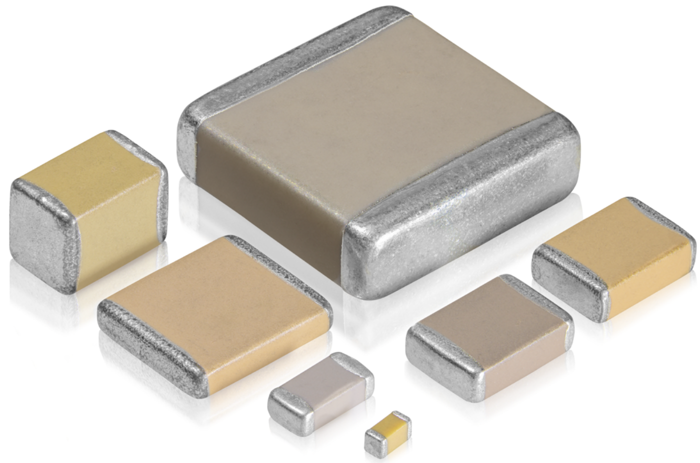
WHITEPAPER

Considerations for Selecting Automotive-Grade Multilayer Ceramic Capacitors in Electric Vehicles

THE RISE OF ELECTRIC VEHICLES

The worldwide electric vehicle (EV) market is exploding in demand and mainstream adoption as governments push for fuel economy improvements and automotive companies look for new market opportunities. According to Forbes, "by 2020, EVs are likely to cost the same as conventional fuel powered equivalents." Major manufacturers – like General Motors, Toyota, and BMW – plan to release "a mouthwatering potential of 400 models and estimated global sales of 25 million by 2025." 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. In order 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 in order to qualify for the EV market, they 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 hybrid electric vehicles (PHEVs), 800V for commercial vehicles, and 48V for hybrid electric vehicles (HEVs).

- **High Power:** In order to complete 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 the boundaries with increased voltages, higher converter frequencies, and smaller footprints as mentioned above, all of 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, the 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 Precision Devices (KPD) automotive-grade capacitors.

Test ref	Test	Termination type	Additional requirements	Sample acceptance			Reference
				P	N	C	
P1	High temperature exposure (storage)	All types	Un-powered. 1,000 hours @ T=150ºC. 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 -55ºC to +125ºC Measurement at 24 ± 2 hours after test conclusion	12	77	0	JESD22 Method JA-104
P3	Moisture resistance	All types	T = 24 hours/cycle. Note: Steps 7a and 7b not required. Un-powered. Measurement at 24 ± 2 hours after test conclusion	12	77	0	MIL-STD-202 Method 106
P4	Biased humidity	All types	1,000 hours 85ºC/85%RH. Rated voltage or 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=125ºC at full rated. Measurement at 24 ± 2 hours after test conclusion	12	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 F	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	-55ºC/+125ºC. Number of cycles 300. Maximum transfer time - 20 seconds, dwell time - 15 minutes. Air-Air	12	30	0	MIL-STD-202 Method 107
P11	Adhesion, rapid temp change and climatic sequence	X7R (2R1): A, F and J only	5N force applied for 10s, -55ºC/ +125ºC for 5 cycles, damp heat cycles	12	27	0	BS EN132100 Clause 4.8, 4.12 and 4.13
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
P13	Board flex	X7R (2R1): A, F and J only	1mm deflection.	12	12	0	BS EN132100 Clause 4.9
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, 40ºC / 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 Precision Devices (KPD) Automotive-Grade Capacitors (P = period in months, N = sample size, C = acceptance criteria)

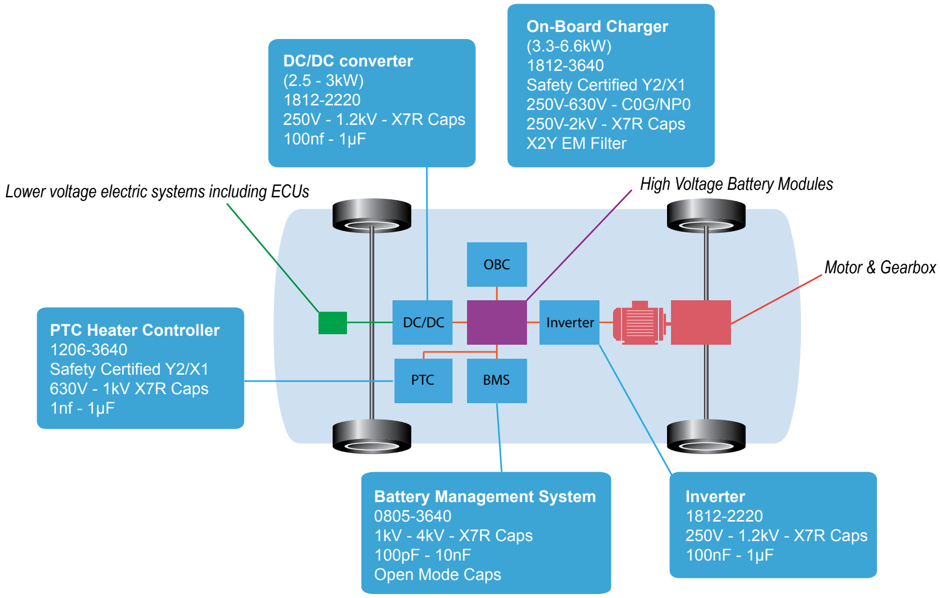


Figure 1. Main subsystems of EVs and PHEVs

COMMON MLCC USE CASES IN ELECTRIC VEHICLES

Now that the universal conditions for automotive-grade MLCCs have been discussed, let us consider the specific capacitor requirements for the major electrical subsystems in an EV. Figure 1 provides a visual overview of the five subsystems that will be discussed, 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, they can offer electric leakage protection of high-voltage systems via insulation resistance monitoring with an RC circuit.

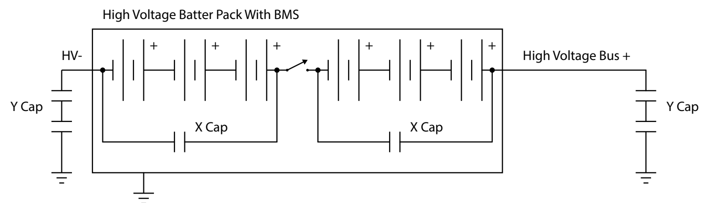


Figure 2. Simplified circuit diagram of a high-voltage battery pack integrated with BMS

Class X and Class Y capacitors are mostly commonly available as ceramic or plastic film RFI/EMI suppression capacitors. However, given the high temperature and tiny size requirements for this subsystem, MLCC is the only viable option that will not melt away in BMS operating conditions. At Knowles Precision Devices, the MLCCs our customers typically use in BMSs 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

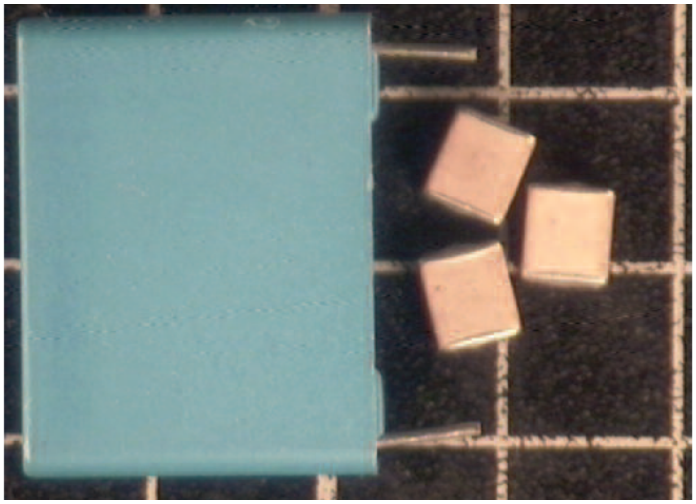


Figure 3. Size comparison of 1.04" x 0.79" x 0.43" 400VDC 1μF polypropylene (PP) film capacitor versus 0.22" x 0.20" x 0.18" 630VDC 1μF MLCC capacitors

ON-BOARD CHARGER (OBC)

The purpose of OBC is to the 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

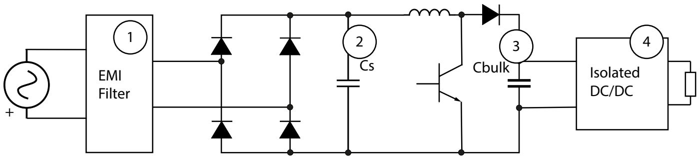


Figure 4a. Simplified block schematic for AC/DC stage of OBC

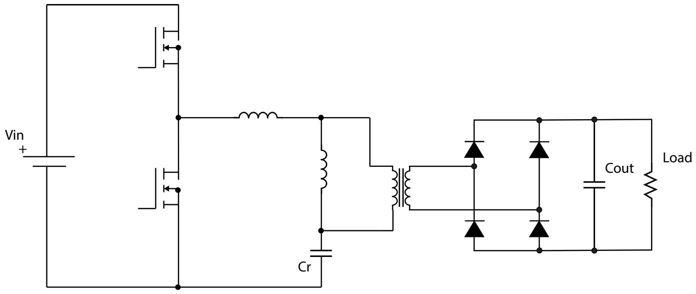


Figure 4b. Tank circuit (or oscillating circuit) in resonant system in DC/DC converter

In order to accomplish these tasks, the primary sections of an OBC (and corresponding capacitors for each circuit) may contain:

	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 and meet appropriate safety regulations (e.g., UL, CSA, VDE).	2220 X1/Y2 1nF-10nF X7R B16
2	PFC circuit	The PFC input capacitor Cs (see Figure 4a) smooths the pulsating DC voltages produced from the AC rectifier and therefore must have comparably high capacitance.	StackiCap large capacitance/ small size MLCCs like 205V-2kV 0.1µF-1µF X7R with FlexiCap termination
3	DC link between the AC/DC and DC/DC converters	The DC link capacitor C*bulk* (see Figure 4a) must be able to handle twice the line frequency. 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 1812-4040 250V-1.2kV 100nF-5.6µF 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 4b) 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 500V-1kV 4.7nF-39nF C0G
		The output filter capacitor C*out* (see Figure 4b) 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

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

DC/DC CONVERTER

In electric vehicles, the DC/DC converter subsystem is required to 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 5 and Table 3 show two types of capacitors commonly seen in DC/DC converters:

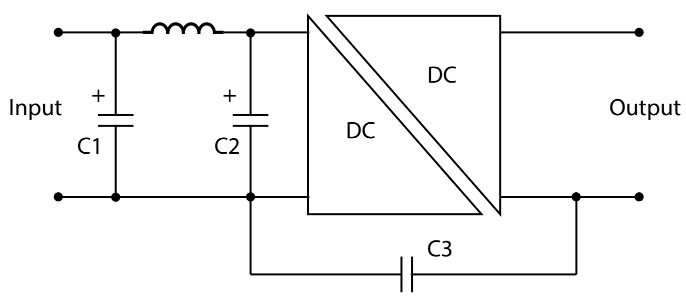


Figure 5. Circuit diagram for isolated DC/DC converter subsystem

	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 1812-3640 250V-1.2kV 100nF-1µF 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 1206-1812 1kV-2kV 2.2nF-4.7nF MLCC

As with the BMS subsystem, ceramic capacitors (instead of film capacitors) are 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:

- 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

As seen in Figure 6 and Table 4 two types of capacitors commonly used in inverter subsystems:

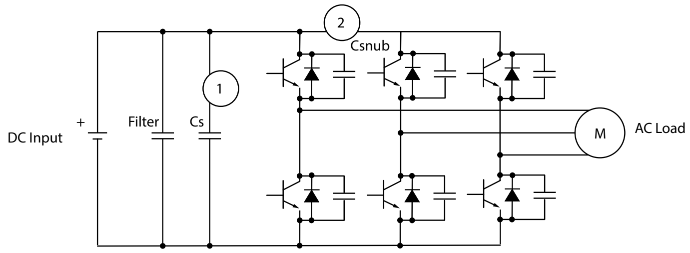


Figure 6. Inverter in motor driver circuit

	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 1812-4040 250V-1.2kV 100nF-5.6μF X7R with high RMS current capacity
2	The snubber capacitor Csnub protects 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 nF- μF C0G or X7R with high withstand voltage, low ESR, low self-heating, and high allowable power capacity

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 heating, ventilation, and air conditioning (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. Common capacitors in this subsystem include:

	Capacitor Requirements	Recommended KPD Capacitors
1	The power supply unit (PSU) circuitry in the controller requires high-voltage capacitors for snubbering, and primary-secondary isolation purposes.	1206-3640 1kV-2kV 1nF-1μF X7R
2	Class X and Y filter capacitors are used at the input of the high-voltage PTC circuit to provide EMI filter and noise countermeasures.	Y2/X1 1812-2220 630V-2kV 100nF-1μF X7R

CONSIDERATIONS 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 electric vehicle space. Automotive experts are accustomed to 12V or 24V applications, whereas EVs deal with medium to high voltage from 250V to as much as 800V systems. An experienced supplier can help advise you very early in the research and design process to avoid costly mistakes like flashovers and current creepage.

With more than 200 years of combined knowledge and expertise, Knowles Precision Devices is the premier global source for Syfer, Novacap, Dielectric Laboratories (DLI), and other name-brand capacitors. We have a long heritage of helping clients with mission-critical applications – such as automotive, military/aerospace, and medical devices – that must have high-end performance and superior reliability. Our team of experts are ready to help you solve tough engineering challenges, find components that meet demanding specifications, and deliver products and solutions with short turnaround time.

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

Contact Us

ABOUT KNOWLES PRECISION DEVICES

At Knowles Precision Devices we make multilayer, high reliability, single layer and precision variable capacitors, EMI filters, and microwave components. Headquartered in Itasca, Illinois, our global scale of 8,500 employees in 30 locations worldwide includes design centers in Europe, Asia and North America. Coupled with our significant investment in research and development, our scale enables us to remain agile and efficient and deliver ground breaking technology to our customers with high-volume economies.

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