WHITE PAPER

CONSIDERATIONS FOR SELECTING AUTOMOTIVE-GRADE MULTILAYER CERAMIC CAPACITORS FOR ELECTRIC VEHICLES

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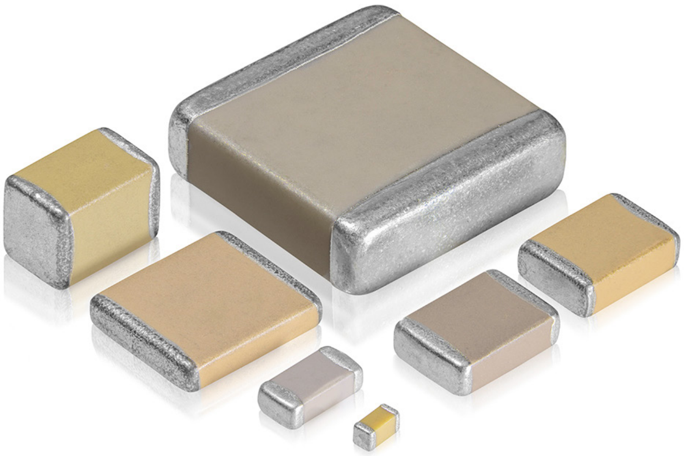
The Rise of Electric Vehicles

Today, electric vehicle (EV) adoption for both consumer and commercial purposes is rapidly growing. In 2023, EVs made up 17 percent of worldwide automobile sales. For EV design engineers and purchasing agents, this drive towards increased electrification results in the challenge of finding cutting-edge components that can handle increasing temperatures, voltage, and power without sacrificing reliability, availability, and footprint.

Multilayer ceramic capacitors (MLCCs) are commonly used in EV electronics and subsystems because of their high temperature ratings, tiny size, and easy surface mount form factor. To help you choose the right automotive-grade capacitors for your EV project, this whitepaper discusses the key considerations and certifications for EV components, common use cases in EV subsystems, and capacitor requirements for specific applications.



Choosing the right MLCC for your automotive application involves researching specifications, certifications, pricing and availability, and many other considerations.

Requirements for Automotive-Grade Capacitors

MLCCs are one of the key building blocks of control electronics, but to qualify for the EV market, these capacitors must meet specialized requirements. Important areas of consideration include:

- **High Voltage:** EV systems are based on high-voltage battery systems, so capacitors must be rated for increased ranges such as 250V to 400V for plug-in electrical vehicles (PHEVs) 800V for commercial vehicles, and 48V for hyprid eletric vehicles (HEVs).

- **High Power:** To compete with combustion engine petroleum-based vehicles that are refilled within minutes, companies are focusing on ultra-fast charging solutions, including EV systems that can handle increasing amounts of power (greater than 3.3kW) and charge directly from the grid.

- **Reduction in Size:** The vehicle's size and weight will affect its overall energy efficiency, so footprint reduction for EV subsystems (and the components they use) is a priority. Capacitors must therefore provide the same high performance within smaller dimensions.

- **High Temperature:** By pushing boundaries with increased voltages, higher converter frequencies, and smaller footprints as mentioned above, all these factors combine to create a high temperature environment that can be inhospitable to standard parts. Components must be rated to withstand and smoothly perform in those conditions.

- **Industrial Reliability:** Automotive-grade capacitors are designed to meet stringent standards of robustness, and special features have been developed for the most demanding applications that require increased reliability and superior mechanical performance.

With regards to specific certifications, the parts manufacturers you work with should be IATF 16949-certified. Published by the International Automotive Task Force (IATF), this technical specification for quality management establishes company-wide policies, processes, and documentation requirements for the automotive supply chain. IATF 16949 ensures that certified parts manufacturers meet an optimal level of quality when producing automotive- grade components for Tier 1 suppliers and OEMs.

Another essential prerequisite is compliance with the AEC-Q200 Stress Test Qualification for Passive Components, as determined by the Automotive Electronics Council (AEC) Component Technical Committee. By subjecting capacitors to rigorous thermal, mechanical, and other stress testing, this standard raises the bar for automotive versus standard capacitors. Poor mechanical design and material selection can result in component failure and short circuits, so AEC-Q200-qualified MLCCs are specifically built with a focus on reliability and robustness to function even in the harshest automotive environments.

Check out Table 1 for information on periodic AEC-Q200 tests conducted on Knowles' automotive-grade capacitors.

Test ref	Test	Termination type	Additional requirements	Sample acceptance			Reference
				P	N	C	
P1	High temperature exposure (storage)	All types	Unpowered, 1,000 hours @ T=150°C Measurement at 24 ± 2 hours after test conclusion	12	77	0	MIL-STD-202 Method 108
P2	Temperature cycling	C0G/NP0 (1B): All types X7R (2R1): Y and H only	1,000 cycles -55°C to +125°C Measurement at 24 ± 2 hours after test conclusion	12	77	0	JESD22 Method JA-104
P4	Biased humidity	All types	1,000 hours 85°C/85% RH. Rated voltage of 50V whichever is the least and 1.5V. Measurement at 24 ± 2 hours after test conclusion	12	77	0	MIL-STD-202 Method 103
P5	Operational life	All types	Condition D steady state TA=125°C at full rated. Measurement at 24 ± 2 hours after test conclusion		77	0	MIL-STD-202 Method 108
P6	Resistance to solvents	All types	Note: Add aqueous wash chemical. Do not use banned solvents	12	5	0	MIL-STD-202 Method 215
P7	Mechanical shock	C0G/NP0 (1B): All types X7R (2R1): Y and H only	Figure 1 of Method 213. Condition	12	30	0	MIL-STD-202 Method 213
P8	Vibration	C0G/NP0 (1B): All types X7R (2R1): Y and H only	5g's for 20 minutes, 12 cycles each of 3 orientations. Note: Use 8" x 5" PCB 0.031" thick 7 secure points on one long side and 2 secure points at corners of opposite sides. Parts mounted within 2" from any secure point. Test from 10-2,000Hz	12	30	0	MIL-STD-202 Method 204
P9	Resistance to soldering heat	All types	Condition B, no pre-heat of samples: Single wave solder - Procedure 2	3	12	0	MIL-STD-202 Method 210
P10	Thermal shock	C0G/NP0 (1B): All types X7R (2R1): Y and H only	-55°C/+125°C. Number of cycles 300. Maximum transfer time - 20 seconds, dwell time - 15 minutes. Air-Air	12	30	0	MIL-STD-202 Method 107
P12	Board flex	C0G/NP0 (1B): All types X7R (2R1): Y and H only	3mm deflection Class I 2mm deflection Class II	12	30	0	AEC-Q200-005
P14	Terminal strength	All types	Force of 1.8kg for 60 seconds	12	30	0	AEC-Q200-006
P15	Beam load test	All types		12	30	0	AEC-Q200-003
P16	Damp heat steady state	All types	56 days, 40°C / 93% RH 15x no volts, 15x 5Vdc, 15x rated voltage or 50V whichever is the least.	12	45	0	BS EN132100 Clause 4.14

Table 1. Periodic AEC-Q200 Tests Conducted on Knowles' Automotive-Grade Capacitors (P = period in months, N = sample size, C = acceptance criteria)

Common MLCC Use Cases in EVs

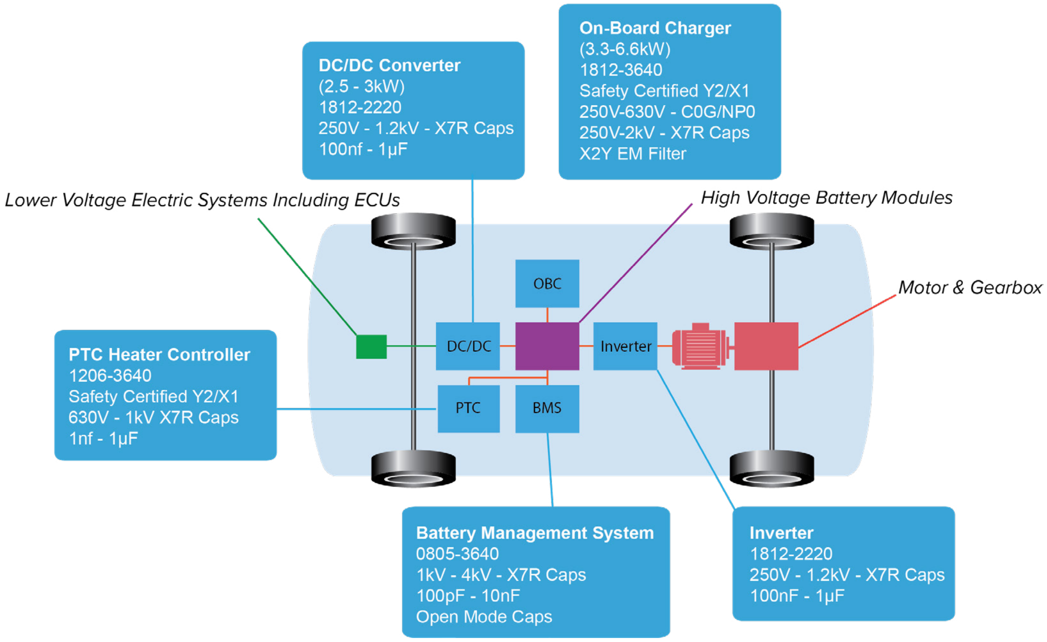


Figure 1. Main subsystems of EVs and PHEVs.

Now that the universal conditions for automotive-grade MLCCs have been discussed, let's consider the specific capacitor requirements for the major electrical subsystems in an EV. Figure 1 provides a visual overview of the five subsystems we will discuss, as well as the types of MLCCs commonly used in each area.

Battery Management System (BMS)

The goal of the BMS is to monitor and control the cells within a high-voltage battery stack. Primary functions include:

- Monitoring the battery cells' voltage, current, temperature, and overall condition
- Providing diagnostic data for the battery
- Managing the current among cells (also known as cell balancing)
- Protecting the battery from over or under charging

Safety-certified capacitors are commonly used at the input and output of major functional blocks like the BMS to help suppress the effects of electromagnetic and radio frequency interference (EMI/RFI). As seen in Figure 2, Class Y safety capacitors at the high-voltage bus and Class X safety capacitors for each cell module are added for protection from EMI noise disturbance. Plus, these capacitors can offer electric leakage protection of high-voltage systems via insulation resistance monitoring with an RC circuit.

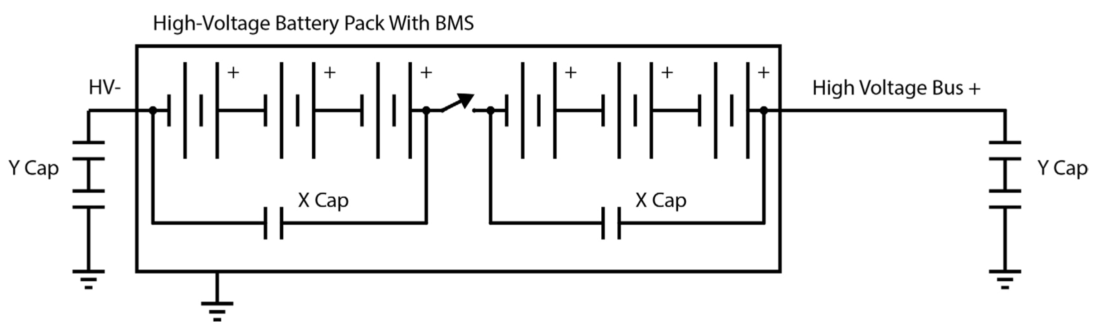


Figure 2. Simplified circuit diagram of a high-voltage battery pack integrated with a BMS.

Class X and Class Y capacitors are most commonly available as ceramic or plastic film RFI/EMI suppression capacitors. However, given the high temperature and tiny size requirements for this subsystem, MLCCs are the only viable option that will not melt in the operating conditions of the BMS. The MLCCs our customers typically use in a BMS include:

- 0805-1210 1kV-2kV 100pF-10nF X7R (2R1) capacitors (option for open mode)
- 0805-1206 50V-100V 15nF100nF X7R capacitors (options for open mode or tandem)
- 2306-2220 1kV-4kV 100pF-10nF X7R capacitors (options for safety certified and open mode)
- 2220 630V 1µF X7R capacitor

On-Board Charger (OBC)

The purpose of the OBC is to charge the traction battery, usually in a range of 48V to 800V. Functions of the OBC include:

- Converting alternating current (AC) from the electric grid into direct current (DC) that charges the vehicle's battery
- Providing power factor correction (PFC) to shape the input current to a power supply, maximizing efficiency and reducing harmonics
- Adjusting the produced DC voltage up or down to provide the correct DC levels to the battery

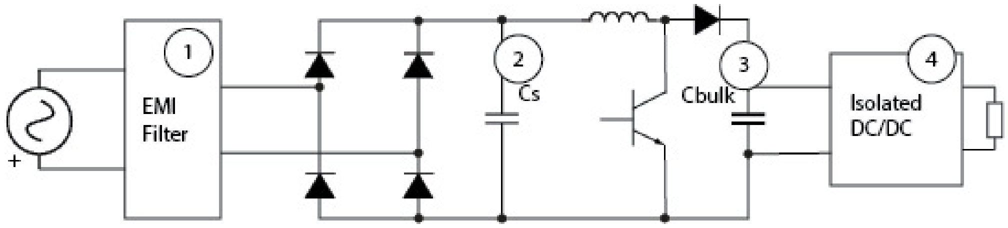


Figure 3a. Simplified block schematic for AC/DC stage of OBC.

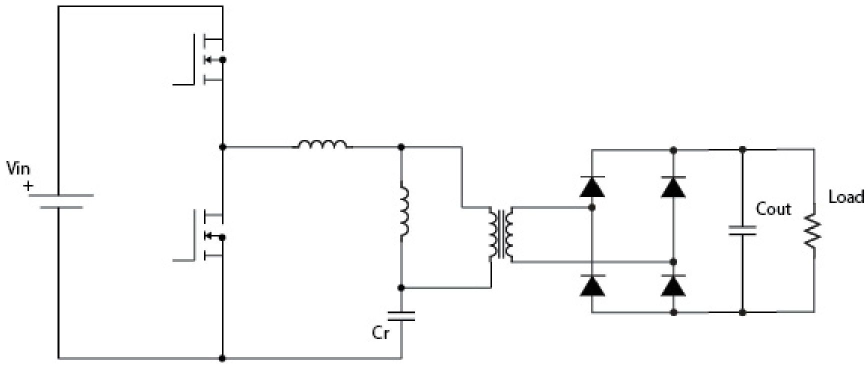


Figure 3b. Tank circuit (or oscillating circuit) in resonant system in DC/DC converter.

To accomplish these tasks, the primary sections of an OBC have the capacitor requirements, and may use the corresponding capacitors, as detailed in Table 2.

	OBC Sections	Capacitor Requirements	Recommended KPD Capacitors
1	EMI filter (or AC line filter)	Safety-certified capacitors are used to absorb the noise on the AC line and therefore must have high reliability, high voltage, and meet appropriate safety regulations (e.g., UL, CSA, VDE).	2220 X1/Y2 150pF – 10nF X7R SYX
2	PFC circuit	The PFC input capacitor Cs (see Figure 3a) protects against voltage spikes and transients, requiring robust construction of high capacitance in a small footprint.	StackiCap large capacitance/ small size MLCCs like 200V – 2kV 0.1µF – 2.2µF X7R with FlexiCap termination/Metal Frame J-Lead option available
3	DC link between the AC/DC and DC/DC converters	The DC link capacitor C*bulk* (see Figure 3a) must be able to handle twice the line frequency and support DC-link filters. Common circuit arrangements include ceramic capacitors connected in parallel with other capacitor technologies to achieve this.	StackiCap MLCCs with low equivalent series resistance (ESR) and high root mean square (RMS) current capacity like 1812 – 3640 250V – 1.5kV 56nF – 3.3uF X7R
4	DC/DC converter	One type of DC/DC topology is called the LLC converter, and it uses a resonant capacitor Cr (see Figure 3b) to tune series or parallel resonant circuits at operating frequencies in the hundreds of kHz.	MLCCs with stable capacitance, tight tolerances, and low dissipation to prevent overheating like 250V – 1.5kV 4.7nF – 100nF C0G
		The output filter capacitor C*out* (see Figure 3b) removes the ripple component of the AC current and smooths the output voltage of the power converter.	High capacitance 250V –2kV nF-µF MLCCs that connect in parallel with aluminum electrolytes

Table 2. Typical capacitor requirements for the primary sections of an OBC and recommended Knowles' capacitors to meet those requirements. (Cs = Snubber capacitor)

It is worth noting that manufacturers are now offering bi-directional OBCs that can convert residual power from the vehicle's battery and feed it back to the grid. As a result, higher MLCC component counts are used in a bi-directional OBC.

DC/DC Converter

In EVs, the DC/DC converter subsystem must transfer energy between the high-voltage battery and low-voltage (e.g., 12V) systems. The vehicle's high-voltage system supplies large loads like the traction motor, air conditioner, and starter. The lower power system is used for components like infotainment systems, sensors, and safety. Figure 4 and Table 3 show two types of capacitors commonly seen in DC/DC converters.

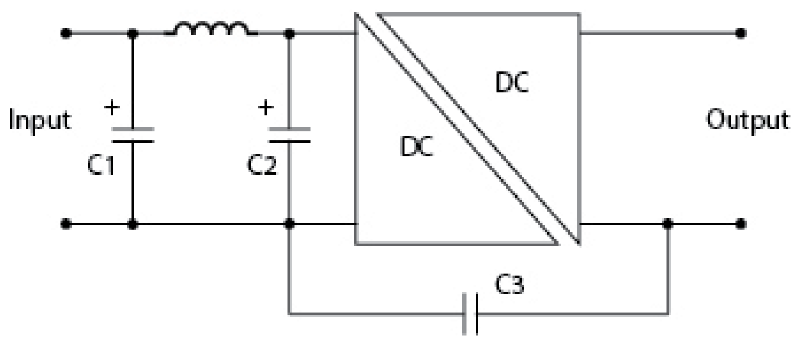


Figure 4. Circuit diagram for isolated DC/DC converter subsystem.

	Capacitor Requirements	Recommended KPD Capacitors
1	EMI filter or input capacitors C1 and C2 are used for noise countermeasures and require very high capacitance.	StackiCap 250V –1.5kV 56nF – 3.3uF X7R
2	The primary-secondary coupling capacitor C3 connects the primary and secondary ground lines to reduce the common mode noise in the secondary side caused by the primary side switching noise. The high voltage rating of the Class Y capacitor must equal the insulation voltage of the transformer.	Safety Certified class Y2/HV DC Cap 1kV – 3kV 150pF – 10nF MLCCs

Table 3. Typical capacitor requirements for the DC/DC converter and recommended Knowles' capacitors to meet those requirements.

As with the BMS subsystem, using ceramic capacitors instead of film capacitors is advised to withstand the high operating temperatures of the DC/DC converter.

Inverter

Inverters convert DC power from the battery to three- phase AC power to drive the traction motors. Important performance metrics for inverter systems include power handling capabilities, efficiency, reliability, and thermal performance. Typical motor control functions include the following:

- Converting from DC to AC during acceleration and AC to DC during braking
- Driving the insulated-gate bipolar transistor (IGBT) power stages
- Detecting the speed and position of the motor
- Diagnosing and managing potential issues to avoid inverter breakdown

Figure 5 and Table 4 show two types of capacitors commonly used in inverter subsystems.

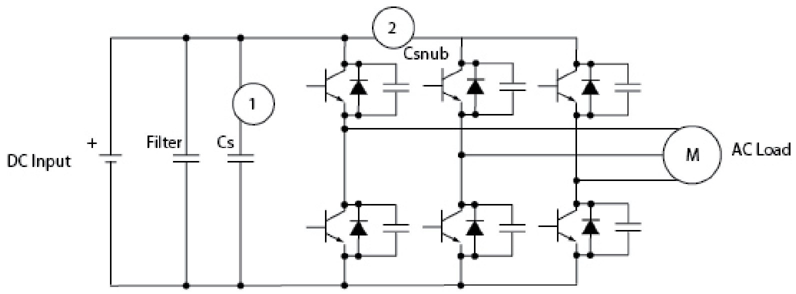


Figure 5. Inverter in motor driver circuit.

	Capacitor Requirements	Recommended KPD Capacitors
1	The DC link or smoothing capacitor Cs is placed 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 together with film and aluminum electrolytic capacitors to integrate closer to the IGBT switching device and improve high frequency attenuation.	StackiCap Class 2 dielectric 1812 – 3640 250V – 1.5kV 56nF – 3.3uF X7R with high RMS current capacity
2	The snubber capacitor Csnub protect the power switching module by absorbing noise caused by 100 – 300kHz high-frequency operation. A power integrated module (PIM) driving a 3-phase load will have at least 6 IGBTs, requiring 6 snubber capacitors to protect the switching semiconductors.	630V – 2kV pF - µF C0G or X7R with high withstand voltage, low ESR, low self-heating, and high allowable power capacity. Metal Frame J-Lead option for better resistance to mechanical stress and thermal shock.
3	EMI filters are used for noise countermeasures.	Safety-Certified Class Y or high-voltage DC-rated capacitors 150pF – 10nF MLCC X7R

Table 4. Typical capacitor requirements for the inverter and recommended Knowles' capacitors to meet those requirements.

Positive Temperature Coefficient (PTC) Heater Controller

Unlike petroleum-based cars that can warm the cabin using the combustion engine's waste heat, EVs use high- voltage PTC heaters as the heat source in the HVAC system. Not only do PTC heaters provide a comfortable cabin environment for passengers, but they maintain optimal operating temperatures for the batteries, allowing them to properly start and charge the car in cold weather. PTC heaters utilize specialized materials that, when cold, have lower electrical resistance, allowing full current to flow and heat to be generated. As the temperature increases, the resistance of the PTC material also increases. This property acts as an automatic safety feature that limits the current flow and prevents overheating. Table 5 shows common capacitors that can be used in this subsystem.

	Capacitor Requirements	Recommended KPD Capacitors
1	Class X and Y filter capacitors are used at the input of the high-voltage PTC circuit to provide EMI filter and noise countermeasures.	Safety-Certified Class Y2/X1/ High-Voltage DC Cap 1812 – 2220 630V – 3kV 4.7nF – 100nF X7R

Table 5. Typical capacitor requirements for the PTC heater controller and recommended Knowles' capacitors to meet those requirements.

Consideration for Choosing an MLCC Supplier

Not only is choosing the right capacitor important, but you also need to choose the right supplier who truly understands high voltages in the EV space. Automotive experts are accustomed to 12V or 24V applications, whereas EVs deal with medium-to-high-voltage systems ranging from 250V to as much as 800V. An experienced supplier can help advise you very early in the R&D process to help you avoid costly mistakes such as flashover and current creepage.

At Knowles, we have a long heritage of helping clients select or develop the highly reliable components required for mission-critical applications across the automotive, military and aerospace, and medtech industries . Our experts are ready to help you solve the toughest engineering challenges with components that meet demanding specifications so that you can deliver products and solutions with short turnaround times.

With the broadest range of high-voltage, high-capacitance, and small-size ceramic capacitors available, our AEC-Q200-qualified MLCCs are uniquely positioned for the automotive EV market. Our unique wet process manufacturing technique allows us to provide some of the fastest lead times in the industry and high flexibility for supporting urgent demand. Talk to us about your EV applications and find out how we can help you choose the right capacitor for your project.

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