

Generating High Voltages Using Marx Generators

Charging high-energy capacitor banks often requires voltage levels well beyond what a single power supply can directly deliver. To achieve these extreme voltages quickly and efficiently, many pulsed power systems use Marx generators.

A Marx generator is a high-voltage pulse generation topology designed specifically for applications that require nanosecond to microsecond-scale discharges.

They operate by charging multiple capacitors in parallel through resistors and then discharging them in series through spark gaps or solid-state switches. This process multiplies the input voltage across each stage, resulting in a single, high-voltage output pulse. For example, a Marx generator with ten stages, each charged in parallel to 20 kV, can theoretically deliver a 200 kV pulse when the stages are discharged in series.

Because the energy stored in a capacitor scales with the square of the voltage, achieving high voltage is a key step toward maximizing total energy storage. Marx generators are especially valuable in systems where rapid, high-voltage pulses are needed. They multiply voltage efficiently, and that multiplied voltage can be used to charge a large capacitor bank. Their modularity and scalability make them ideal for experimental platforms where pulse energy requirements evolve over time.

Shaping Pulses with Pulse Forming Networks

Once a capacitor bank is charged, the next step is to shape the resulting pulse to meet system requirements. Although the RLC network provides the basic discharge, its natural waveform may not offer the ideal rise time, duration, or peak amplitude for the load. To achieve more precise control, engineers implement pulse forming networks (PFNs) that modify the pulse profile for optimized energy delivery.

A PFN, shown in Figure 4, is a circuit built from inductors and capacitors arranged to produce specific waveforms. They're commonly implemented in several forms, depending on space, performance, and waveform requirements:

- Transmission lines, including coaxial cables and stripline geometries, connected in specific configurations generate defined pulses.
- LC ladder networks, which use alternating inductors and capacitors to simulate transmission line behavior, are useful when physical space constraints make full-length lines impractical.
- Blumlein lines, a specialized transmission line configuration, are effective when ultra-fast rise times are a priority and space can be managed accordingly.

In many systems, engineers design lumped-element PFNs to mimic the physics of transmission lines in a more compact footprint. By replacing physical line length with carefully chosen inductors and capacitors, they can produce longer or more precisely shaped pulses without relying on bulky cables or oversized structures.

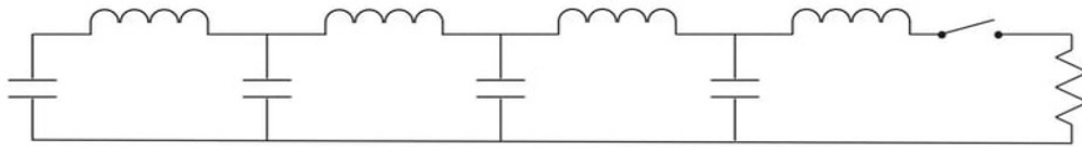


Figure 4. The Type E Guillemin network is a widely used PFN topology.

They typically produce flat-topped, rectangular pulses or sharply peaked impulses based on the needs of the application. Whether the goal is to minimize voltage overshoot, match impedance, or deliver energy uniformly over a defined duration, a PFN enables precise pulse shaping at the output of the capacitor bank.

Matching the PFN's impedance to the load minimizes energy reflection and maximizes power transfer. For example, in plasma physics or other high-voltage or high-current systems, the load may require a clean, rectangular pulse to ensure predictable performance or measurement accuracy.

PFNs are usually triggered by fast-switching devices (e.g., spark gaps or solid-state switches) and integrated as the final stage of the pulse generation system.

The Role of Capacitors in the Future of Energy

From RLC circuits to pulse forming networks, each stage of a pulsed power system is designed to control how energy is stored, shaped, and delivered. These systems power some of the most ambitious scientific experiments in the world.

Fusion research is a great example. Companies across the globe are engaged in fusion research; some are large national and international labs while others are start-ups looking for lower-cost alternatives to traditional fusion techniques.

After decades of experiments in nuclear fusion, in 2022, the [National Ignition Facility \(NIF\)](#) achieved [fusion ignition](#), where more energy was produced from fusion than was used to trigger it. Fusion is positioned as an attractive option in the face of climate change because it's a potential source of nearly limitless energy. With that in mind, fusion ignition was lauded as a breakthrough achievement.

In these experiments, physicists and engineers are tasked with overcoming the intense repulsion between two light nuclei when they're forced together (i.e., the Coulomb Barrier). This is traditionally accomplished using very high heat. Under those conditions, it's challenging to keep high-energy plasma in one place (i.e., confinement).

There are two main approaches to confinement. Magnetic confinement is achieved by arranging strong magnetic fields to hold the hot, dense plasma in place. Inertial confinement is achieved by compressing the plasma from all sides simultaneously. In either case, achieving fusion depends on concentrating and maintaining that high temperature and pressure in the center of the ignition chamber. The NIF experiment leveraged inertial confinement.

Capacitors play a key role in these exciting experiments with their energy storage capabilities. In [NIF's experiment design](#), lasers are the initial energy source. The system draws energy from a massive capacitor bank for nearly 200 pulsed laser beams and rapidly releases that energy at the target capsule. Marx generators are responsible for the incredibly high voltage requirements, and by implementing PFNs, physicists and engineers can shape the pulse of energy to meet their experimental needs.

Outside of fusion experiments, physicists and engineers leverage the energy storage capabilities of capacitors for [short pulses](#) of high-voltage, high-current energy in plasma physics experiments. This includes flash radiography, x-ray generation and weapons effects simulation (e.g., nuclear electromagnetic pulses (EMPs) and packaged pulsed power).

Pulsed power systems rely on precise coordination between energy storage, switching, and waveform control. From the fundamental behavior of RLC circuits to the complexities of capacitor bank configuration, Marx generator design, and pulse shaping through PFNs, every stage in the system contributes to how effectively energy is delivered.

Choosing the right capacitor is directly related to performance. Engineers must balance energy density, power density, ESR, and thermal behavior while working within space, voltage, and reliability constraints. As systems develop in complexity from lab-scale experiments to full-scale fusion ignition platforms, hardware selection becomes even more critical.

For further reading on capacitor selection and energy delivery, review [Capacitors for the Pulsed Power Industry](#).

Author



Peter Matthews

Peter Matthews is the Director of Technical Marketing at Knowles Precision Devices. As a division of Knowles Corporation, Knowles Precision Devices (KPD) focuses on production of a wide variety of highly engineered capacitors and microwave to millimeter-wave components for use in critical applications in military, medical, electric vehicle, and 5G market segments. Peter has over 20 years of experience in technology sales, marketing, and product management.

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