The Electrical Engineer's Guide to Safety Capacitors

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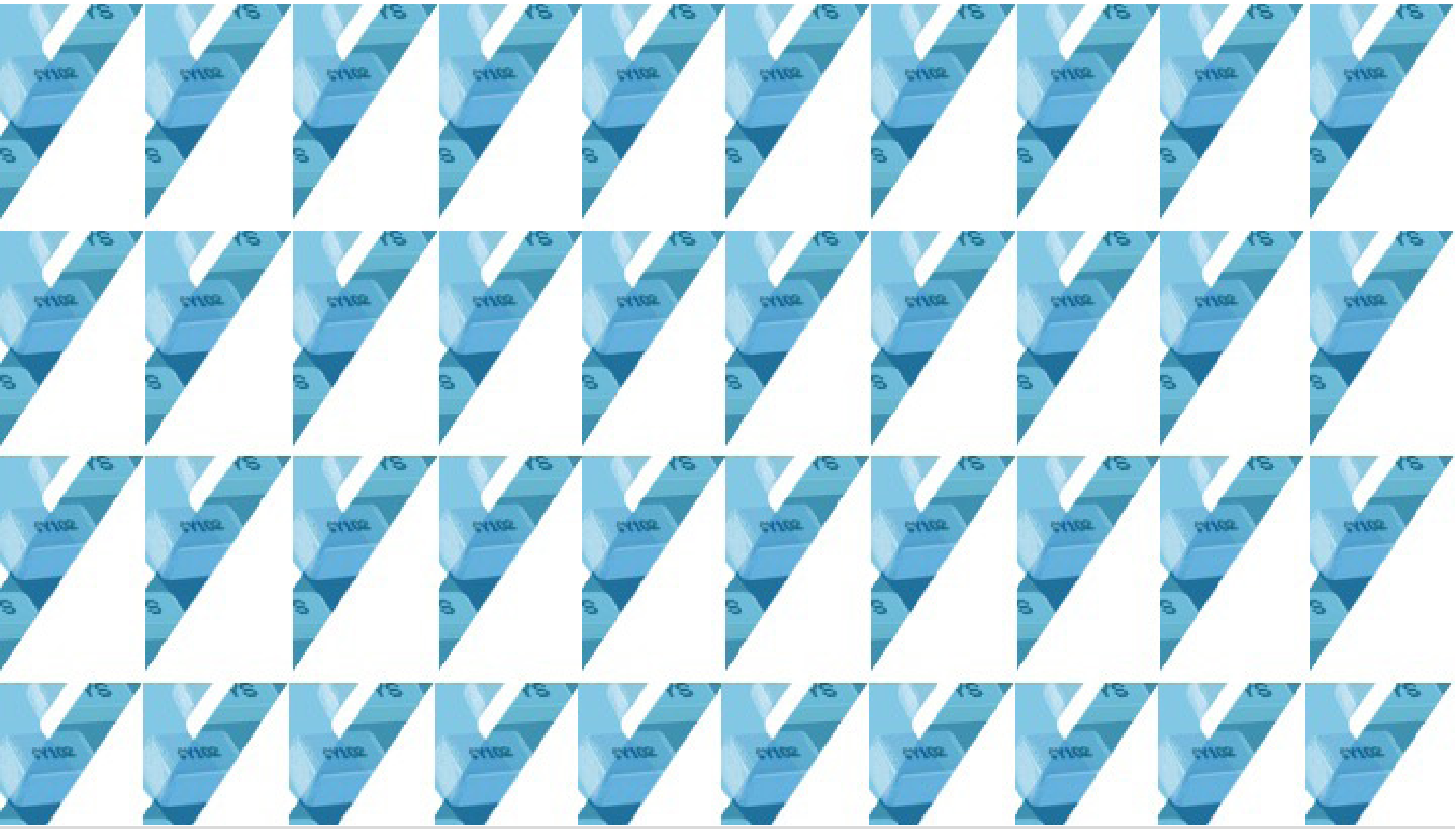


In high-voltage, high-reliability applications, safety is non-negotiable, which is why safety capacitors are essential. These passive components are engineered to mitigate the risks associated with transient voltages and electrical interference, helping protect both users and equipment from hazards, even in the event of component failure.

Beyond the need to mitigate these risks, many applications today are demanding miniaturized surface-mount components that can perform reliably at ever-increasing working and testing voltages. This is especially true for the high-voltage power electronics required for applications ranging from electric vehicle (EV) onboard chargers to datacenter servers.

To help electrical engineers address these needs, this eBook dives deep into the functionality of safety capacitors and provides in-depth guidance for selecting the best option for reliably mitigating the effects of transient voltages and electromagnetic interference (EMI), ensuring safe operation.

Topics include:

- The role safety capacitors play in a circuit
- The different classes and subclasses safety capacitors are divided into
- Dielectric material selection for your application
- How to select the appropriate safety capacitor for EMI filtering in the power factor correction (PFC) stage of an AC/DC converter
- The broad range of safety capacitor options from Knowles, including our newly expanded portfolio of enhanced safety-certified multilayer ceramic capacitors (MLCCs)

What Are Safety Capacitors?

Safety capacitors are passive electronic components designed to mitigate the effects of transient voltages and interference in electrical circuits. Safety capacitors are made to help safeguard users and equipment from electrical hazards, even in the event of failure. Since these components are commonly used in AC line filtering and power supply circuits where failure could lead to electric shock, fire, or equipment damage, safety capacitors are subject to stringent testing and certification requirements.

The Role of the Safety Capacitor

In a circuit, safety capacitors used on AC lines filter high-frequency EMI, or 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. This is known as EMI filtering, with the filter providing a safe path for noise while maintaining electrical isolation and safety.

When placed in combination with a series of inductors or resistors, safety capacitors form low-pass filters that attenuate the high-frequency signals (EMI) and allow the lower-frequency power signals to pass (Figure 1). This is the classic EMI filter setup—attenuating unwanted noise above a cutoff frequency. As more electronic devices enter the market, EMI filtering becomes even more crucial as there is an increased likelihood that EMI could cause a device to malfunction, crash, or fail.

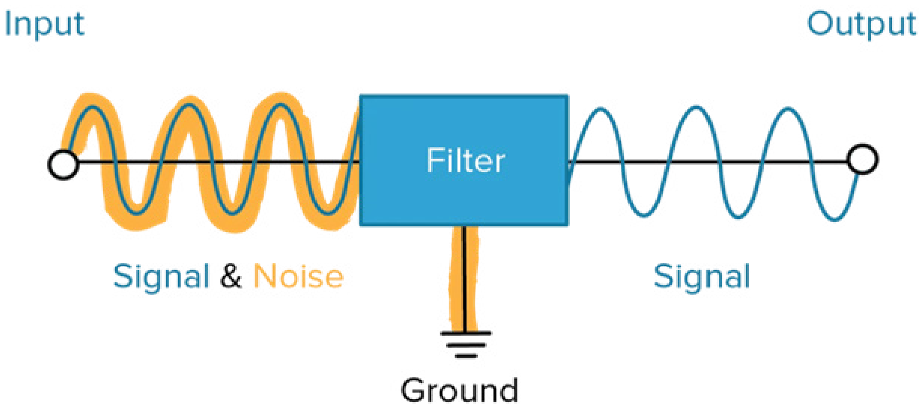


Figure 1. An illustration of how safety capacitors form low-pass filters that attenuate the high-frequency signals (EMI) and allow the lower-frequency power signals to pass.

In power electronics specifically, EMI filters take the form of power line filters that protect the line from upstream noise.

While this list may differ depending on system requirements, the core components of a power line filter include:

- A common-mode filter circuit with two or more line-to-chassis capacitors and a common-mode inductor
- A differential mode (DM) filter circuit with at least one pair of series inductors and one line-to-line capacitor
- Compensation networks to adjust the filter's quality (Q) factor and adapt the output impedance as needed
- Transient voltage suppression device(s) to defend against surges

Figure 2 shows an EMI filter structure that could be useful for single-phase AC applications or for DC power inputs.

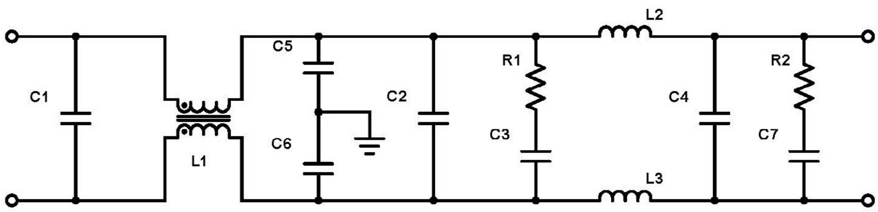


Figure 2: EMI filter structure designed for single-phase AC applications or DC power inputs.

Where Safety Capacitors are Commonly Used

To ensure safe operations and compliance with electrical safety standards, you'll find safety capacitors in nearly every electronic device developed today including:

• Industrial motor drives	• Medical devices
• HVAC systems	• Telecommunications equipment
• Consumer appliances	• Automotive electronics

For many of these applications, safety capacitors are crucial components that ensure user safety and reliable performance.

Safety Capacitor Classes

Safety capacitors are divided into two classes of capacitors – Class-X and Class-Y.

Class X Capacitors
Class-X capacitors, also known as "across-the-line capacitors," are used between the wires carrying the incoming AC current. These capacitors offer line-to-line protection, so if there is a failure, a short may occur but there is no risk of shock. This is because an X capacitor failure usually results in a short circuit, triggering a fuse or circuit breaker to open.

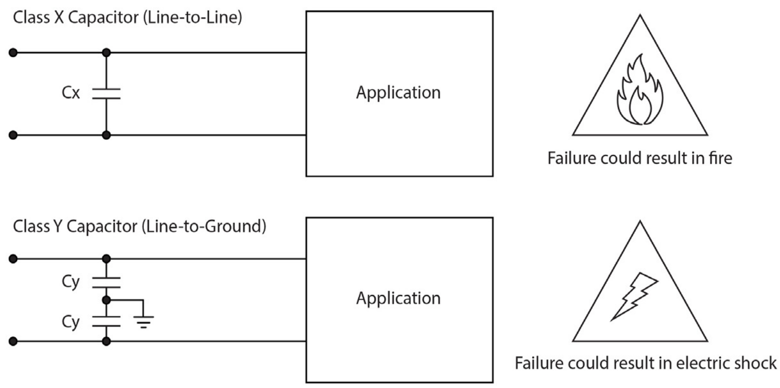


Figure 3. A representation of where Class X and Class Y safety capacitors are placed and the associated risks.

Class 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. Class-Y safety capacitors must meet rigorous specifications, and are designed to fail open, minimizing the chance of electric shock.

X/Y Capacitors
Some safety capacitors handily combine classes, for example, X1/Y2 (details below). 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 Subclasses

Both X and Y capacitors are further broken into the following subclasses according to their pulse voltage withstand capability and rated voltage (more details in Table 1):

- **X Capacitor Subclasses:**
  - **X1:** For higher surge levels (≥2.5 kV and ≤4 kV)
  - **X2:** Most common in consumer electronics (≤2.5 kV)
  - **X3:** For ≤1.2 kV, less common
- **Y Capacitor Subclasses:**
  - **Y1:** For higher insulation and impulse voltage (>500 VAC, up to 8 kV)
  - **Y2:** Common for 250 VAC operation
  - **Y3/Y4:** Lower ratings, used in less critical applications

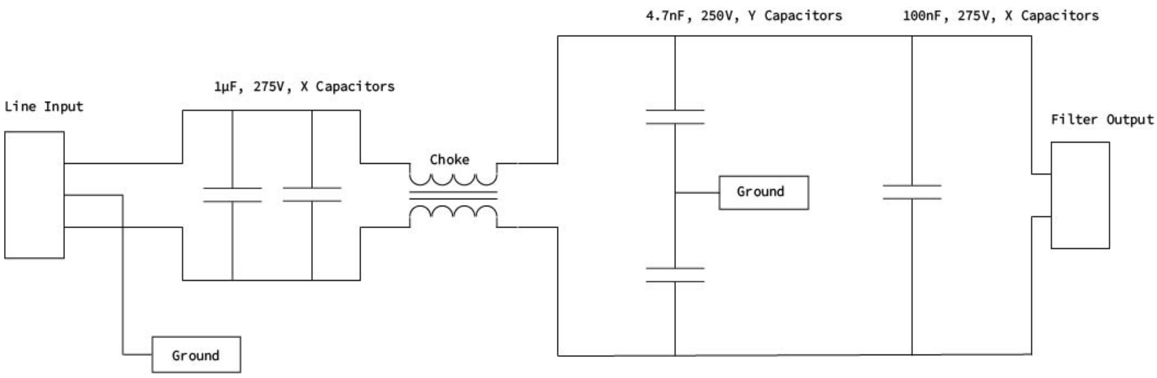
Class	Rated voltage	Impulse voltage	Insulation bridging	May be used in primary circuit
Y1	250Vac	8000V	Double or reinforced	Line to protective earth
Y2	250Vac	5000V	Basic or supplementary*	Line to protective earth
Y4	150Vac	2500V	Basic or supplementary*	Line to protective earth
X1	250Vac	4000V	—	Line to line
X2	250Vac	2500V	—	Line to line
X3	250Vac	None	—	Line to line

Table 1. A high-level overview of the key specifications for a range of different safety-certified classes.

A Real-World Example

Class X and Class Y capacitors often work in tandem within the same circuit. For example, Figure 4 shows a section of a schematic for an EMI filter board in and AC/DC power converter. In this example, the input and output X capacitors are Knowles MXT series film safety capacitors and the Y capacitors are SYS series MLCC safety capacitors.

By understanding the differences between capacitor classes and subclasses, you can optimize product development while ensuring user safety, product compliance, and reliable circuit performance.



Capacitor	Type	Example
1μF, 275V, X Capacitors	Film	MXT105K305G20
4.7nF, 250V, Y Capacitors	MLCC	2220YA250472JJTSYX
100nF, 275V, X Capacitors	Film	MXT104K305E10

Figure 4. A section of a schematic for an EMI filter board in and AC/DC power converter.

Ceramic vs. Film: Choosing the Right Technology for Your Safety Capacitors

When selecting a safety capacitor for your application, you typically have two choices in dielectric material – ceramic and film. To select the right technology for your application, it is important to both understand your requirements and the differences between what each material has to offer.

General Considerations for Selecting a Safety Capacitor Technology

When comparing whether to use an MLCC or film capacitor for your safety capacitor, you need to consider the capacitor's construction, performance characteristics, and suitability for specific safety roles as well as the capacitor's:

- Temperature range
- Size constraints
- Voltage rating
- Capacitance value
- Cost

Let's further explore the characteristics of both MLCCs and film capacitors.

Ceramic Capacitors

In general, for line-to-ground configurations, or Class Y capacitors, safety requirements dictate that failure must not result in a conductive path that could pose a shock hazard. MLCCs, when properly rated, can meet these requirements. Some benefits of using MLCCs include the following:

- Compact size, allowing for high capacitance in a small footprint, which is ideal for space-constrained designs
- Cost-effective manufacturing makes ceramics attractive for high-volume, cost-sensitive projects
- Low equivalent series resistance (ESR) and equivalent series inductance (ESL) support effective high-frequency EMI suppression

Some challenges with using ceramic include that ceramic generally has a lower voltage rating than film, which can limit its use in high-power designs. Additionally, while some MLCCs can withstand high temperatures and humidity, others may be susceptible to performance drift under environmental stress, which can impact long-term reliability.

As a result, ceramic is well suited for Y1 and Y2 safety capacitors, especially those used in appliances, chargers, or compact consumer electronics where space and cost are driving factors.

Film Capacitors

Film capacitors are most commonly used in Class X applications where they are installed across the AC line. Therefore, these capacitors must be able to withstand large voltage surges and recover from a dielectric breakdown with only a small reduction in capacitance. Advantages of using a film capacitor include the following:

- High voltage tolerance that enables reliable performance
- Self-healing properties that allow the capacitor to recover from small dielectric failures without catastrophic failure
- Excellent stability over time and varying environmental conditions to ensure long service life and consistent safety compliance

Since film capacitors are typically larger in size, it may be challenging to use these capacitors in densely packed assemblies. Film capacitors also typically cost more than ceramic options, which may be a consideration for cost-sensitive markets. As a result, film is typically a good fit for X1 and X2 safety capacitors used in industrial equipment, power supplies, or any design that must withstand line surges and operate over extended periods.

Selecting the Right Dielectric for Your Design

The choice between using ceramic or film for your safety capacitors requires a clear understanding of the capacitor's role, requirements, and environmental operating conditions. Ceramic capacitors offer compactness and cost advantages, making them well suited for many Class Y roles. Film capacitors, with their robust voltage handling and reliability, are typically the preferred choice for demanding Class X applications.

Capacitor Material	Best Suited For	Strengths	Limitations
Ceramic	Y1/Y2	Small size, low cost, high-frequency performance	Lower voltage handling, environmental sensitivity
Film	X1/X2	High voltage tolerance, self-healing, long-term stability	Larger size, higher cost

Table 2. A side-by-side comparison of ceramic and film technologies for safety capacitors.

Safety Capacitors for EMI Filtering in the PFC Stage of an AC/DC Converter

One common use for safety capacitors in an AC/DC converter is the PFC circuit. PFC circuits are required to ensure the input current is in phase with and proportional to the input voltage, improving power quality and efficiency. But the high-frequency switching that occurs in the PFC circuit can generate significant EMI. To prevent this noise from disrupting nearby electronics or violating regulatory limits, EMI filters are essential. This next section provides a comprehensive set of steps for selecting the appropriate safety capacitors to perform EMI filtering in the PFC stage of an AC/DC converter.

Step 1: Determine Your Filtering Requirements

To determine your filtering requirements, you first need to understand exactly what kind of noise you're dealing with. To do this, examine your conducted emission test data to identify frequency bands where noise exceeds regulatory limits such as those set by the International Special Committee on Radio Interference (CISPR) or the Federal Communication Commission's (FCC) Code of Federal Regulations Part 15.

Let's look at a real-world example. If your circuit fails by 25dB at 500kHz, you need to select a filter that provides at least 30dB attenuation at that frequency to ensure a 5 dB buffer for safety and component tolerance. This type of analysis provides a clear target for what your capacitor needs to block, forming the foundation for all subsequent choices.

Step 2: Match the Capacitor to Your Voltage Conditions

You also need to ensure your capacitor can safely withstand your circuit's voltage levels, including both the nominal line voltage and any expected voltage surges. When doing this, keep in mind that AC and DC voltage ratings are not interchangeable. A capacitor rated for 275V DC may not be suitable for 275V AC applications; therefore, be sure to choose capacitors explicitly rated for AC voltage.

It is also important to consider the impact of transients. For example, in an industrial environment with frequent switching, your capacitor may experience repetitive surges. Choose a safety capacitor that exceeds your worst-case voltage scenario, not just your nominal input.

Step 3: Evaluate the Circuit's Configuration

To determine the appropriate circuit configuration, you need to consider your device's impedance characteristics, required filtering performance, and any space constraints. The common configurations you might consider may range from single grounded capacitors to more complex three-element circuits.

Step 4: Assess Key Performance Parameters of Potential Capacitors

With general specs defined, you should then dig into the electrical characteristics of candidate capacitors including:

- **Capacitance Value**: Will determine filtering effectiveness at specific frequencies, which should be the dominant noise frequencies in your emissions profile.
- **ESR**: Lower ESR generally means lower losses and better performance, especially under high-frequency switching.
- **Dissipation Factor (DF)**: Represents the total losses in the capacitor and is related to both ESR and reactance.
- **Q Factor:** This is the ratio of stored versus lost energy per oscillation cycle, and, in some industries, is used as a measure of capacitor performance.

Balancing these characteristics is key to achieving effective filtering without excess heat or instability.

Step 5: Consider Construction and Installation Methods for the Capacitor

Capacitors come in many shapes and mounting styles. Therefore, it is important to evaluate the physical aspects of the capacitor including:

- **Size and Form Factor**: The capacitor must fit within your design constraints while still meeting electrical performance and thermal management requirements.
- **Installation Method**: Options can include solder-in, bolt-in, or screw-in mounting and will impact how well your capacitor can handle mechanical stress and heat dissipation
- **Environmental Ratings**: Temperature range, humidity resistance, and vibration ratings can all impact the performance and lifespan of your capacitor.

Step 6: Verify Safety Certifications and Failure Modes

Since PFC EMI filters connect directly to mains power, safety isn't optional, it's mandatory. Only use capacitors with clearly marked safety approvals, such as UL, VDE, or ENEC. Additionally, keep in mind that Class X capacitors, or "across-the-line" capacitors, should fail short to trigger upstream protection (like a fuse or breaker) and Class Y capacitors, or line-to-ground capacitors, must fail open to avoid shock hazards.

Step 7: Test and Validate Under Real-World Conditions

Finally, even the best-specified capacitor is only as good as its performance in your real system. Once installed, retest your product for both conducted and radiated EMI to verify compliance with relevant standards. And, keep in mind, EMI filtering often involves a bit of iteration and tuning, so be ready to make adjustments.

Explore Knowles' Comprehensive Safety Capacitor Portfolio

Choosing the right safety capacitor isn't just about ticking boxes on a datasheet, it's about ensuring your circuit can effectively do its job and is safe for long-term operation. To support this, Knowles offers a broad range of safety-certified multilayer ceramic (MLC) and film capacitors designed to meet rigorous standards and support diverse applications from electric EV battery systems to industrial power supplies. Below is a breakdown of what we offer.

Class X Safety Capacitors

Our Class X offerings range from 5.6 pF to 40 µF and are available in both MLCC and film formats.

Key options include:

- **SYX/UYX family:** These are both X1 and Y2 capacitors and are ideal for use in high-voltage EV battery systems
- **MXT Class X2:** Film capacitors that meet demanding 85/85 temperature-humidity-bias (THB) standards, making them ideal for use in harsh environments.

Refer to Table 3 below for a full comparison of our Class X product lines.

Class Y Safety Capacitors

Our Class Y safety capacitors, which are most commonly MLCCs, range from 5.pF to 1 µF and include the following options:

- **SYX/UYX family**
- **SYS:** Class X1/Y2 safety capacitors that have a humidity robustness grade III rating and 5kV impulse and a 1kVdc rating approved by TÜV and UL
- **MYH series:** Film capacitors that are AEC-Q200 qualified and meet a 2,000-hour THB life test. Ideal for use in many applications including motors, automated meter readers, uninterruptible power supplies (UPS), power supplies, charging systems, and appliances

Table 3 provides a comparison of the characteristics of our Class Y safety capacitor offerings.

Choosing the right safety capacitor isn't just about ticking boxes on a datasheet, it's about ensuring your circuit can effectively do its job and is safe for long-term operation.

Class	Series/ Family	Type	Voltage Rating (AC)	Voltage Rating (DC) per IEC60384-14 Annex H	Capacitance Range	Package/ Lead Type	Certifications	Special Features
X1	SYS/UYS	MLCC	305Vrms	1000V	5.6 pF – 3.9 nF	1808, 1812 SMD	UL, TÜV, CSA, IEC 60384-14	For IEC 62368, min. 4 mm creepage
X2	S2X	MLCC	1808 - 2220 (305Vrms); 2720 (310Vrms, 440Vrms, 500Vrms)	1808 - 2220 size (1000V), 2720 size (1500V)	150 pF – 10 nF	1808, 1812 SMD	UL (1808-2220), TÜV, CSA, IEC 60384-14	FlexiCap™, min. 4–5 mm creepage, AEC-Q200, humidity grade IIIB
X1	SYX/UYX	MLCC	2220 (305Vrms); 2720 (310Vrms, 440Vrms, 500Vrms)	2220 size (1000V), 2720 size (1500V)	5.6 pF – 12 nF	1808–2720 SMD	UL (2220), TÜV, CSA, IEC 60384-14	Open Mode (crack-resistant), min. 4–5 mm creepage, AEC-Q200
X1	SYM/UYM (Open Mode)	MLCC	250Vrms	1000V	150 pF – 12 nF	2220, 2720 SMD	UL, TÜV, CSA, IEC 60384-14	FlexiCap™; RoHS; AEC-Q200 (auto)
X2	S3X	MLCC	305Vrms	1000V	10 nF – 56 nF	2220 SMD	UL, TÜV, CSA, IEC 60384-14	FlexiCap™; RoHS; AEC-Q200 (auto)
X2	MXH	Film	305	630VDC	0.1 µF – 15 µF	Leaded, box	UL, CSA, VDE, CQC, IEC 60384-14	AEC-Q200; flame-retardant; self-healing
X2	MXT	Film	305	630VDC	0.1 µF – 40 µF	Leaded, box	UL, CSA, VDE, CQC, IEC 60384-14	Flame-retardant; self-healing; RoHS
Y2	SYS/UYS	MLCC	250Vrms	1000V	5.6 pF – 3.9 nF	1808, 1812 SMD	UL, TÜV, CSA, IEC 60384-14	For IEC 62368, min. 4 mm creepage
Y2	SYX/UYX	MLCC	1808 - 2220 (250Vrms); 2720 (310Vrms, 440Vrms, 500Vrms)	1000V	5.6 pF – 12 nF	1808–2720 SMD	UL (1808-2220), TÜV, CSA, IEC 60384-14	FlexiCap™, min. 4–5 mm creepage, AEC-Q200, humidity grade IIIB
Y2	SYM/UYM (Open Mode)	MLCC	2220 (250Vrms); 2720 (310Vrms, 440Vrms, 500Vrms)	2220 size (1000V), 2720 size (1500V)	150 pF – 12 nF	2220, 2720 SMD	UL (2220), TÜV, CSA, IEC 60384-14	Open Mode (crack-resistant), min. 4–5 mm creepage, AEC-Q200
Y2	MYH	Film	300Vrms	1500VDC	1.0 nF – 1 µF	Leaded, box (various sizes)	UL, CSA, VDE, CQC, IEC 60384-14, AEC-Q200	Flame-retardant; self-healing; RoHS

Table 3. A summary comparing many of our most popular Class X and Class Y capacitors.

A New Line of High-Performance Safety-Certified Capacitors

Knowles also recently released a new range of X1/Y2 safety-certified surface-mount MLCCs. With a voltage rating between 310Vrms and 500Vrms, including the first class Y2 MLCC on the market featuring a voltage rating as high as 500Vrms (Table 4), these new MLCCs are ideal for ensuring safe operation of the high-power AC/DC converters required for a variety of industrial and automotive applications.

Y2/X1	2720	
	Min	Max
310/310	5.6nF	12nF
440/440	3.9nF	4.7nF
500/500	1nF	3.3nF

Table 4. The electrical characteristics of the newest Knowles safety capacitors.

Key features of our new range of safety-certified MLCCs include the following:

- **High Working Voltage**: Voltage rating and maximum capacitance value of 12nF in 310Vac class Y2
- **Critical Safety Features in a Compact Case**: An innovative design that offers a creepage distance of up to 5 mm minimum packed into a 2720 case size, reducing required board space
- **Higher DC-Rated Voltage**: 1,500V in compliance with EN60384-14 Annex H
- **Tested for Operation in Harsh Environments:** Rated to humidity grade IIIB (85°C/85%RH,1000hr)
- **Wide Operating Range:** -55C to 125C

As with all our safety-certified MLCCs, these new capacitors are available AEC-Q200 qualified and with a flexible termination option using FlexiCap™, our proprietary flexible epoxy polymer termination material.

Whether you’re designing electrical components for EVs, consumer appliances, or industrial systems, Knowles is sure to have a safety-certified capacitor that fits your needs.

Author

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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.

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