High-Energy Density Capacitors for Electric Vehicle Traction Inverters

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***Abstract*—DC bus capacitors take up substantial space in a traction inverter, limiting the traction drive power density. Thus, several commercial capacitor technologies, under consideration for use as DC bus capacitors for electric vehicle traction inverters, were reviewed for their ability to optimize the volume of traction inverters and are evaluated in this paper. Three promising capacitor technologies–film, ceramic, and PLZT have been selected for detailed experimental characterization. Experimental results for equivalent series resistance, equivalent series inductance, and effective capacitance with respect to DC bias voltage for various operating frequencies and temperatures are presented. The results reveal the superiority of the PLZT capacitor in terms of power density, current conduction capability, and redundancy.**

Keywords*— *Electric traction drive, PLZT capacitor, high-energy density capacitor, capacitor characterization

I. Introduction

THE purpose of the DC bus capacitor within a voltage source traction inverter is to decouple the load from the DC supply unit. Thus, the bus capacitor absorbs a large ripple current generated by the inherent switching sequence of the inverter. The DC bus capacitor for a three-phase inverter can take up to 60% of the root mean square (RMS) load current [1], [2]. The capacitor must store a certain amount of energy to avoid a large DC bus voltage ripple [3], [4]; thus, the capacitor occupies substantial space within an inverter. The volume breakdown of traction inverters found in the literature indicates that the capacitor bank can take up 30% of inverter space [5]. Therefore, minimizing the volume and maximizing the power and energy density of the capacitor bank is crucial to optimize the traction inverter's volume.

A simplified equivalent circuit of a capacitor with four different components (Fig. 1) shows the component values are not fixed but depend on operating conditions (e.g., temperature, frequency, DC bias voltage). The combined electrode and dielectric losses are modeled as equivalent series resistance (ESR), which is a limiting factor for the current conduction

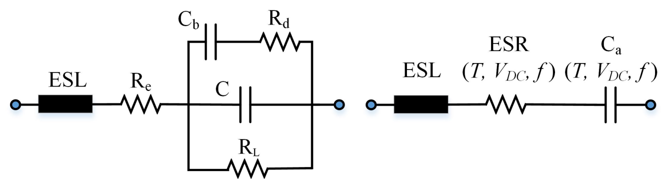

Fig. 1: Lumped parameter circuit model of a capacitor.

capability of a capacitor. The capacitors' termination and electrode inductances are modeled as equivalent series inductances (ESL) that contribute to the commutation loop inductance of the inverter, thus deteriorating the switching performance of the inverter. Finally, the capacitance and DC losses due to capacitor current are represented as C and ESR, respectively. These parameters are highly dependent on operating temperature (T), bias voltage (V_{DC}), and operating frequency (f). Thus, it is necessary to extract the equivalent circuit parameters of a capacitor accurately for volume optimization.

Volume optimization of a DC bus capacitor for three-phase motor drive applications has been studied in several papers. In [2] and [6], the process of identifying the RMS current stress on the DC link capacitor, along with the required capacitance for a three-phase inverter, is presented for the optimal selection of the capacitor bank. A new modulation technique is proposed in [7] to reduce the DC link capacitors RMS current stress for a dual three-phase motor. In this method, two three-phase inverters are utilized instead of a single inverter; thus, overall inverter volume may not be optimized. In [8], an additional current source inverter is used to control the DC link voltage at the low-speed region, thus reducing the RMS current stress of the DC link capacitor. This method will increase the capacitor lifetime by reducing capacitor losses but will adversely affect the overall inverter's volume. Other papers discuss different capacitor technologies and their advantages and disadvantages for motor drive applications [9], [10]. Although DC link capacitor volume optimization topics for three-phase motor drive applications are widely discussed in the literature, very few references compare different capacitor technologies for the inverter volume optimization.

This paper presents an overview of suitable capacitor technologies that can be utilized for electric vehicle (EV) traction inverters. Three promising capacitor technologies under consideration for use as a DC bus capacitor for EV traction

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inverters, are identified. A laboratory test bed has been set up for detailed characterization to determine the best capacitor technology in terms of energy density, current conduction capability, and high-temperature handling capability.

II. Emerging and Existing Capacitor Technologies

The most commonly used DC bus capacitors available on the market are electrolytic capacitors, ceramic capacitors, and film capacitors. Electrolytic capacitors have the lowest cost and the highest energy density. Although these capacitors are the most popular choice for conventional motor drive applications, their short lifespan, limited current conduction capability, and low-frequency operation [9], [11] make them untenable for use as DC bus capacitors in EV traction inverters. Thus, in this paper, characterization of electrolytic capacitors is not presented.

In contrast, film capacitors are widely used as DC bus capacitors for EV traction drive applications due to their higher reliability, high current conduction capability, high-frequency operation, and lower ESR compared to electrolytic capacitors. Film capacitors use plastic/polymers as the dielectric and have very low temperature dependency; thus, the change in the dielectric characteristic is minimal. The relative permittivity of these dielectrics is low (i.e., 2-3), and therefore, film capacitors are bulkier in comparison to electrolytic capacitors. Furthermore, the operating temperature of commercially available film capacitors is also low, $\sim$105°C, thus necessitating an active cooling strategy [12]. Owing to these factors, film capacitors may not be the optimal choice for the next generation of power-dense inverters.

The third promising candidate for use as a DC bus capacitor is the ceramic capacitor, which uses ceramic dielectric with a very high dielectric constant. These capacitors can be constructed using a single-layer structure for small capacitance or by stacking multiple layers to achieve higher capacitance; the latter is commonly known as the multilayer ceramic capacitor (MLCC). These capacitors have a much higher RMS current rating, can withstand higher temperatures, and have much higher energy density than film capacitors. The most common dielectric used in MLCCs is barium titanate ($BaTiO_3$), which is a class II ferroelectric dielectric material, and the parameters are highly temperature dependent [13]. Table I and Table II present the properties of common dielectric materials in high-power capacitors. Moreover, the capacitance of the class II ceramic capacitor decreases rapidly with the DC bias voltage. Thus, a higher number of capacitors are required for a given energy density compared to film capacitors; this introduces an additional challenge in the capacitor layout for equal current distribution. There are also reliability issues associated with ceramic capacitors; the ceramic dielectric material is rigid and can crack due to mechanical and thermal stress, thus creating a short-circuit between DC terminals [13]. Therefore, ceramic capacitors have not gained popularity for safety-critical applications such as EV traction inverters.

Another emerging ceramic capacitor technology available on the market is the PLZT (lead lanthanum zirconate titanate)--based capacitor. The PLZT is an antiferroelectric dielectric material that can withstand higher currents and temperatures [17]. Unlike ferroelectric material, the antiferroelectric material exhibits an incremental capacitance with respect to the bias voltage, and it can store a much higher amount of energy than the ceramic capacitor at rated DC voltage. Furthermore, the PLZT capacitor is more reliable compared to MLCCs. Its reliability is achieved by utilizing the series connection of two MLCC geometries in one component, meaning the capacitor will be operational in the event of a crack in the dielectric (Fig. 2). The copper electrodes on these capacitors improve electrical and thermal performance and can withstand a higher operating temperature (150^{o}C); thus, these capacitors may enable development of high-power density traction inverters.

To compare available capacitor technologies, 50 samples of ceramic, PLZT, and film capacitors were chosen, and their capacitance density and energy density were plotted (Fig. 3 and Fig. 4). These commercial-off-the-shelf capacitors have

TABLE I: Dielectric constant of different materials.

Material	Class 1 ceramic	Class 2 ceramic	PLZT	Plastic/ polymer
$BaTiO_3$	-	300 - 7000	-	-
$Ba_2Ti_9O_20$	40	-	-	-
$(ZrSn)TiO_4$	37	-	-	-
$ZnTaO_6$	37	-	-	-
PLZT	-	-	500 - 1500	-
Polypropylene	-	-	-	2.2
Polyethylene	-	-	-	2.3

TABLE II: Dielectric material characteristics.

Material	Temperature dependency	Capacitance with bias	Operating temperature
$BaTiO_3$	High	↓↓↓	High
$Ba_2Ti_9O_20$	Stable	–	High
$(ZrSn)TiO_4$	Stable	–	High
$ZnTaO_6$	Stable	–	High
PLZT	High	↑↑	High
Polypropylene	Stable	–	Low
Polyethylene	Stable	–	Low

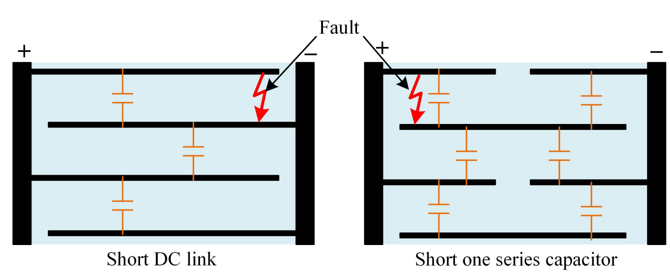

Fig. 2: Schematic of a multilayer ceramic capacitor (left), series connected multilayer PLZT capacitor (right).

TABLE III: Comparison of selected capacitors parameters.

	Film ECW-FE2W105J [14]	MLCC C5750X7T2W105K250KA [15]	PLZT B58031U5105M062 [16]
Material	Metallized polypropylene	BaTiO3	PLZT
Capacitance	1 μF	1 μF	1 μF
Dimensions	17.6 x 7 x 12.5 mm	5.6 x 4.9 x 2.5 mm	7.5 x 8.3 x 4.5 mm
Current rating @ 50 kHz, Ta = 85°C	3.5 A	5 A	8 A
Max. voltage	450V	450V	650V
Max. temperature	105°C	125°C	150°C
Temperature rise	case to ambient - 20°C	case - 125°C	case - 150°C

rated voltages between 450 and 1000V. It can be seen from Fig. 3 that the PLZT capacitor has the highest energy and capacitance density, and thus it can be used to optimize the traction inverter's volume.

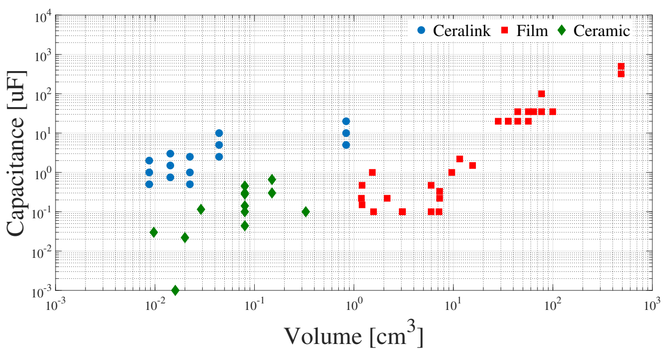

Fig. 3: Capacitance density of three selected capacitor technologies [18].

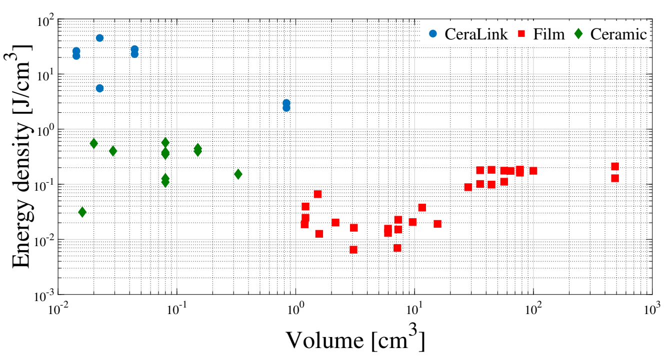

Fig. 4: Energy density of three selected capacitor technologies [18].

To optimize the DC bus capacitor volume, three capacitor technologies–film, MLCC, and PLZT were selected for detailed experimental characterization. The objective was to identify the equivalent circuit (shown in Fig.1) parameters of the selected capacitors for various temperatures, bias voltages, and frequencies. The datasheet parameters of the selected capacitors are shown in Table III. The results of the detailed experimental characterization of the selected capacitors is discussed in the following section.

III. Experimental Setup and Results

The selected capacitors' performance was examined under operating conditions replicating traction inverter operation. The DC bus capacitor used for a traction inverter is charged by a DC source (i.e., battery); thus, the capacitor always sees the rated DC voltage. The RMS current amplitude seen by the capacitor is dependent on the modulation index and the power factor. It was proven in [2] that the maximum RMS current stress, which is more than 60% of the phase current, occurs around 0.5 modulation index at unity power factor. Moreover, the frequency of the DC link current is the same as the switching frequency. Thus, a PCB-based capacitor characterization board is developed incorporating selected capacitors and an adjustable isolated DC-DC power supply (Fig. 5). This PCB is used to characterize the capacitors under various DC bias voltage (0V - 400V), various operating temperatures (25°C - 100°C), and injection frequencies up to 200kHz.

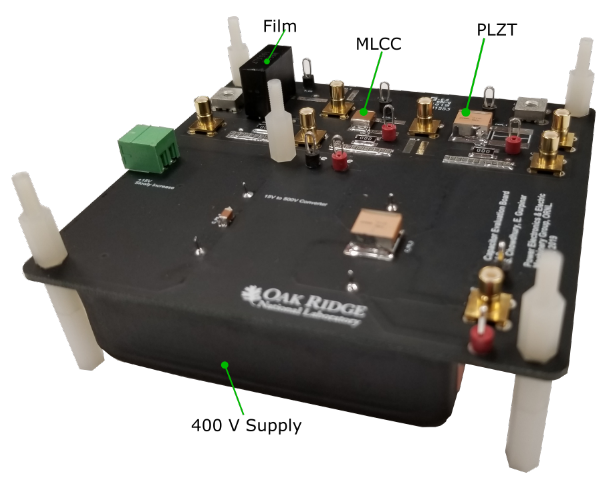

Fig. 5: PCB-based capacitor characterization board.

The test setup used to adjust the operating point of the capacitor is shown in Fig. 6. A small sinusoidal signal was injected using a frequency response analyzer, and then the current and voltage across the capacitor under test (CUT) were measured to calculate the ESR and the capacitance variation during different operating conditions. The frequency of the AC signal varied from 5kHz to 200kHz, and a 400V DC source was used in series with the AC source to vary the bias voltage of the CUT. A linear amplifier was used to control the amplitude of the AC signal in conjunction with an isolation transformer to protect the oscillator port of the

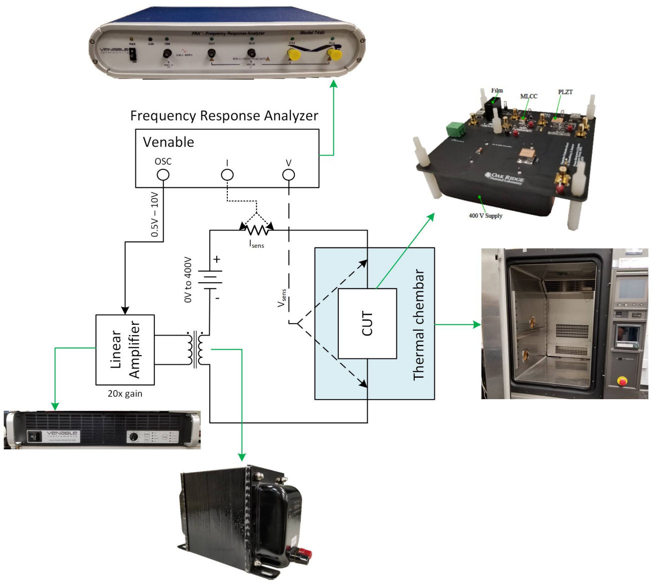

Fig. 6: Experimental setup to adjust the capacitors operating point.

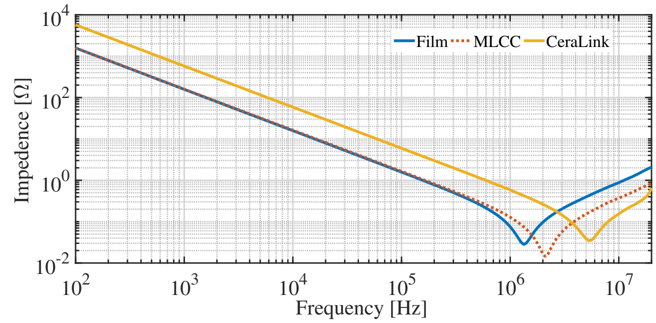

Fig. 7: Impedance variation of the selected capacitors, V_{DC}=0V.

frequency response analyzer. The input current and voltage ports of the analyzer were isolated up to 600V, so no isolation was required for these ports. The CUT was enclosed in an environmental chamber to determine the characteristics under various operating temperature (25°C, 50°C, 75°C, and 100°C). The test results for the selected capacitors are plotted in Figs. (7-17).

The impedance plots (Fig. 7) of the selected capacitors show that the resonant point of PLZT-based capacitor is around 5.5MHz meaning the PLZT will behave as a capacitor up to a couple of MHz operating frequency which is much higher than film and MLCC. The ESR results of the selected capacitors are presented for zero-bias condition and full-bias (400V) condition to show the difference. The results indicate that the film capacitor has the lowest ESR at room temperature (Fig. 8 and Fig. 9), meaning the losses in the capacitor will be lower and will increase slightly with increased operating temperature. However, the bottleneck in the film capacitor is the fixed temperature rise due to self-heating [19]; the self-heating temperature for the selected capacitor is 20^{o}C. This limited temperature rise significantly reduces the film capacitor's current conduction capability.

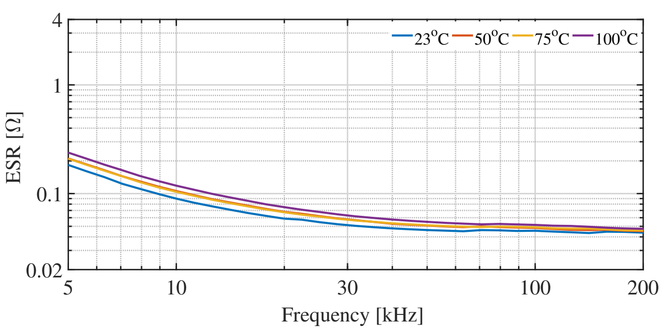

Fig. 8: Variation of ESR with respect to frequency and temperature in Film capacitor, V_{DC}=0V.

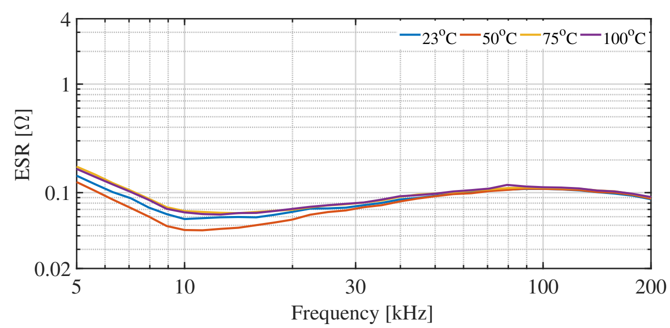

Fig. 9: Variation of ESR with respect to frequency and temperature in Film capacitor, V_{DC}=400V.

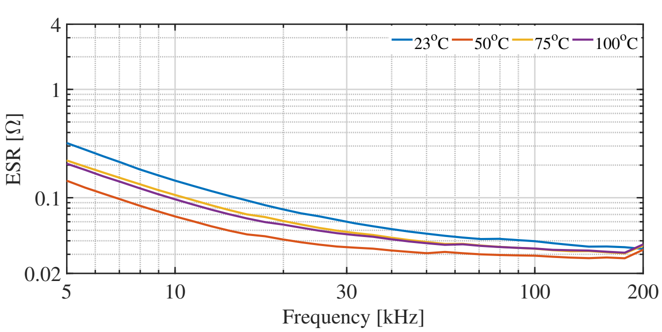

Fig. 10: Variation of ESR with respect to frequency and temperature in MLCC capacitor, V_{DC}=0V.

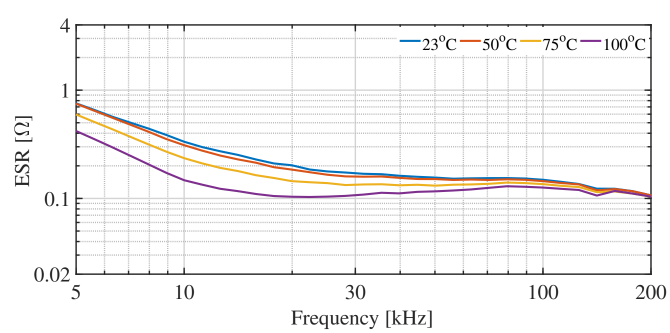

Fig. 11: Variation of ESR with respect to frequency and temperature in MLCC capacitor, V_{DC}=400V.

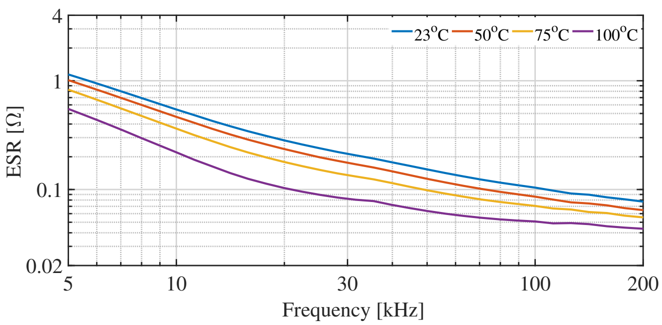

Fig. 12: Variation of ESR with respect to frequency and temperature in PLZT capacitor, V_{DC}=0V.

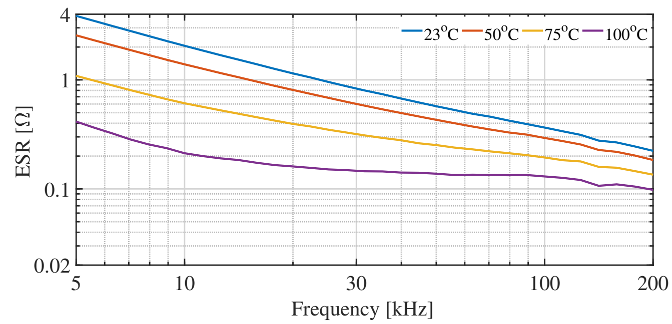

Fig. 13: Variation of ESR with respect to frequency and temperature in PLZT capacitor, V_{DC}=400V.

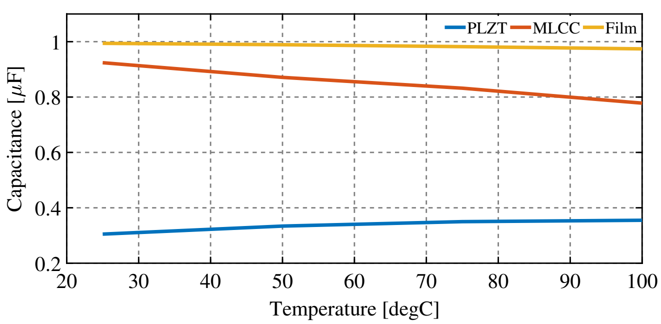

Fig. 14: Variation in capacitance with respect to operating temperature, V_{DC}=0V.

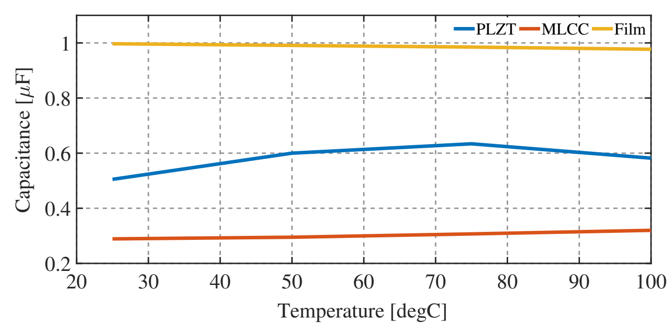

Fig. 15: Variation in capacitance with respect to temperature, V_{DC}=400V.

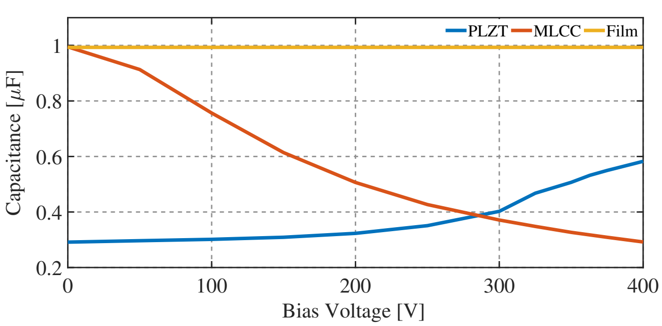

Fig. 16: Variation in capacitance with respect to different bias voltage.

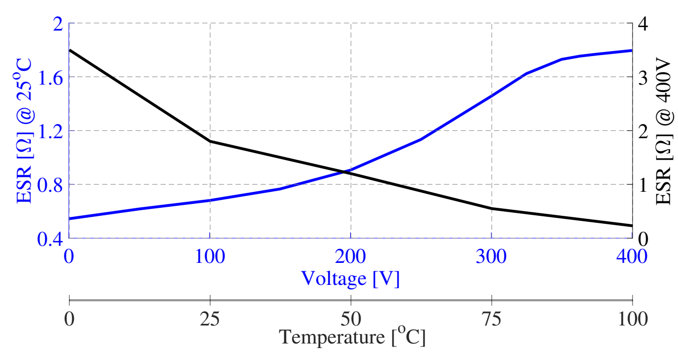

Fig. 17: Variation in ESR with respect to bias voltage and temperature for the selected PLZT-based capacitor.

The film capacitor can conduct only 4 Amps of current, necessitating heat sink to support a higher current or higher temperature operation. In contrast, the PLZT and ceramic capacitors have much higher maximum operating temperatures and no obstruction on the self-temperature rise. Thus, ceramic and PLZT capacitors can conduct much higher current.

Although MLCC and PLZT based capacitors can conduct higher current than the film capacitor, higher ESR at room temperature and with DC bias condition makes it worse. It can be seen from Fig. 10 - Fig. 13 that the ESR of the PLZT and MLCC based capacitors significantly increases with DC bias at room temperature, then again, decreases significantly with higher operating temperature and becomes almost equal to the ESR of the film capacitors.

This means that the losses in MLCC and PLZT capacitors decrease with temperature for a given frequency. This change in ESR is rapid in PLZT based capacitors and are plotted in Fig. 17 which show that even though ESR in PLZT capacitor increases with increased DC bias the higher operating temperature will bring it down to a lower ESR value thus the PLZT based capacitors can take much higher current among the three selected capacitor technologies. The variation of capacitance with DC bias voltage and operating temperatures of the selected capacitors are shown in Fig.14 - Fig.16. It is evident from Fig. 16 that the capacitance of the film capacitor is independent of the DC bias voltage but decreases by 2% with higher operating temperature (Fig.14 and Fig. 15).

In contrast, the capacitance of the ceramic capacitor decreases by 70% with DC bias voltage but increases with

TABLE IV: Identified parameters along with the advantages and disadvantages of the selected capacitors.

Parameter	Film	MLCC	PLZT
Energy density	80 J/dm^3	350 J/dm^3	172 J/dm^3
Capacitance density	0.47 mF/dm^3	4.37 mF/dm^3	2.25 mF/dm^3
Thermal runaway	Immune	Prone	Immune
Reliability	High	Low	Medium
Temperature	105°C	125°C	150°C
Inductance, ESL	High	Medium	Low
Current carrying capability)	4 Amps @ 50 kHz, 85°C 0 Amps @ 50 kHz, 105°C	5 Amps @ 50 kHz, 85°C 3.5 Amps @ 50 kHz, 105°C	8 Amps @ 50 kHz, 85°C 6.5 Amps @ 50 kHz, 105°C
Actual ESL)	13 nH @ 10 MHz	4.58 nH @ 10 MHz	3.57 nH @ 10 MHz
ESR)	Low	Medium	Medium
BMW-13 capacitor (0.644 L))	0.612 L	0.123 L	0.155 L

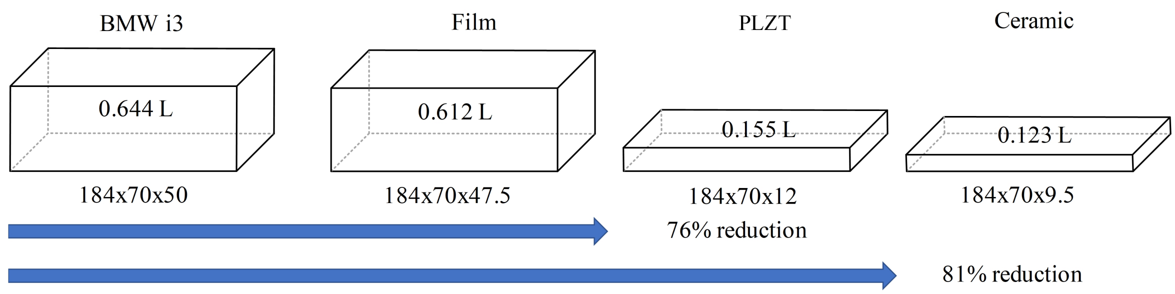

Fig. 18: Volume comparison of selected capacitors with respect to the BMW i3s capacitor volume.

higher operating temperatures. Increase of capacitance will decrease the impedance of the capacitor thus the capacitor with higher temperature will take more current and may experience thermal runaway, resulting in capacitor's failure. The PLZT capacitor demonstrates slightly different characteristics: unlike the ceramic capacitor, the capacitance of the PLZT capacitor increases with the bias voltage (up-to 400V) and with temperature (up-to 75°C) and then decreases with increased voltage and temperature. The capacitance reaches the maximum value (0.63 μF) at 400V DC bias when the operating temperature is 75°C, and the capacitance value decreases with incremental changes to the operating temperature (Fig. 15). The decrease in capacitance increases the capacitor impedance after 75°C, meaning the hottest capacitor will conduct the lowest current (positive temperature coefficient), ensuring natural current balancing through parallel capacitor branches thus increase reliability of the PLZT capacitors by avoiding thermal runaway. Table IV shows the identified parameters along with the advantages and disadvantages of the three capacitors.

It can be seen from Table IV that the PLZT capacitor has much higher energy and capacitance density than the film capacitor. Though the PLZT capacitor exhibits higher loss (i.e., higher ESR), it is counterbalanced by the high temperature and high current operation. When the capacitor is also compared with the BMW i3 traction inverter capacitor bank, it can be seen that the use of the PLZT capacitor can bring down the capacitor volume of the BMW i3 traction inverter by 70%. Relative volumes are shown in Table IV and in Fig.18

IV. Conclusion

In this paper, different capacitor technologies were reviewed to optimize EV traction inverter volume. Three promising capacitor technologies have been identified, and their advantages and disadvantages were summarized. A laboratory test bed has been set up to characterize the selected capacitors at rated voltage under different operating temperatures and frequencies. The results show that the PLZT capacitor has much higher energy density than the film capacitor, higher current conduction capability than the film and ceramic capacitors, and much higher reliability than the ceramic capacitor. Using PLZT capacitors could substantially reduce the volume of the passive component in traction inverter, providing a solution for development of high-power density traction inverters for EV applications.

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