J Electr Eng Technol Vol. 8, No. 4: 808-812, 2013
http://dx.doi.org/10.5370/JEET.2013.8.4.808

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Design and Analysis of Electrical Properties of a Multilayer Ceramic Capacitor Module for DC-Link of Hybrid Electric Vehicles

Jung-Rag Yoon†, Bong Hwa Moon*, Heun Young Lee, Dae Yong Jeong*** and Dong Hee Rhie*****

Abstract – Multilayer capacitors with high ripple current and high capacitance were manufactured. The electrical properties of these capacitors were characterized for potential application for DC-link capacitors in hybrid electric vehicle inverters. Internal electrode structures were designed to achieve high capacitance and reliability. A single multilayer capacitor showed 0.46 $\mu F/cm^3$ of capacitance, 0.65% of dielectric loss, and 1450 V to 1650 V of dielectric breakdown voltage depending on the design of the internal electrode. The capacitor module designed with several multilayer capacitors gave a total capacitance of 450 μF, which is enough for hybrid electric vehicles. In particular, an equivalent series resistance of 4.5 mΩ or less will result in 60 A_{rms}, thereby reaching the allowed ripple current for hybrid electric vehicles.

Keywords: Multilayer ceramic capacitor, Hybrid electric vehicle, Ripple current, ESR

1. Introduction

In this era of renewable energy and smart grid systems, the power electronics industry needs more efficient energy conversions and larger volumes of inverter devices. Switching devices, such as insulated-gate bipolar transistors, passive devices, and capacitors, are major devices that determine energy conversion efficiency in an inverter circuit. High-power capacitors must be capable of enduring high ripple current. Aluminum electrolytic capacitors are currently applied in economical and miniaturization aspects. Complementary metal deposited films are increasingly applied to increase reliability of film capacitors [1-3]. However, this type of capacitor has a large volume, thus prompting many researches to develop compact capacitors [3]. Compact capacitors for DC-link application require capacitor materials to have large breakdown voltage per unit thickness of film and high dielectric constant. Capacitors should be thin and wide through complex modularity. High-power DC-link capacitors should also have high temperature reliability, reduced volume and weight, and economic feasibility [4, 5]. In terms of capacitance and high temperature reliability, multilayer capacitors based on ceramic dielectric substance, such as $BaTiO_3$, are preferred over polymeric films because the former has a 1000-fold higher dielectric constant [5-7]. Increasing the capacitance per unit volume of the ceramic multilayer capacitor also means increasing the number of layers but still maintaining the thinness of the dielectric substance. However, increasing the number of dielectric layers increases the number of electrode layers between dielectric substances, thus resulting in higher fabrication costs. Thus, cheaper electrodes such as Ni have been widely applied to internal electrodes instead of precious metals, such as Ag, Ag-Pd, Pd, and Pt. Most studies on electrodes focus on general products for capacitors in electronic circuits, but rarely on high-power and high-voltage electrodes. This study manufactured a multilayer chip capacitor, which enables high power, high voltage, and high capacitance, in a reduction atmosphere by applying Ni internal electrode. An internal electrode was specifically designed to withstand voltage and capacitance required by hybrid electric vehicle inverters. The temperature, frequency, and ripple characteristics of the internal electrode were characterized, and the applicability of the internal electrode to power inverters was verified.

† Corresponding Author: R&D Center, SAMWHA CAPACITOR CO. Ltd., Korea (yoonjungrag@samwha.com)
* Dept. of Electrical Engineering, Myongji University, Korea. (hylee @mju.ac.kr)
** Dept. of Materials Science Engineering, Inha University, Korea. (dyjeong@inha.ac.kr)
*** Dept. of Electrical Engineering, Suwon University, Korea. (dhrhie @suwon.ac.kr)
Received: July 2, 2012; Accepted: December 28, 2012

2. Experimental

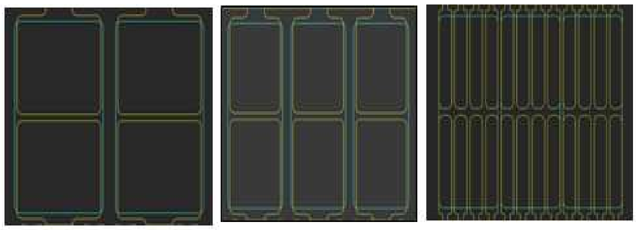
$BaTiO_3$, which is synthesized by using the hydrothermal process, was employed in a multilayer ceramic capacitor. The typical particle size of final power (D_{50}) was adjusted to (0.4 to 0.5)μm, and the specific surface area of power was adjusted to 4.5 m^2/g ± 0.5 m^2/g. MgO, Y_2O_3, MnO_2, and Er_2O_3 were added to enhance the electrical properties of the capacitor, and $(Ba_{0.4}Ca_{0.6})SiO_3$ glass frit was included to lower sintering temperature. A general multilayer chip manufacturing process was applied to fabricate a high-capacitance and high-voltage multilayer ceramic capacitor.

Fig. 1. Photos of a ripple current test system (left) and a capacitor module (right).

A slurry was prepared in a basket mill by mixing toluene/ ethanol solvent, dielectric substance power, polyvinyl butyral binder (Sekisui, BM-SZ), and dielectric fluid dioctyl phthalate (DC Chemical). A 50 μm thick green sheet was processed by means of a doctor blade system. Ni electrode was drawn into the green sheet as internal electrode. A series-parallel pattern was used to enhance high voltage withstanding characteristics of the capacitor. The patterned green sheet was cut into multilayer chips with sizes of $40 \times 32 \times 4.0\ mm^3$. Binder removal was performed for 60 h at 260 °C. After binder burnout, the multilayer chips were sintered for 4 h at 1250 °C. Oxygen partial pressure (Po_2) was maintained at 10^{-11} MPa by adjusting N_2/H_2. Thermal treatment was performed again for 2 h at 1000 °C under Po_2 of 10^{-7} MPa to enhance insulation resistance and reliability. An external electrode, which was formed by using Cu, was thermally treated for 10 min at 800 °C in a reduction atmosphere. The temperature was made to comply with the X7R characteristics, in which a change rate in capacitance satisfies 0 ± 15% in the temperature ranging from −55 °C to 125°C. For the hybrid electrical vehicle inverter, 20 multilayer ceramic capacitors with capacitance of 23 μF ± 0.5 μF in 1 kHz were mounted onto both surfaces of a printed circuit board (PCB) substrate, thus forming a capacitor module with total capacitance of 450 μF. The capacitance, equivalent series resistance (ESR), and loss of capacitor module were characterized by using an impedance analyzer (HP4194A). Allowance ripple current was measured at ambient temperature by using a DC power supply (GP0650-05R, Takasago Inc.) and an amplifier (NF Inc., Oss40262) as power source. The measurement system and module are shown in Fig. 1.

3. Results and Discussion

Floating electrode patterns were designed by varying the number of series-parallel electrodes without deteriorating rated voltage characteristics (Fig. 2). In designing internal electrode patterns, a valid area of electrode should be spared to maximize capacitance. However, given that considerable stress exists between electrodes and ceramic materials, special care should be given when designing the internal electrode pattern [7, 8].



(a) (b) (c)

Fig. 2. Patterns of internal electrode: (a) two-column; (b) three-column; (c) twelve-column electrodes.

Table 1. Electrical properties according to internal electrode pattern

Pattern class	Capacitance (μF)	Loss (%)	Breakdown voltage (V)
two-column electrode	23.5	0.64	1450
three-column electrode	23.2	0.65	1550
twelve-column electrode	22.8	0.64	1650

Table 1 shows the calculated electrical properties measured with various electrode patterns. Increasing the number of electrode column did not affect the capacitance and dielectric loss, but instead significantly increased the dielectric breakdown voltages. Therefore, increasing the number of columns decreases the valid area, which results in a decrease of capacitance.

Considering that large electrodes are generally divided into smaller areas, electric field and mechanical cohesion are uniformly distributed with voltage increase. Electro-mechanical breakdown could be relieved to provide a higher breakdown voltage in the twelve-column electrode [6, 9, 10]. Based on various test results, a three-column electrode was selected for electrical vehicle application (Fig. 3), in which the external terminal was designed according to the mechanical strength in module mounting.

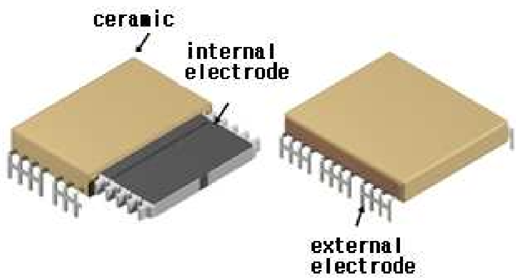


Fig. 3. Appearance of a multilayer ceramic capacitor for hybrid electric vehicle inverters.

Fig. 4 describes the impedance characteristics of the multilayer ceramic capacitor, which is modularized on the PCB substrate according to frequency at different temperatures. For an ideal capacitor, impedance usually decreases with increasing frequency. However, for an actual capacitor, impedance is minimal at the resonant frequency and then increases at higher frequencies because of inductance and resistance. The module manufactured in this test utilized a resonant frequency of 13 kHz, which may affect PCB inductance and the lines on the multilayer ceramic capacitor. Resonant frequency minimally changed and remained in the range 20°C to 125°C. This stable behavior may be caused by minimal changes in capacitance.

Fig. 5 shows the capacitance characteristics according to temperature for various frequencies. The change in parasitic capacitance occurring in the module with 455 μF at 1 kHz was within ±15%, which satisfies the X7R temperature characteristics. Capacitance was proved to increase with increasing frequency. This frequency dependence of capacitance is related to the increase of impedance gradient around the resonant frequency, which may be affected by the increase in equivalent series inductance (ESL). Accordingly, electrode patterns of multilayer capacitors should be designed to minimize the ESL.

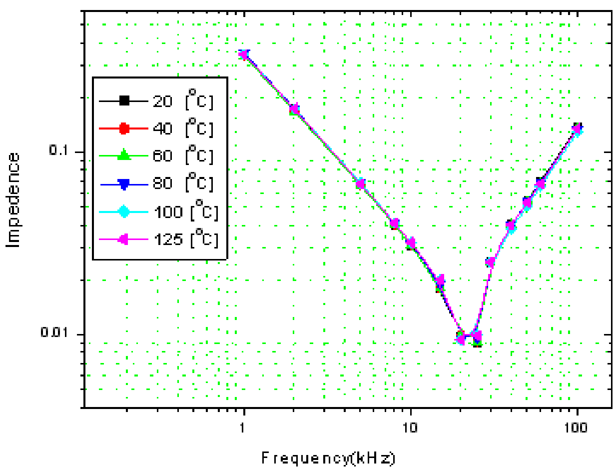


Fig. 4. Frequency dependence of the impedance of ceramic capacitor modules for various temperatures.

Fig. 6 presents the ESR characteristics according to frequency change at various temperatures. ESR is equal to 3.6 mΩ in the frequency band ranging from 1 kHz to 2 kHz; however, ESR decreased to less than 3.0 mΩ in the frequency band ranging from 5 kHz to 10 kHz. ESR can be expressed as follows (Eq. 1):

$$ESR = R_s + \frac{\tan\delta}{2\pi fC}, \tag{1}$$

where R_s is the electrode resistance, tan δ is the dielectric loss, and f is the frequency. When ESR is small, heat generation by ripple current is also low; thus, manufacturing a capacitor with excellent reliability and dielectric breakdown voltage characteristics is possible. ESR should be small especially in high frequency domains to minimize heat generation by ripple current in circuits for power electronics. High temperatures in electronic circuits may decrease the lifetime of a product; thus, temperature changes during operation should be characterized to secure high reliability. Internal heat generation by ripple current occurs in the capacitor because of dielectric loss and ESR.

Fig. 7 shows the temperature change according to ripple current at different temperatures. Heat generation in the capacitor generally occurs because of the ripple current flowing through ESR and the leakage current by direct voltage. Power loss in a circuit can be determined by using Eq. 2:

$$W = (I_R{}^2 \times ESR) + (V \times I_L), \tag{2}$$

where W is the power loss of a circuit, I_R is the ripple current of a circuit, and I_L is the leakage current of a

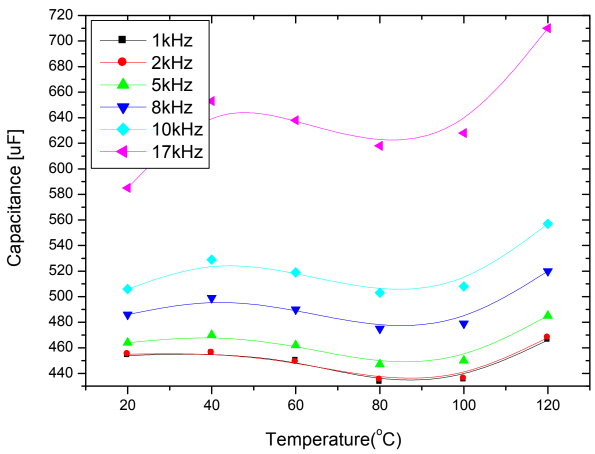


Fig. 5. Capacitance characteristics according to temperature for various frequencies.

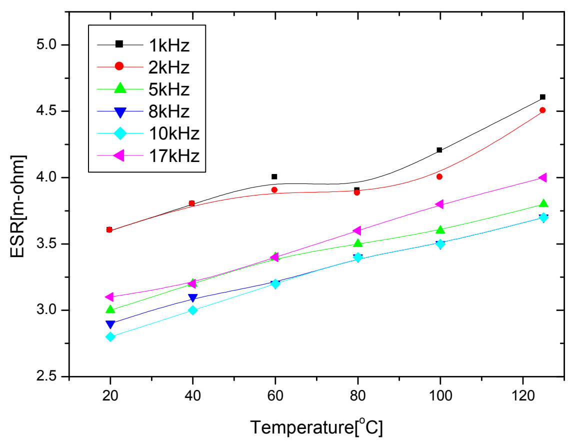


Fig. 6. ESR characteristics according to temperature at various frequencies.

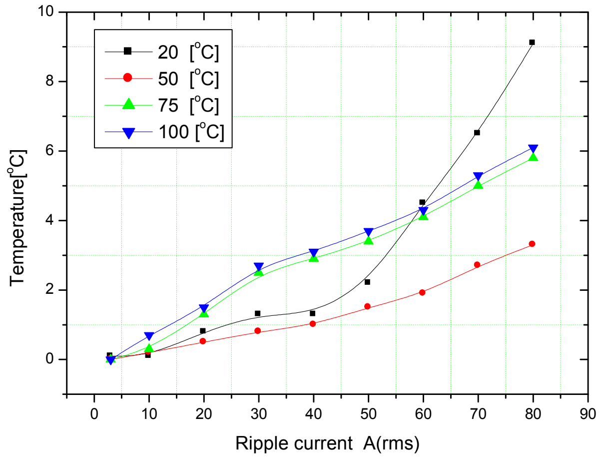


Fig. 7. Temperature change versus ripple current of ceramic capacitor module at different ambient temperatures.

capacitor. The leakage current within the actual capacitor is less than a few nA and is small compared with ripple currents with hundreds of mA to tens of A. Therefore, the loss by leakage current is small. The power loss of the capacitor may be expressed by using Eq. 3:

$$W = I_R^{\ 2} \times ESR \ . \tag{3}$$

Eq. 4 shows a conditional equation wherein temperatures caused by internal heat generation and heat radiation of the capacitor are parallel:

$$\beta \times A \times \Delta T = I_R^{\ 2} \times ESR \ , \tag{4}$$

where β is the heat radiation coefficient of the capacitor, A is the surface area of the capacitor, and ΔT is the temperature change capacitor. From the above equation, the temperature increase caused by capacitor heat generation via ripple current is expressed as follows:

$$\Delta T = (I_R^{\ 2} \times ESR)/(\beta \times A) \tag{5}$$

Ripple current increases with increasing temperature, and the ESR characteristics (Fig. 6) can be explained by Eq. 5.

When the ambient temperature is within 20 °C to 50 °C, a temperature increase within 10 °C by ripple current is appropriate. Moreover, when the ambient temperature ranges from 50 °C to 100 °C, a temperature increase within 5 °C is appropriate when product lifespan and reliability are considered [8, 9]. Accordingly, the proposed capacitor could endure a ripple current of 60 Arms because of the reliability and lifetime characteristics of the capacitor. Therefore, we are expecting that the ceramic multilayer capacitor would be applicable for DC-link capacitors in hybrid electric vehicles.

5. Conclusion

We fabricated a multilayer chip ceramic capacitor for 40 ×32×4.0 mm^3 and characterized the electrical properties of the capacitor for DC-link capacitor application. The capacitor had a capacitance of 23 µF and dielectric loss of 0.65%. By designing the electrode patterns, we could achieve a breakdown voltage ranging from 1450 V to 1650 V. The capacitor module made of several multilayer capacitors showed a capacitance of 450 µF, resonant frequency at 18 kHz, and excellent frequency characteristics. The capacitor module has an ESR of less than 4.5 mΩ and a ripple current of 60 A_{rms}, which conforms to the requirement of hybrid electric vehicles. Compared with existing electrolytic capacitors or film capacitors, the multilayer chip ceramic capacitor allows higher ripple current per unit volume and can help in the miniaturization of both hybrid and actual electric vehicles.

Acknowledgements

One of the authors (D. Jeong) thanks the financial support of a grant funded by the ADD.

References

[1] C. R. Neuhaus., “Control scheme for switched reluctance drives with minimized DC-link capacitance.” IEEE Transactions on power electronics, 23(5), pp. 2557-2561, 2008.

[2] Tomohiro Kageyama., “Murata's Ceramic Capacitor Serves Next Series of Power Electronics.” AEI, Dempa Publications, Inc., pp. 31-33. April 2007.

[3] Teppei Akiyoshi, Guanghui Wang and Mike Lanagan, “Ripple Current and Electrical Noise Characterization of DC BUS Capacitors for Future Power Electronics.” CARTS 2007 Proceedings, pp. 159-171. 2007.

[4] Jung-Hyo Lee, Doo-Yong Jung, Sang-Hoon Park, Taek-Kie Lee, Young-Ryul Kim and Chung-Yuen Won, “Battery Charging System for PHEV and EV using Single Phase AC/DC PWM Buck Converter ”, Journal of Electrical Engineering & Technology 7(5), pp. 736-744, 2012.

[5] Jung-rag Yoon, Min-gi Kim, and Seok-won Lee “AC, DC breakdown properties according to dielectric thickness of multi-layer chip capacitor for high capacitance and internal electrode shape”, KIEEME, 21(12), pp. 118-122, 2008.

[6] Chul-seung LEE, Byung-sung KANG, Kang-heon HUR, and Jin-woo Park, “Investigation and Analysis of Cracks in Multi-layer Ceramic Capacitor” J. Kor. Ceram. Soc. 46(2), pp. 211-218, 2009.

[7] Bong-Gi You, Jong-Soo Kim, Byoung-Kuk Lee,

Gwang-Bo Choi and Dong-Wook Yoo, "Optimization of Powder Core Inductors of Buck-Boost Converters for Hybrid Electric" Journal of Electrical Engineering & Technology 6(4), pp. 527-534, 2011.
[8] Jung-Rag Yoon, Kyung -Min Lee, and Serk -Woon Lee, "Analysis the Reliability of Multilayer Ceramic Capacitor with inner Ni Electrode under highly Accelerated Life Test Conditions" Trans. Electr. Electron. Mater. 10(1), pp. 5-8, 2009.
[9] Jung-Rag Yoon, Jeong-Woo Han, Kyung-Min Lee, and Heun-Young Lee, "Dielectric Properties of Polymer-ceramic Composites for Embedded Capacitors" Trans. Electr. Electron. Mater. 10(4), pp. 116-120, 2009.
[10] J. R. Yoon, D. S. Shin, D. Y. Jeong, and H.Y Lee, "Control of connectivity on Ni electrode with heating rates during sintering and electrical properties in $BaTiO_3$ based multilayer ceramic capacitors" Trans. Electr. Electron. Mater. 13(4), pp. 181 -184, 2012.

Jung-Rag Yoon He received B.S, MS, and Ph.D degree in electrical engineering from MyongJi university. Korea, 1991, 1993, and 1999, respec- tively. His research interests are dielectric material and energy storage device. Currently, he serves as an R&D Center Manager for Samwha Capacitor Co., Ltd.

Bong Hwa Moon He received B.S degree in Physics from INJE university. Korea 1997 His research interests are dielectric material and energy storage device. Currently, he serves as an R&D Center General Manager for Samwha Capacitor Co., Ltd.

Heun Young Lee He received Ph.D degree in electrical engineering engineering from Korea University. Korea 1983. His research interests include dielectric, semiconductor, piezoelectric materials and their applications. Currently, he serves as an associate professor in MyongJi University, Korea.

Dae Yong Jeong He received B.S, MS degree in the department of materials science & engineering from Seoul National University. Korea 1994 and 1996, respectively. After working for the COSMO. Ind. Korea, he completed Ph.D degree in Materials from Pennsylvania State University in 2004. His research interests include dielectric, ferroelectric, piezoelectric materials and their applications. Currently, he serves as an associate professor in Inha University, Korea.

Dong Hee Rhie He received Ph.D degree in electrical engineering engineering from Korea University. Korea 1990. His research interests include dielectric, semiconductor, piezoelectric materials and their applications. Currently, he serves as an associate professor in Suwon University, Korea.