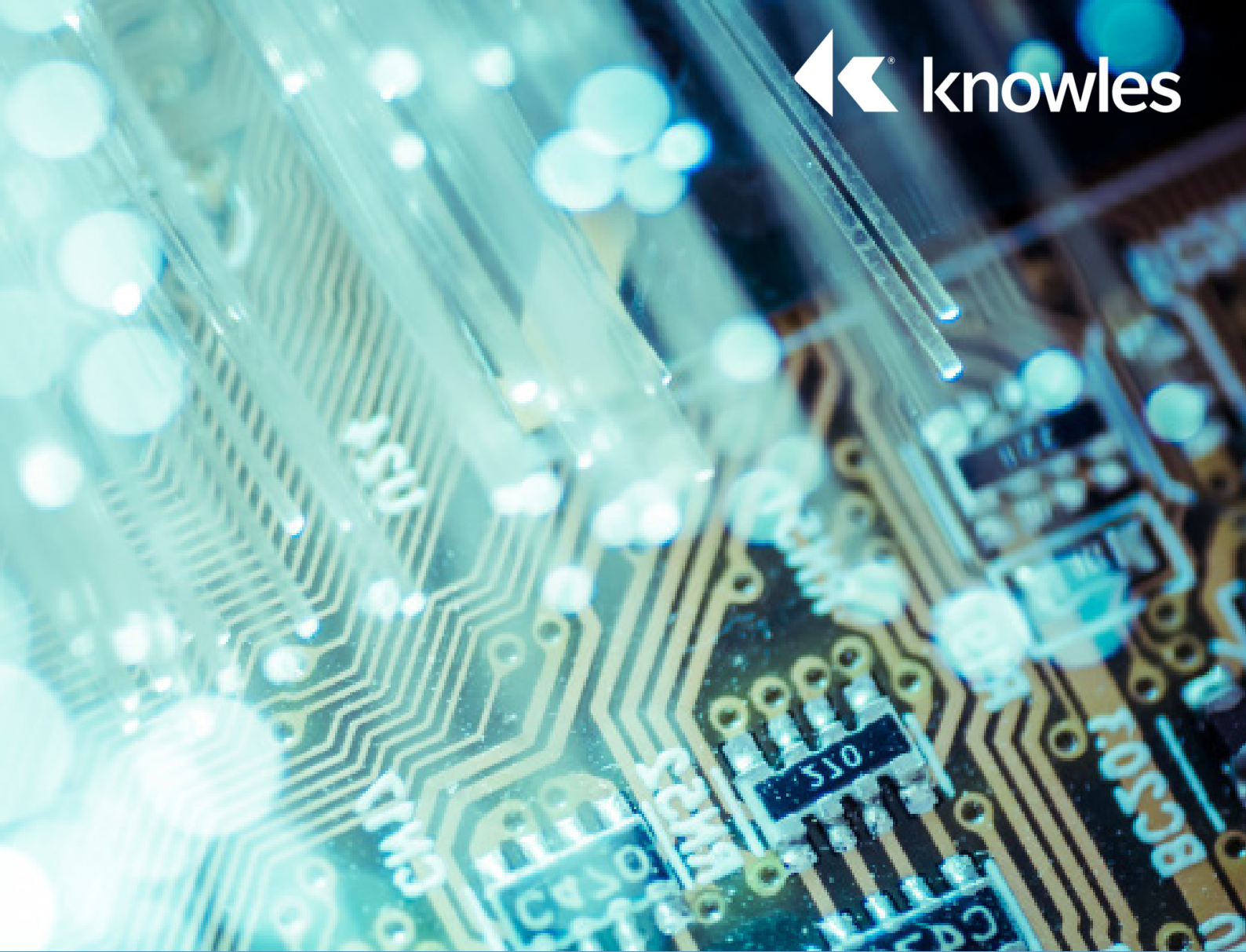




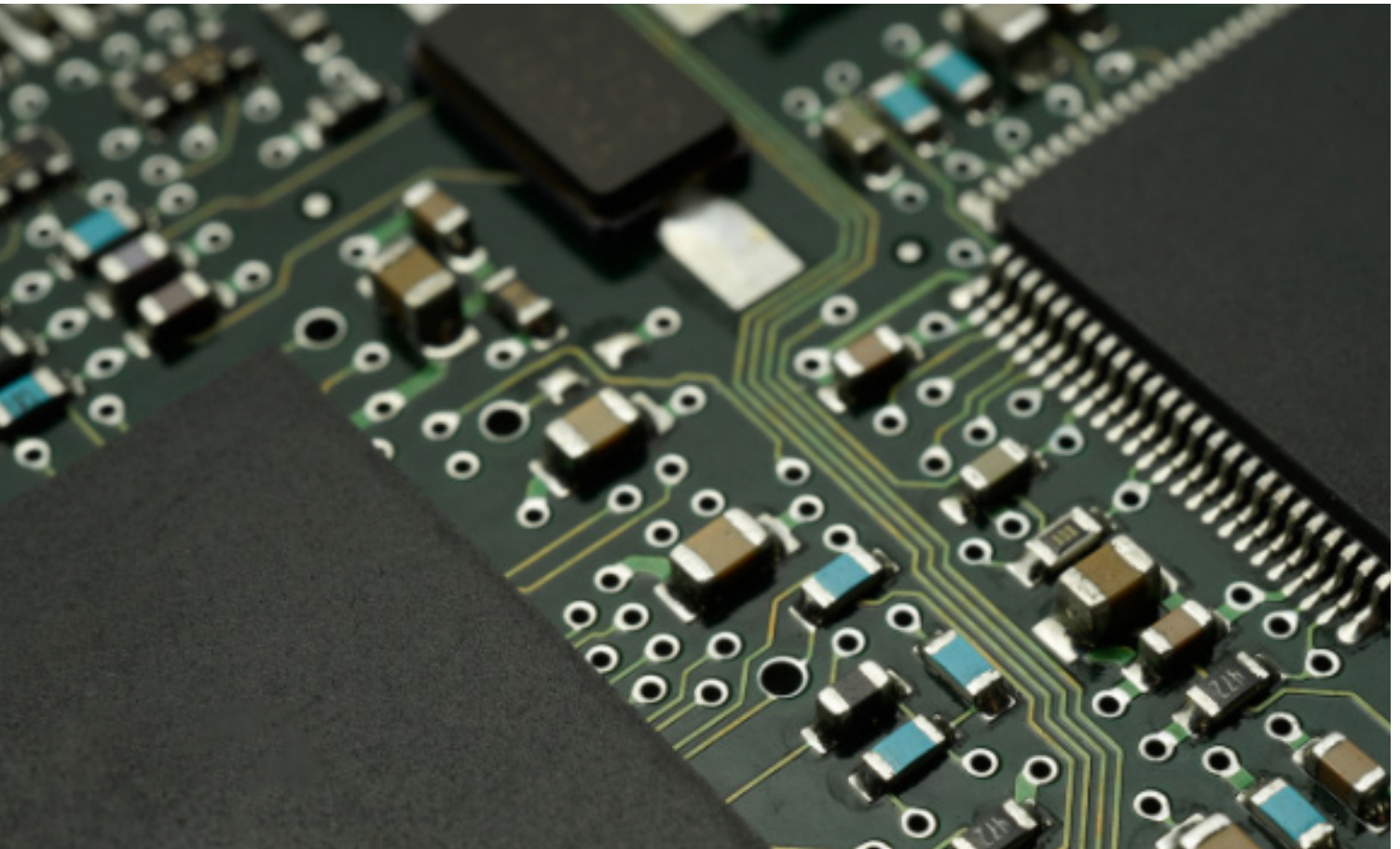
Specialty Capacitors Ebook

The Roles of Specialty Capacitors in Power Electronics

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Electronic devices provide the tools we need to power the world. From cell phones to modern vehicles and scientific equipment, we rely on electronics to sustain, improve and even lengthen our lives. As you likely know, capacitors are small electronic components used in the electronic circuits of these devices to store energy locally and stabilize power supply voltage.

Modern circuit boards are covered in capacitors, passive electronic components consisting of two conductive plates separated by a dielectric, as shown in Figure 1. Once power is applied, the capacitor stores energy on the plates until it reaches equilibrium with the supplied voltage. If an outside event causes a low voltage on the supply line, the capacitor feeds its stored charge back onto the line. If an overvoltage event occurs, the excess crosses the dielectric and shunts to ground.

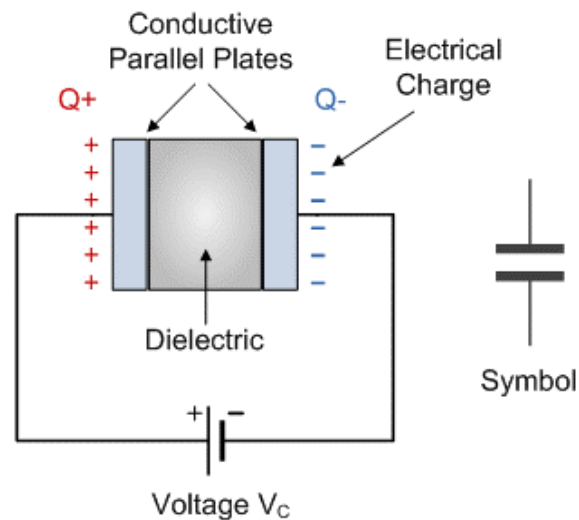


Figure 1. Capacitor physical diagram. [Source](#).

Many of these capacitors are standard fare, but a few play highly specialized, functional roles. To meet application-specific demands, these capacitors must be selected carefully based on function, size and interoperability. Because of the variables involved, it's imperative to understand what role each specialty capacitor plays and how it impacts the rest of the board.

This ebook outlines the roles of specialty capacitors and details design considerations for selection and implementation.

Selecting Capacitors Based on Application Demands

Two common types of capacitors are multilayer ceramic capacitors (MLCCs) and plastic film capacitors. Each has its benefits depending on the specific application. Some characteristics to consider when choosing between capacitors include the following:

- Temperature range
- Size constraints
- Voltage rating
- Capacitance value
- Certification standards (like X and Y ratings for line-to-line and line-to-ground applications)
- Cost

Film Capacitors

Film capacitors can withstand a wide temperature range and often have higher capacitance values. Film capacitors also offer self-healing, which enables these devices to recover from a dielectric breakdown with only a small reduction in capacitance. Film capacitors are large in size relative to their capacitance, but they cover voltage and capacity ranges that smaller ceramic capacitors cannot.

Multilayer Ceramic Capacitors

MLCCs can achieve higher capacitance values in a smaller volume than film capacitors. They are usually better for low-power applications. For example, MLCCs are well-suited for space-sensitive applications like antenna coupling. They are also available with special terminations to accommodate automotive technology with applications like onboard chargers, inverters, DC/DC converters and other equipment in electronic vehicles (EVs).

And while film capacitors have an impressive temperature range, MLCCs can also withstand high temperatures, high voltage and high power.

EMI Filters: Filter Out High-Frequency Impedance

EMI filters are used to suppress and filter out unwanted high-frequency electromagnetic noise generated by the switching operations of power electronic circuits.

EMI filters help ensure reliable operation of power electronics systems by effectively reducing EMI noise and preventing interference with sensitive electronic components which minimizes the risk of malfunction or data corruption, and helps manufacturers meet electromagnetic compatibility (EMC) standards.

EMI filters typically consist of a combination of capacitors and inductors. The capacitors provide a low-impedance path for high-frequency EMI noise to flow to ground, while the inductors block the flow of this noise. Capacitors are also used in EMI filters to decouple circuits and to provide power factor correction.

EMI filter products include:

- Surface Mount Filters
- Panel Mount Filters
- Discoidal Capacitors
- Planar Capacitor Arrays

In electronic device development, EMI filters are used to ensure that electronic devices comply with EMC standards. These standards regulate the amount of EMI that electronic devices can emit and the amount of EMI they can withstand.

EMI filters are commonly used in applications such as power supplies, inverters, motor drives, LED lighting and other electronic devices where EMI mitigation is critical. With proper EMI filtering, these devices can be trusted for use in mission-critical applications where failure is not an option, such as medical devices and aerospace and defense equipment.

What is Electromagnetic Interference (EMI)?

EMI refers to undesirable electromagnetic emissions or disturbances generated either by electronic devices or natural sources in the environment that can interfere with the proper functioning of other nearby devices or systems. EMI is a factor handled by many different types of capacitors.

EMI can be induced from multiple human causes or naturally occurring sources, such as power line emissions, radio transmitters, electric motors, relays, electrostatic discharge (ESD) and lightning.

EMI noise can propagate through power supply lines and radiate into the environment, potentially causing disruptions or malfunctions in other electronic systems. For many devices, this could cause critical issues, which is why many government organizations have developed regulatory standards for electromagnetic compatibility (EMC). EMC refers to the ability of two pieces of electronic equipment to function in the same environment without adversely impacting one another.

How EMI Filters Work

The main function of ceramic EMI filters specifically is to provide a low-impedance path for the unwanted high-frequency noise while allowing the desired power signals to pass through with minimum impedance. The EMI filter acts as a low-pass filter, attenuating the high-frequency noise and preventing its propagation (Figure 2).

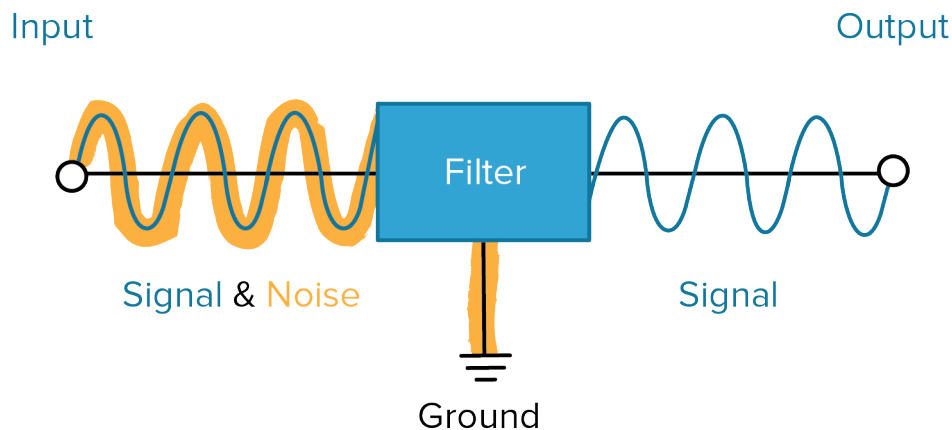


Figure 2. An illustration of the basic concept of how an EMI filter works.

Choosing EMI Filters to Further Minimize Impedance

MLCCs or ceramic disc capacitors are designed to have high capacitance values and low Equivalent Series Inductance (ESL) and Equivalent Series Resistance (ESR), minimizing the impedance of the desired power signals. EMI filters made with ceramic are also designed to exhibit high impedance at high frequencies, effectively filtering out the EMI noise.

When ceramic capacitors are used for EMI filters, the filters are typically connected in parallel with the power supply lines or between the power supply and the electronic device being protected. The MLCC used as a filter can be integrated into the printed circuit board (PCB) design or implemented as discrete components. The number and configuration of the filters will depend on the specific EMI requirements and the complexity of the power electronics system.

More About EMI Filters

Check out our range of [EMI filtering options](#) and learn more about our commitment to [continue investing in surface-mount EMI filters](#), even as other manufacturers scale back.

Bypass Capacitors: Filter High-Frequency Noise

The bypass capacitor ensures devices safely meet their power specifications by circumventing noise-producing sources.

All electronics depend on clean power but every electronic system has the potential to be affected by EMI.

Each source can couple with power and signal traces in a design, introducing noise. Even with careful layout considerations, any direct current (DC) power line can act as an inductor that absorbs and transmits electromagnetic fields. Figure 3 shows a common scenario in which household 60 Hz power induces power glitches on a DC power line.

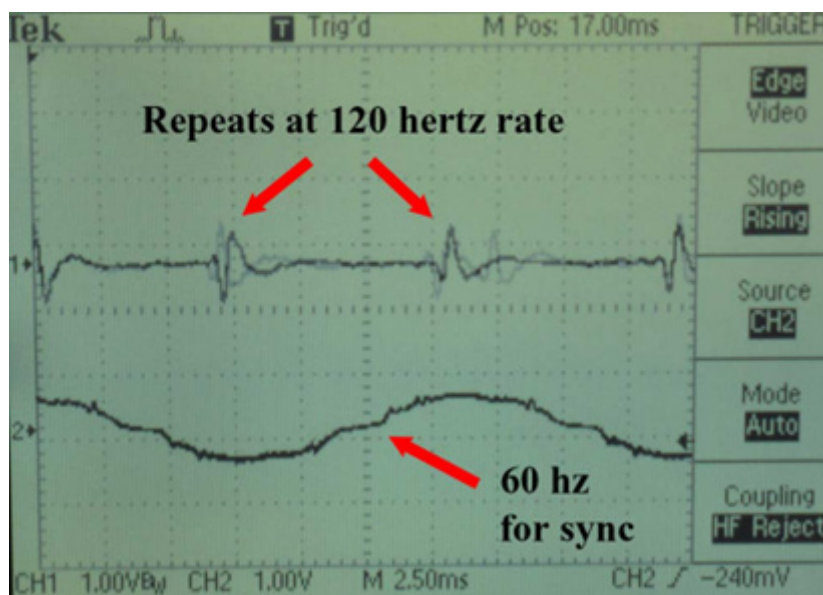


Figure 3. 60 Hz-induced EMI on a DC line. [Source](#).

The quality of the power provided is reduced when these emissions are loaded on top of the desired steady-state DC voltage. Some potential EMI-induced failure modes range from single-bit flips and glitches that robust hardware and software solutions are designed to correct – to an integrated circuit (IC) latch-up which forces a system reset. Large ESD spikes may cause total IC failure.

How a Bypass Capacitor Works

To ensure that expensive, high-speed components receive clean power consistently, designers add bypass capacitors as close to the IC power input leads as possible. The bypass capacitor acts as a filter, providing infinite resistance to steady-state voltage and bypassing high-frequency noise. This attenuates noise on the power line, as shown in Figure 4.

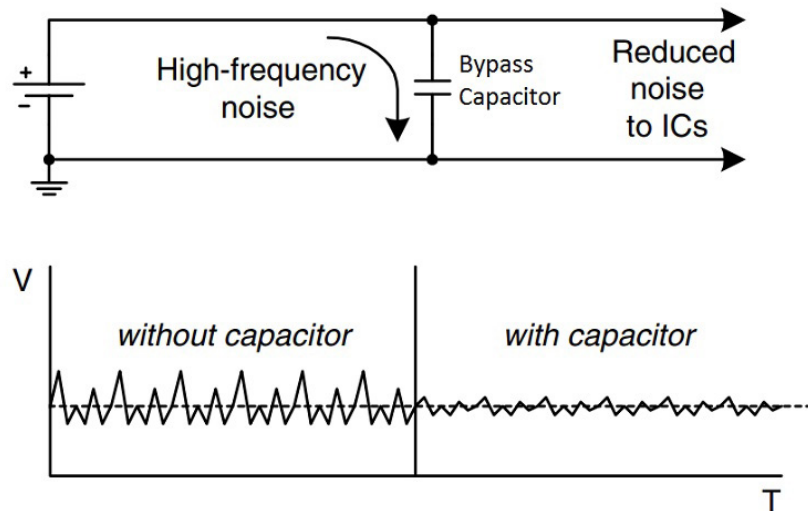


Figure 4. Circuit diagram and resulting trace.

The ability of a capacitor to filter high-frequency signals can be tuned according to the capacitive reactance formula:

$$X_c = 1 / (2 * \pi * f * C)$$

Where:

- X_c is the capacitive reactance in ohms
- f is the frequency in hertz
- C is the capacitance of the capacitor in farads

At low frequencies (e.g., DC power), the capacitive reactance approaches infinity, acting like an open circuit that allows the DC line voltage to power the targeted device. High-frequency noise on the line passes through to ground. Capacitors can be chosen to inhibit specific EMI frequencies by solving for f in the equation, assuming a suitably high resistance value. The components of the capacitor manufacturing (such as leads) add ESR and ESL to the devices, so careful consideration must be given to capacitor design to ensure these values remain low.

Improving Reliability in Specific Electronic Systems with Bypass Capacitors

Beyond providing clean power to ICs, bypass capacitors play a critical role in many fields of electronics. Because bypass capacitors reduce noise and stabilize the power to the design, the following systems see noticeable benefits as listed:

- Audio amplifiers achieve reduced distortion and improved audio quality
- Wi-Fi receivers and transmitters improve signal reception and transmission, allowing higher data transfer rates
- MRI imaging RF pulse generators deliver accurate and precise pulses
- Analog-to-digital converters (ADCs) attain improved conversion accuracy
- Microcontrollers encounter fewer errors resulting in enhanced reliability and performance
- LED lighting systems provide improved lighting quality and reduced visual discomfort

Each of these systems exhibit unique vulnerabilities to specific bands and frequencies of EMI. Bypass capacitors, in conjunction with shielding and layout considerations, can be specifically chosen to limit EMI in problematic areas of the design.

More About Bypass Capacitors

Knowles Precision Devices designs MLCCs that exhibit excellent high-frequency performance and can be tuned to filter out specific bands. Systems designed with our MLCCs, such as our line of [X7R capacitors](#), ensure a lifetime of consistent performance, even in harsh environments.

Decoupling Capacitors: Suppress AC Interference to Provide a Clean Signal

Decoupling capacitors isolate or decouple AC signals from DC signals or vice versa.

Decoupling capacitors act as a buffer, supplying clean and stable power to components, which minimizes the risks of malfunctions, noise coupling or signal integrity issues. For example:

- If input voltage drops, decoupling capacitors provide adequate power to an IC to maintain the voltage level.
- If input voltage surges, a decoupling capacitor provides adequate power to maintain the voltage level.

How a Decoupling Capacitor Works

Decoupling capacitors are primarily used to suppress voltage fluctuations or noise on power supply lines so that there is no impact to the operation of sensitive components. In power supplies, decoupling capacitors are strategically placed near the power pins of ICs or other sensitive components. The decoupling capacitors are connected in parallel to the power supply lines and act as a local energy reservoir that can quickly supply or absorb current as needed (Figure 5).

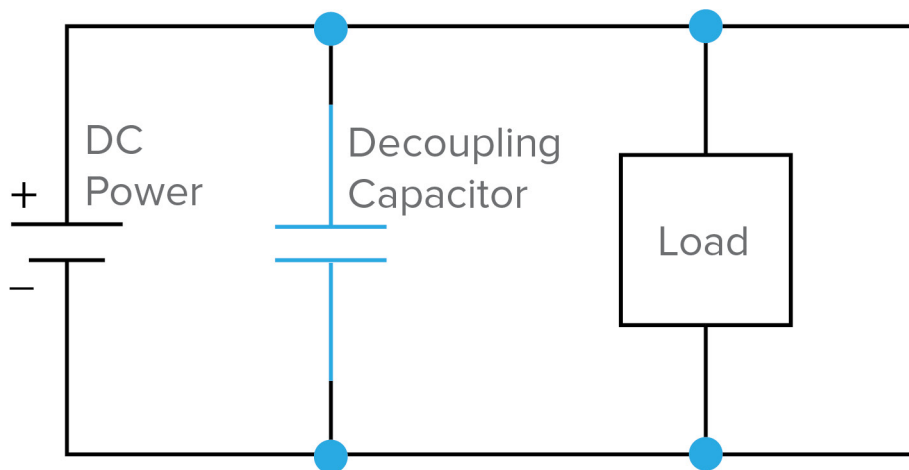


Figure 5. A typical configuration of where a decoupling capacitor is placed in a power supply.

This configuration helps reduce voltage ripple, minimize voltage droops during transient events and provides a stable and clean power supply to other components.

Using Ceramic Capacitors for Effective Decoupling

Ceramic capacitors are widely used as decoupling capacitors because ceramic has many favorable electrical characteristics, including the following:

- **High Capacitance in a Small Form Factor:** Ceramic capacitors offer high capacitance values in a compact size, allowing for sufficient energy storage capacity in a small form factor. This is especially beneficial when space on the PCB is limited.
- **Low ESR:** Ceramic capacitors exhibit low ESR, which means they can effectively deliver or absorb current without significant voltage drops. This low resistance allows the capacitor to respond quickly to dynamic changes in current demand, providing immediate energy when needed.
- **Low ESL:** Ceramic capacitors typically have low ESL, enabling them to offer good high-frequency filtering capabilities. They can effectively suppress high-frequency noise and provide a low impedance path for high-frequency currents.
- **Wide Frequency Response:** Ceramic capacitors have a broad frequency response, making them suitable for filtering out a wide range of noise frequencies commonly found in power supply lines.
- **Temperature Stability:** Ceramic capacitors can maintain their capacitance and performance over a wide temperature range, ensuring consistent decoupling performance even in varying operating conditions.

More About Decoupling Capacitors

You can learn more about the capacitors we have available for decoupling including high-reliability [broadband blocks](#), which are ideal for medium voltage and very high frequency applications. For higher voltage, stacked capacitors with leads, checkout our range of [ST & SM capacitor assemblies](#).

DC-Blocking Capacitors: Remove Unwanted DC Line Levels

DC-blocking capacitors are used to provide clean waveforms and correctly amplified voltages in applications requiring signal integrity and accurate power amplification.

Generally, waveform systems can be broadly defined as power-related alternating current (AC) and communications-related radio frequency (RF) applications. Both employ waveforms to provide power or information.

All these devices require a blocking capacitor to ensure the waveform conforms to the desired specifications:

- Audio amplifiers
- RF systems such as radio, broadcast television and microwave communications devices
- Power converters and amplifiers, AC-DC, DC-AC and DC-DC
- Communications connectors
- Sensor interfaces
- RF filters

In AC and RF waveforms, the desire is to have the waveform highs and lows navigate around a known base voltage. Typically, this is designed to be a waveform centered around zero volts. Some designs, like audio amplifiers, require the waveform to circulate a known DC voltage.

However, this desire to achieve a known center level can be thwarted by the unwanted injection of a DC voltage onto the line. Sources of DC pollution may include the following:

- Power supply residual voltage
- Offset voltage generated by a device
- Biasing circuits to control voltage levels between two (or more) levels
- Electrochemical effects such as galvanic corrosion
- Faulty or imbalanced components within a system

When any of these sources are added to (or subtracted from) the desired waveform, the center voltage shifts into a range that corrupts or prevents data processing in RF applications or alters power amplification into unusable or dangerous ranges.

How DC-Blocking Capacitors Work

In the case of blocking capacitors, the electronic device is placed in series with the load. The capacitor acts as an open circuit to the DC voltage, not allowing it to pass through the dielectric and ultimately blocking the unwanted DC voltage. In Figure 6 below, capacitor C2 acts as a blocking capacitor in this voltage divider design with the output waveform around zero volts.

Any waveform on the line produces electromagnetic waves that transit the dielectric in inverse polarity to the originating wave. Thus, the DC voltage is blocked, and the wave, with a properly valued capacitor, circulates about zero volts, as desired.

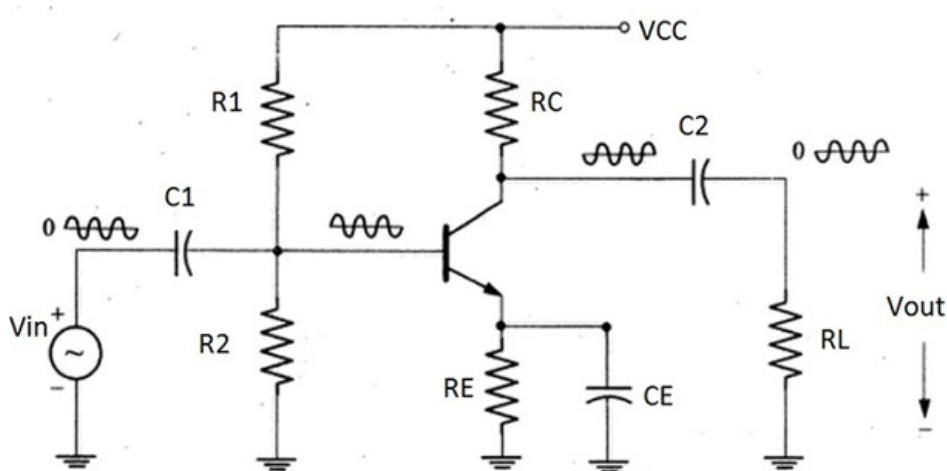


Figure 6. Voltage divider with blocking capacitor C2. [Source](#).

In the communication world, RF signals can be transmitted over lines that require blocking capacitors to ensure the correct level is transmitted or received. For example, in coaxial lines with an inner core and outer sheath, the capacitor can be applied as an inner DC block or an outer DC block, or a capacitor can be applied as both an inner and outer DC block.

To better understand how a capacitor acts in a DC-blocking (otherwise known as AC-coupling) application, and how to select the correct blocking capacitor, let's consider the behavior of an RC high pass filter. In Figure 7A, you can see the RC high pass filter consists of a capacitor in series and a resistor in parallel. To find the 3dB frequency cutoff of this filter, you can use the formula in Figure 7C. When we plot the power that gets through this filter on a Bode plot (Figure 7B) we can see that the frequency has dropped by -3dB at the frequency cutoff we get using the formula. It drops off further at frequencies lower than the frequency cutoff, showing us how different capacitance values can attenuate low frequencies.

RC High Pass Filter (Passive)

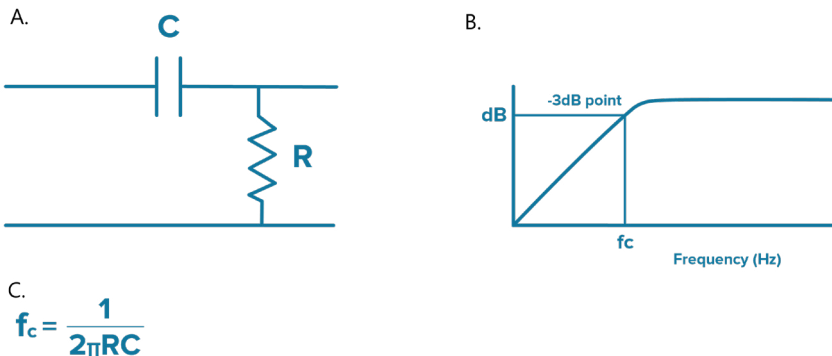


Figure 7. An example of a passive RC high pass filter.

In practice, the above formula assumes ideal conditions. Real-world manufacturing processes introduce parasitic inductance that moves the equation to an approximation. But using this we can get a sense of the capacitance value required to pass frequencies we are interested in and to block frequencies we do not want. Any capacitance can block DC, but a designer should consider the minimum frequency they want to pass when selecting a capacitor value.

Understanding Current Flows to Choose the Correct Blocking Capacitor

Finding blocking capacitor solutions for complex real-world electronic systems requires a deep understanding of current flows. Figure 8 shows a blocking capacitor system added to each side of a DC-DC step-down converter used in an electronic vehicle charging device. Our engineering team used sophisticated modeling tools to arrive at this solution, ensuring quality fast-charging levels.

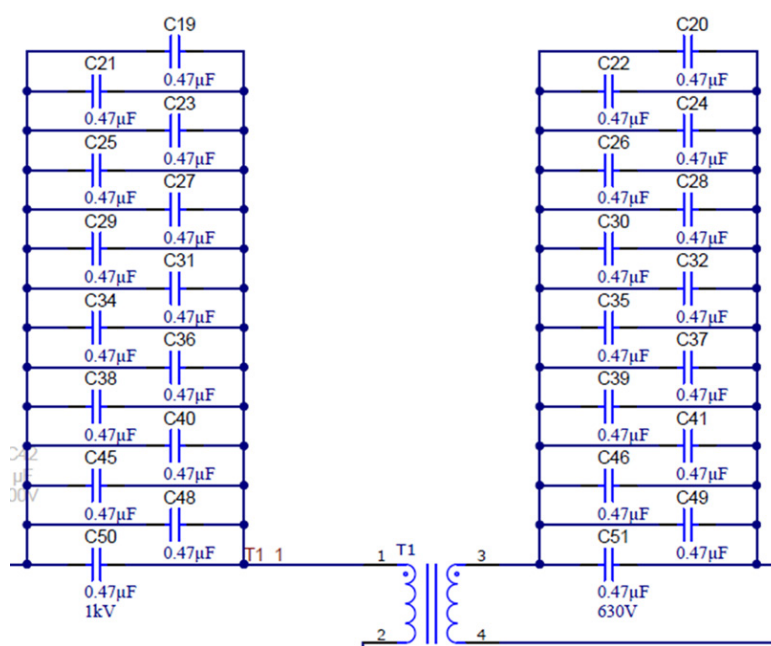


Figure 8. DC-DC converter bypass capacitor configuration. [Source](#).

Whether you're designing for communications with frequencies from hertz to gigahertz, power and signal amplification systems or ultra-sensitive sensors, we can provide MLCCs that remove unwanted DC levels from your design.

More About Blocking Capacitors

Learn more about using our AEC-Q200-certified capacitors for critical DC-blocking capacitor roles including [C0G](#) and [X7R](#) options as well as our [StackiCap](#) range. Or, [read this blog post](#) to see other ways our parts are used in DC-blocking applications.

DC-Link Supporting Filters: Store and Release Energy

A DC-link supporting filter is a capacitor that connects the input and output sides of a power conversion system.

The primary function of the DC link is to store energy during the times when the input power is higher than the output power and release energy when the output power demand exceeds the input power.

How DC-Link Supporting Filters Work

In power electronics, the DC link refers to the section that connects the input and output sides of the power conversion system (Figure 9). The DC link should include a capacitor that serves as a supporting filter to act as a buffer, minimize voltage ripples, and smooth and stabilize the power flow between various components such as rectifiers, inverters, and other converters in the power system.

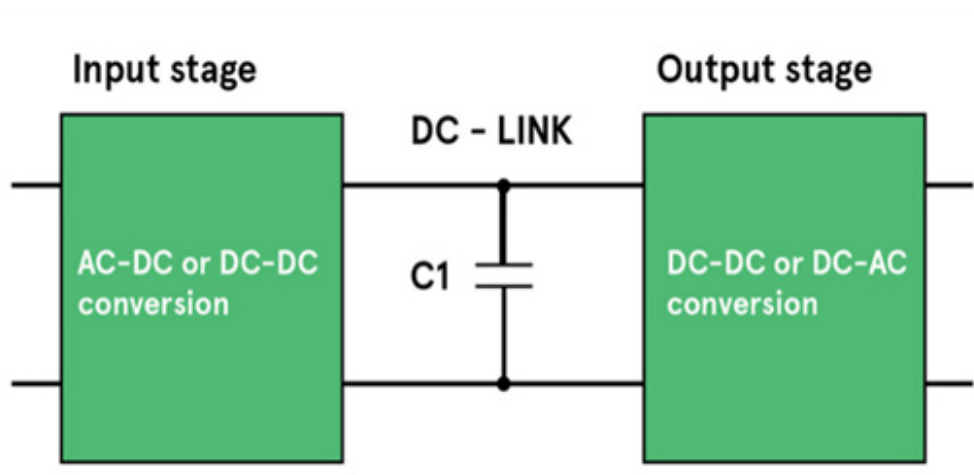


Figure 9. A representation of where the DC link is positioned in a power conversion system. [Source](#).

Using The Right Materials for DC Link Supporting Capacitor Filters to Achieve Optimal Performance

To efficiently operate a power electronics system, it is essential to have large capacitors on the DC link. These capacitors are typically aluminum, electrolytic and film capacitors as these options offer high capacitance values and are suitable for energy storage.

The key functions of these capacitors include the following:

- **Smoothing Ripples:** During the power conversion processes there are fluctuations and ripples in the DC voltage output. The large capacitors on the DC link help smooth out these voltage ripples, ensuring a more stable and constant voltage supply to the load.
- **Energy Storage:** Large capacitors on the DC link act as energy reservoirs, storing surplus energy during periods of low load demand and releasing energy when the load requires additional power. This energy buffering capability enhances the overall efficiency and performance of the power electronics system.
- **Surge Suppression:** Power electronics systems may encounter voltage surges or transients during switching events or external disturbances. The presence of large capacitors on the DC link enables them to absorb and suppress these voltage surges, protecting sensitive components from damage.

However, relying solely on these large capacitors may not be sufficient for addressing all the requirements of the power electronics system.

To enhance the performance and reliability of the DC link supporting capacitor filter, it is imperative to include ceramic capacitors in the design as well. Ceramic capacitors have unique characteristics that complement the qualities of the aluminum electrolytic and film capacitors nicely including the following:

- **Fast Response Time:** Ceramic capacitors have significantly faster response times compared to electrolytic and film capacitors. This means ceramic capacitors can efficiently handle high-frequency noise and transients that other capacitors might struggle to address adequately.
- **Low ESR and ESL:** The ESR and ESL of ceramic capacitors are much lower than the ESR and ESL of electrolytic capacitors. This results in reduced power losses and improved filtering capabilities
- **Compact Size:** Ceramic capacitors offer high capacitance values relative to their compact size. Integrating these capacitors into the DC link supporting capacitor filter allows for efficient space utilization and helps reduce the overall size and weight of the power electronics system.

To efficiently operate a power electronics system, it is essential to have large capacitors on the DC link.

A Closer Look at DC Link Capacitors in Electric Vehicles

DC-link capacitors offer more stable DC voltage to help limit fluctuations caused by spikes in the inverter's current demand. They also serve as filters that protect EV subsystems from voltage spikes, surges and EMI.

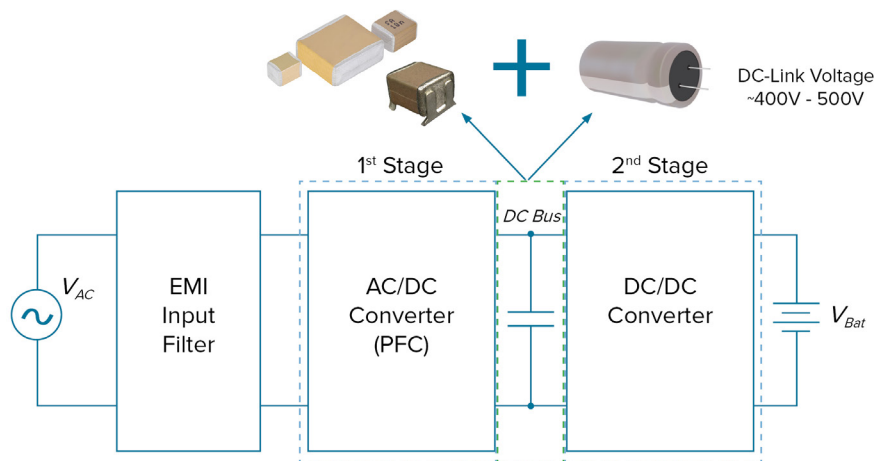


Figure 10. An example of where ceramic capacitors can be used in an electric vehicle on-board charger to stabilize the DC link.

Inside an EV, the on-board charger (OBC) is responsible for charging the traction battery (Figure 11). The OBC houses:

- The AC/DC converter, which converts AC from electric grid into direct current (DC) using rectification and power factor correction (PFC)
- An intermediate DC-link circuit for energy buffering
- The next stage DC/DC converter to adjust the DC voltage and supply the correct DC levels for the battery

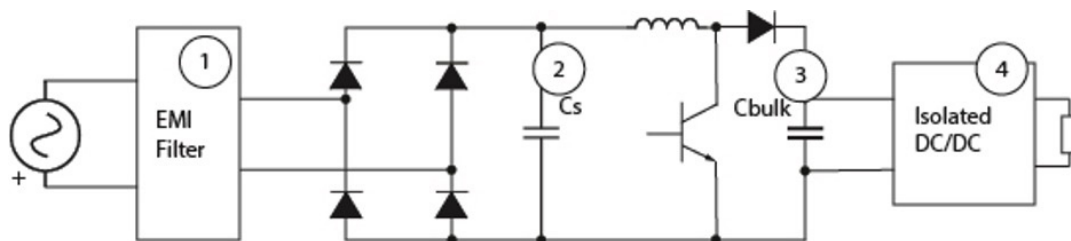


Figure 11. Simplified block schematic for AC/DC stage of OBC.

The DC-link capacitor, C_{bulk} in Figure 11, is placed between the rectifier and DC/DC converter. In this example, the desired characteristics for the DC-link capacitor include:

- High DC voltage rating: 300V to 500V
- Very large capacitance: 200 μ F to 1500 μ F
- Operating temperature range: -40°C to +250°C
- Low ESR: < 1.5m Ω
- High root mean square (RMS) current capacity
- High mechanical ruggedness

To meet the large capacitance requirements, multiple capacitors or a capacitor array is required. The DC-link capacitor must be also able to handle twice the line frequency. A common circuit arrangement to achieve this includes MLCCs connected in parallel with other capacitor technologies.

DC-link capacitors are also found in the inverter portion of motor drive circuits (Figure 12). The inverter converts DC power from the battery to three-phase AC power to drive the traction motor during acceleration, and then it converts AC power back to DC during braking. The inverter also detects the motor's speed and position and drives the insulated-gate bipolar transistor (IGBT) power stages.

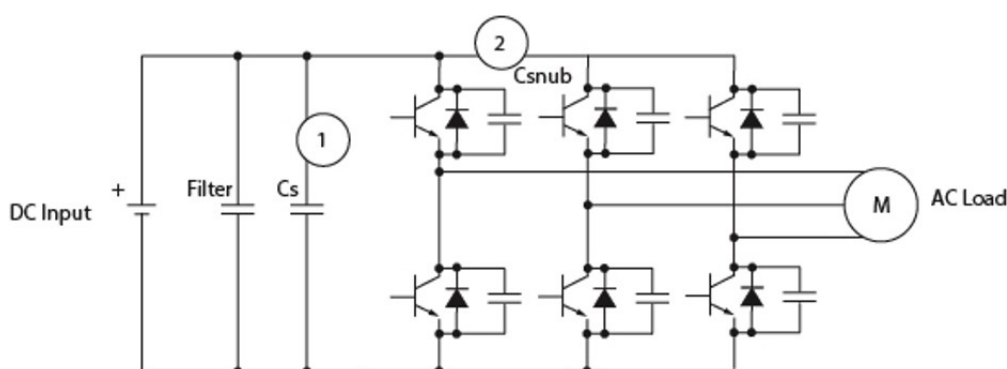


Figure 12. Simplified block schematic for inverter in motor driver circuit.

In Figure 12, the DC link or smoothing capacitor, C_s , is placed in parallel between the DC (battery) and the AC (load) sides of the voltage inverter. Due to the high capacitance requirements, small-sized MLCCs can be used alongside film and aluminum electrolytic capacitors to integrate closer to the IGBT switching device and improve high frequency attenuation. Given the high number of converters and inverters found in EV applications, selecting the right high-voltage, high-capacitance DC-link capacitor is of great importance to the overall system success.

More About DC-Link Supporting Filters

For further information, explore [some of our filter options](#).

Safety Capacitors: Mitigate the Effects of Transient Voltage and EMI

Safety capacitors protect circuits and users from high-voltage surges by shunting impulse energy to ground.

Safety capacitors are especially important in high-voltage applications, ensuring their safe operation, and in everyday products including:

- Modems and other telecoms equipment
- AC-DC power supplies
- Power distribution switchgear
- EVs and other automotive applications

In addition, safety capacitors filter EMI to block adverse inferences and ensure a cleaner signal.

How Safety Capacitors Work

In general, there are two classes of capacitors, Class-X and Class-Y, that are both used to minimize EMI in different applications.

- **X Capacitors:** Class-X capacitors, also known as “across-the-line capacitors,” are used between the wires carrying the incoming AC current. These offer line-to-line protection, which means that if there is a failure, a short may occur, but there is no risk of shock. An X capacitor failure usually causes a fuse or circuit breaker to open.
- **Y Capacitors:** Class-Y capacitors, also known as “line-to-ground capacitors” or “line bypass capacitors,” offer line-to-ground protection, which generally means that if a failure with the ground occurs, there is a risk for shock. However, Class-Y safety capacitors must meet rigorous specifications, minimizing the chance of electric shock.
- **X/Y Capacitors:** Some safety capacitors handily combine classes, for example, X1/Y2. This simply means that the capacitor can be used as an X1 capacitor in an across-the-line application or as a Y2 capacitor in the line-to-ground portion of the circuit.

SAFETY CAPACITOR CLASSIFICATIONS

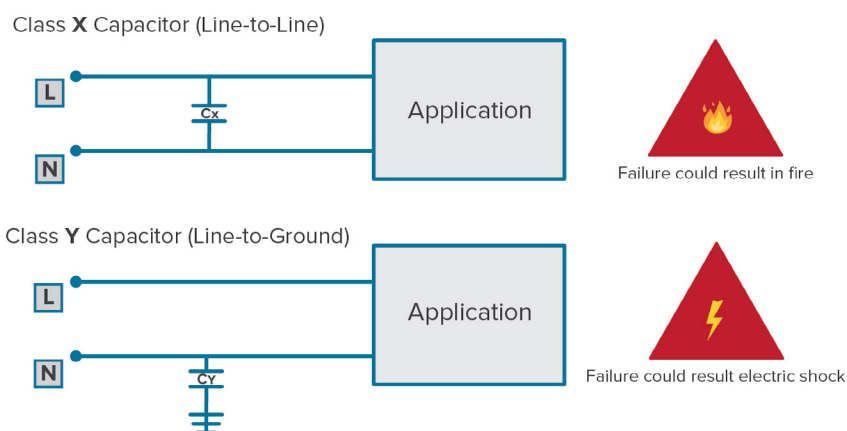


Figure 13. A representation of where Class X and Class Y safety capacitors are placed and the associated risks.

Using Certified Safety Capacitors for Reliable Applications

AEC-Q200 qualified safety certified capacitors comply with international UL/cUL and IEC/EN specifications and offer designers the option of using a surface MLCC to replace film types.

The safety advantages of leading MLCCs include:

- Class Y2 250Vac ranges
- Class X1 & X2 305Vac ranges
- All ranges have a safety-certified DC voltage rating (unique in the industry)
- All ranges are certified as humidity robustness grade IIIB (unique in the industry)

More About Safety Capacitor

Surface-mount safety capacitors comply with international UL60384-14 and EN60384-14 specifications and can be used instead of leaded film capacitors in AC-DC power supplies where a lightning strike or other voltage transients represent a threat to the electronic equipment. Find out more about [safety capacitors](#).

Snubber Capacitors: Suppress Voltage to Protect Circuits

A snubber capacitor is a capacitor connected to a high-current switching node to protect the power switching module by absorbing noise. It's designed to protect electronics from voltage spikes and transients that can occur during switching.

How Snubber Capacitors Work

It's common for the actions of a switch (i.e., opening or closing) to induce a high voltage across a device. Voltage spikes cause failures if they exceed component ratings. Snubber capacitors offer an alternate path for excess energy to be absorbed and dissipated, ultimately reducing voltage spikes and ringing effects. Implementing snubber capacitors improves efficiency, reduces EMI and protects components.

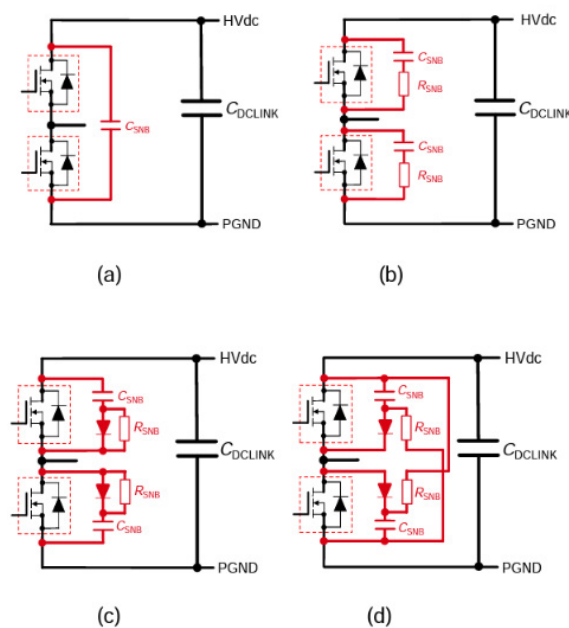


Figure 14. Diagramming the four most common snubber circuit configurations: (a) C snubber, (b) RC snubber, (c) Discharge RCD snubber, (d) Non-discharge RCD snubber. [Source](#).

While there are many snubber designs, resistor-capacitor (RC) and resistor-capacitor-diode (RCD) are the most common. RC snubbers suppress peak voltage and minimize ringing; RCD snubbers have the additional benefit of reducing circuit loss, but the diode across the resistor causes resistance to reduce to zero while the capacitor is charging.

Improve Circuit Reliability with Snubber Capacitors

Snubber capacitors are powerful tools for improving circuit reliability and efficiency. They allow users to leverage the benefits of switching without the potentially harmful effects of voltage spikes.

More About Snubber Capacitors

For advice on design and manufacturing, [contact us](#).

Resonant Capacitors: Overcome Real-World Application Challenges of Resonant Circuits

Resonant capacitors store and discharge energy to achieve specific circuit behaviors that can improve power conversion efficiency, reduce losses and minimize switching stress.

At a foundational level, the ability to store electric charge and more easily pass higher-frequency AC currents are two of the most identifiable properties of capacitors. However, at very high frequencies, the ideal behavior of a capacitor can be compromised by resonance, a phenomenon where the circuit's impedance reaches a minimum at a specific frequency, known as the resonant frequency. At this frequency, the circuit efficiently stores and transfers electrical energy.

How Resonant Capacitors Work

Resonant capacitors play a crucial role in resonant circuits by storing and releasing electrical energy at the resonant frequency.

Ideal capacitor math describes a scenario where impedance approaches zero as frequency increases. Real-world testing reveals an application- and component-specific frequency boundary for impedance. At that boundary, the ESL of the capacitor forms an LC resonance circuit with itself. This is referred to as self-resonance. Up to its self-resonant frequency, a capacitor acts like it's supposed to—like a capacitor. Beyond this frequency, it starts to act like an inductor, which impedes AC current.

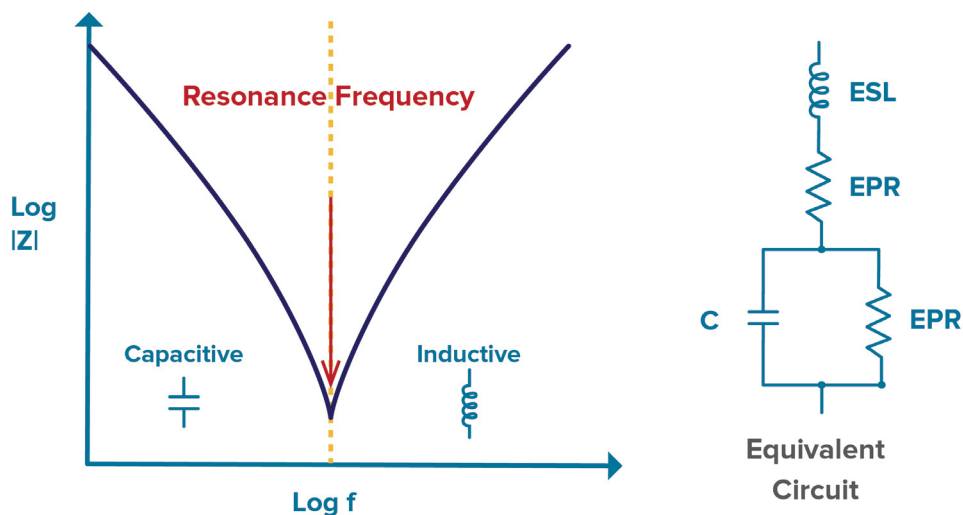


Figure 15. Behavior of a capacitor before and after meeting its self-resonant frequency.

It's crucial to note that the Q factor of a capacitor typically reaches a minimum at its self-resonant frequency. Q factor, defined as the ratio of a capacitor's reactance to its ESR, serves as a measure of efficiency, particularly in terms of energy loss. For optimal performance, operations should remain below this frequency.

Managing Extremely High Voltages and Currents with Resonant Circuits

Resonant capacitors are typically designed with high voltage and current ratings to handle the significant energy fluctuations in these circuits. Additionally, resonant capacitors have low ESR, minimizing power losses and ensuring efficient energy transfer.

Key characteristics of resonant capacitors include:

- **High Capacitance Values:** Resonant capacitors typically have higher capacitance values compared to standard capacitors to store and release substantial amounts of electrical energy.
- **High Voltage and Current Ratings:** Resonant circuits often operate at high voltages and currents, demanding capacitors capable of handling these conditions without breakdown or failure.
- **Low ESR:** Low ESR is essential for minimizing power losses and ensuring efficient energy transfer in resonant circuits.
- **High Stability and Reliability:** Resonant capacitors must maintain their capacitance and other electrical properties over time and under varying operating conditions to ensure circuit stability and performance.

Resonant capacitors are able to store and discharge energy to achieve specific circuit behaviors that can improve power conversion efficiency, reduce losses and minimize switching stress.

More About Resonant Capacitors

For advice on designing circuit elements for high-frequency filters and noise suppression, [contact us](#).

Flying Capacitors: Balance Voltage Differences

Flying capacitors store and transfer energy between different levels of the inverter, using multiple capacitors connected in series and parallel to produce a desired voltage level.

As demand for high-efficiency and high-power-density inverters continues to grow, the so-called “flying” capacitor multilevel inverter is emerging as a strong choice for many power electronics systems because they generate multiple voltage levels from a single DC input voltage.

Since these capacitors can “float” to different electric potentials depending on the connected semiconductor switching structure and state, they help balance out voltage level differences due to manufacturing tolerances, temperature variations and other factors. These capacitors are also helpful in balancing voltage across the structure by temporarily storing and releasing energy as needed, increasing power density and quality and optimizing the use of existing voltage availability. Flying capacitors are common in applications such as EV inverters, battery management systems (BMSs), renewable energy systems and other power electronics.

How Flying Capacitors Work

Popular application areas for flying capacitors include EVs and solar inverters due to their lightweight, compact nature and ability to help even out voltage and extend longevity of components.

For example, within an EV BMS, a flying capacitor can be used to smooth out fluctuations in the voltage of the battery pack. The battery pack in an EV typically consists of many individual cells connected in series and parallel, and these cells can have slight variations in their voltage levels due to manufacturing tolerances, temperature variations and other factors.

The flying capacitor can be used to balance the voltage across the cells by temporarily storing and releasing energy as needed. This helps ensure all the cells in the battery pack are operating at optimal voltage levels, prolonging the overall life of the battery pack. Additionally, the flying capacitor can help reduce the harmonic distortion of the voltage waveform, improving the overall power quality of the system.

As demand for high-efficiency and high-power-density inverters continues to grow, the so-called “flying” capacitor multilevel inverter is emerging as a strong choice for many power electronics systems because they generate multiple voltage levels from a single DC input voltage.

Managing High-Performing Applications with Ceramic Flying Capacitors

While electrolytic capacitors can be manufactured from various materials, ceramic capacitors are particularly suited for use cases needing the functionality of a flying capacitor. Because of the physical properties of ceramic capacitors, many companies are choosing this route to leverage the benefits of ceramic, including:

- **High Dielectric Constant:** Ceramic capacitors can store a large amount of energy in a small package.
- **Low ESR:** Ceramic capacitors can transfer energy quickly and efficiently.
- **Size and Lifespan:** Ceramic capacitors are small and lightweight with a long lifespan, which helps reduce the size and weight of the inverter, making them ideal for use in compact electronic devices.
- **Speed of Transfer:** Ceramic capacitors can quickly transfer energy between different levels of an inverter, helping reduce losses and improve the overall efficiency of the system.

More About Flying Capacitors

Since these architectures are commonly found in the rapidly growing EV field, it's important to note we possess substantial expertise in this application area, and can support our customers in meeting the [AEC-Q200 specifications](#) when needed.

[Learn more about our AEC-Q200-qualified flying capacitors](#) and their potential to improve power density and quality for your application.

Bootstrap Capacitors: Expand Voltage Limits in an Application

A bootstrap capacitor is a specific type of capacitor used to drive high-side MOSFETs efficiently.

As EVs, renewable energy systems, and consumer electronics quickly become more powerful, the demand for high-voltage power electronics is quickly increasing.

The bootstrap capacitor plays a critical role in maintaining the gate voltage required to turn on the high-side MOSFET in a half-bridge or full-bridge configuration.

How Bootstrap Capacitors Work

The bootstrap capacitor plays a critical role in maintaining the gate voltage required to turn on the high-side MOSFET in a half-bridge or full-bridge configuration. By using the charge stored in the bootstrap capacitor, the high-side MOSFET's gate voltage can be boosted above the supply voltage, ensuring proper switching operation and enabling efficient power conversion (Figure 16).

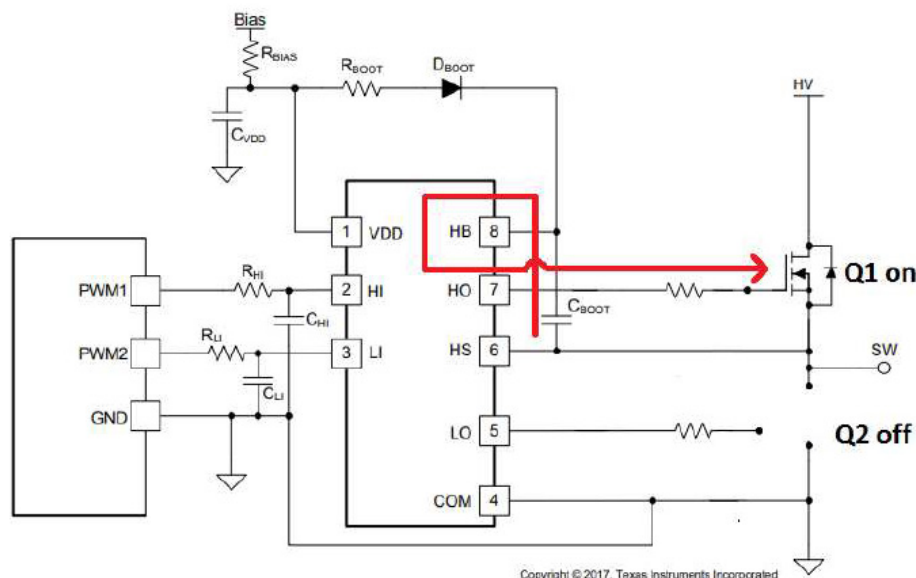


Figure 16. A representation of the discharge path of the bootstrap capacitor. [Source](#).

Achieving High Performance with Bootstrap Capacitors

Bootstrap capacitors should be high-quality capacitors with:

- **High Reliability:** Low failure rates and stable performance over extended operating periods to enhance the longevity of power electronics systems.
- **Compact Form Factor:** A small footprint for space-saving designs, required in modern, miniaturized power electronics applications.
- **Temperature Stability:** Maintenance of capacitance and performance across a wide range of operating temperatures, ensuring consistent functionality in diverse environments.
- **Wide Voltage Range:** Availability in a wide range of voltage ratings, providing flexibility in design for various power electronics systems.
- **Low ESR:** A low ESR ensures minimal power loss during switching, contributing to higher overall efficiency in power electronics circuits.

Since MLCCs are compact and have high capacitance and low ESR, these components are generally well-suited for use as bootstrap capacitors. Integrating MLCCs in the capacitor role within bootstrap circuits can improve system performance, reduce the PCB space required and enhance overall energy efficiency.

More About Bootstrap Capacitors

If you need help designing a bootstrap capacitor into your system or simply need a high-reliability MLCC to fill the role, [contact us](#) today.

How Knowles Precision Devices Can Help with Capacitor Selection

Increasingly, devices need to be designed to maintain EMC, which means devices will not emit or receive electromagnetic energy causing EMI. Knowles Precision Devices carries a wide array of MLCCs that can meet these rigorous standards for your product designs. When you have a specific problem to tackle, we can help you select or design the bypass capacitor solution for your system.

Our MLCCs exhibit excellent high-frequency performance and can be tuned to filter out specific bands. Our capacitors are designed with very low ESL and ESR, and new layer topology and packaging methods have significantly improved insertion loss performance.

Compared to other capacitor manufacturing materials, like films, ceramic devices operate across a wide range of temperatures without significant degradation while maintaining high stability. Additionally, [Knowles Precision Devices MLCCs](#) are available with a [FlexiCap™](#) termination. FlexiCap™ is a proprietary flexible epoxy polymer termination material that is applied to the device under the usual nickel barrier finish to accommodate a greater degree of board bending than conventional capacitors, reducing the risk of mechanical cracking.

Whether you're designing for defense systems that require conforming to various MIL-SPECS, or medical devices regulated by the Food and Drug Administration's Quality System Regulation (QSR), we can work with you to rigorously test components to meet or exceed these standards.

There's a growing number of specialty roles for capacitors, and it's important to work with a team that understands how component choice will impact the rest of your design. With catalog, build-to-print, and custom design capabilities, we're ready to support your efforts to design in or source specialty capacitors for your power electronics systems. [Contact us](#) for a project consultation.

If you need help selecting from our portfolio please [contact us](#) and we can guide you through the selection process.