Arc-Over-Resistant Multilayer Ceramic Capacitors for High-Voltage Applications

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Abstract

Applying voltages of 1000 VDC or higher to multilayer ceramic capacitors can result in arc over from terminal to terminal or even from terminals to the internal electrodes. For this reason, MLCCs in larger case sizes have been used in high-voltage (>500 VDC) applications that allow for thicker layers of ceramic over the internal electrodes and large separation between terminals. In some cases, designers are still using leaded capacitors or applying coating to the high-voltage sections of the board to avoid arc over. These approaches, although effective, result in increased costs of components as well as making it difficult to reduce the circuit board real estate. This presentation describes the properties of arc-over-resistant higher-voltage surface mount MLCCs that address these shortcomings.

Design modifications were made to standard 500-VDC designs to improve arc over performance in various case sizes of class-II dielectrics (X7R type) and class-I dielectrics (NP0 type) MLCCs. The suppression of arc over in the modified designs as well as increased average voltage breakdown (VBD) was observed by comparing the voltage breakdown in air with the standard designs. The failures were analyzed, confirming the absence of arc over in the modified designs.

The electrical characteristics such as equivalent series resistance (ESR), series inductance, and dielectric withstanding levels of X7R and NP0 standard and modified designs are compared in this presentation. Life test data for MLCCs to achieve higher voltage ratings per EIA-198 is shown, and other factors affecting field reliability, such as surge resistance, are also reviewed. The improved performance shown in the High-Voltage Arc Guard Capacitors (HVArc Guard^{TM}) will enable smaller components to be developed for use in high-voltage circuits as well as extended capacitor ranges for a given body size and dielectric type.

The small size and arc-resistant high-voltage characteristics of these parts can reduce board space for applications such as DC power supplies, dc-to-dc converters, filters, amplifiers, and communications equipment that encompass a broad range of frequencies. The incorporation of these arc-resistant capacitors will eliminate voltage fluctuations in bypass, coupling, and isolation circuits where signal integrity must be maintained.

Introduction

MLCCs in large case sizes have been used for many years to avoid arc over across the surface of the components, as well as to increase the separation between pads in the design of the circuit boards. The UL recommendations for separation between pads over the surface and through the air are shown and compared to the terminal-to-terminal separations of MLCCs for different voltage ratings in Table 1.

Case Size	Maximum Voltage Rating	Minimum Spacings Between Terminations		Minimum Spacings per UL Specification #810			
				Through Air		Over Surface	
		Inch	mm	Inch	mm	Inch	mm
0805	1000	0.035	0.89	0.750	19.1	0.750	19.1
1206	2000	0.062	1.57	0.750	19.1	0.750	19.1
1210	2000	0.062	1.57	0.750	19.1	0.750	19.1
1808	3000	0.107	2.72	1.000	25.4	0.750	19.1
1812	3000	0.107	2.72	1.000	25.4	0.750	19.1
1825	3000	0.107	2.72	1.000	25.4	0.750	19.1
2225	4000	0.150	3.81	1.000	25.4	0.750	19.1
3640	4000	0.285	7.24	1.000	25.4	0.750	19.1

Table 1. Termination spacing vs. UL recommendations for maximum voltage ratings

Clearly the separations recommended by the UL are not convergent with the current MLCC capability to withstand high voltages, although it should be noted that techniques such as conformal coating and slotting of boards significantly reduce the board space required.(1) The use of flexible circuit solutions has further increased the tools for the designer to reduce the size associated with the circuit board. However, there is still a demand for MLCC producers to further reduce the size of the components, even for high voltage ratings. Apart from the potential to miniaturize the circuits by reducing the size of MLCCs, their cost is also reduced.

Initial Development Work

The initial development work was carried out on 1206-case-size, 500-V, 33-nF MLCCs made with Vishay's advanced X7R dielectric system. On applying 500 V/sec to 50-piece samples, (2) failures occur at relatively low voltages in air. Repeating this test with inert fluid surrounding the parts and test fixture, the voltage breakdown is significantly higher (Figure 1).

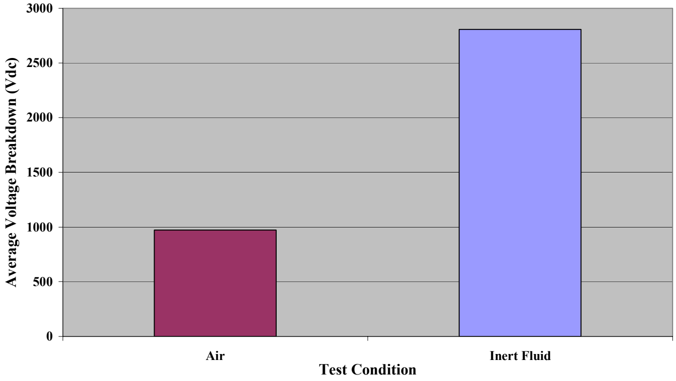

Figure 1. Voltage breakdown of a standard 1206, 500-V, 33-nF, X7R MLCC in air and inert fluid

The failures in air were examined and three types of failure modes were identified:

1. Termination-to-termination arcing (Figure 2.)
2. Termination-to-active arcing (Figure 3.)
3. Internal breakdown (Figure 4.)

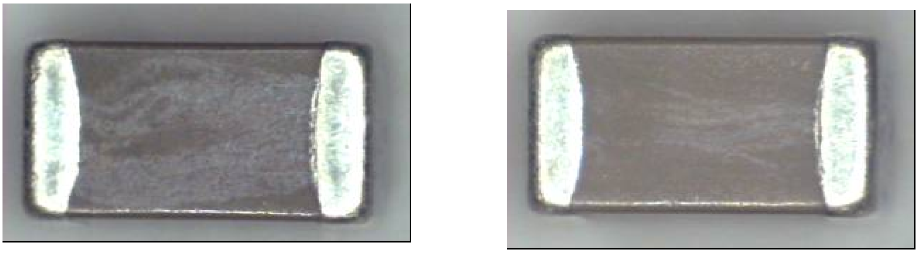

Figure 2. Typical termination-to-termination surface arcing on MLCCs (shown in polarized light)

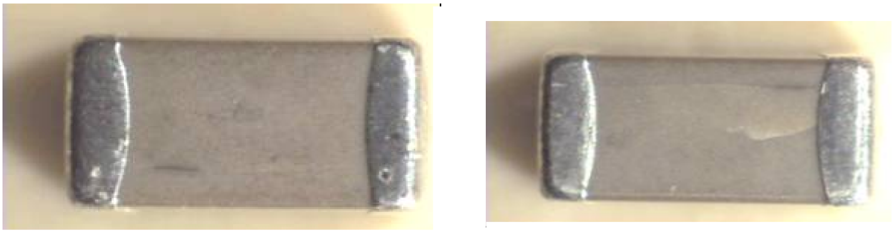

Figure 3. Typical termination-to-active arcing on MLCCs

Figure 4. Typical internal voltage breakdown damage on MLCCs

Insulation resistance (IR) measurements of the post-breakdown failures from the parts tested in air found 37/50 had acceptable IR, whereas all 50 pieces from the inert fluid test were IR failures. The explanation is that for the parts tested in air, the failures were due to surface arc over that did not create internal degradation of the capacitors. However, as shown in Figure 4, when the parts were tested in inert fluid, surface arc over was prevented, which increased the voltage breakdown level that caused eventual internal voltage breakdown of the capacitors, thus lowering their insulation resistance. Following this work we concluded that if capacitors could be redesigned to eliminate the surface arc over failures shown in Figures 2 and 3, the resulting failures on applying high voltage would be solely due to internal breakdown of the dielectric, significantly increasing the voltage handling capability. With this goal in mind, several design modifications were made to improve the VBD performance for 1206, X7R high-voltage MLCCs. (3)

HVArc Guard Development

A voltage breakdown comparison test was performed on 1206-size capacitors. The average breakdown in air of the HVArc Guard capacitors is greater than 2500 VDC, almost matching the average voltage breakdown level of the standard design's inert fluid tests as shown below in Figure 5.

IR measurements of the post-breakdown failures indicate that none of these MLCCs (0/50) remained insulators. The high-voltage breakdown in air is therefore associated with internal failures within these capacitors and not due to surface arcing.

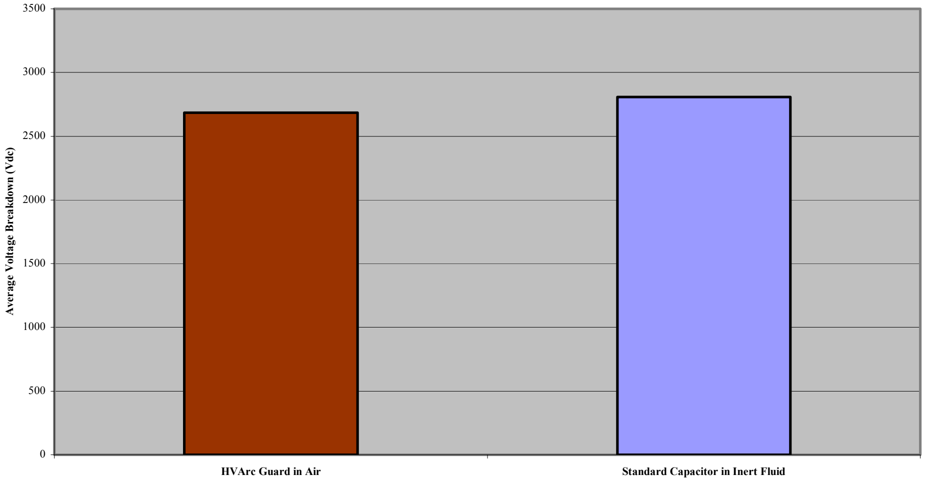

Figure 5. Voltage breakdown comparison of HVArc Guard tested in air vs. standard capacitor tested in fluid.

The reliability of the standard design 1206, 500V X7R was compared to an intermediate 1206, 500-V X7R design and the HVArc Guard capacitor. The intermediate design had only some of the modifications present in the HVArc Guard capacitor. A general description of these MLCC designs and properties is given in Table 2.

Description	Standard Design	Intermediate Design	HVArc Guard Design
Number of actives	26	27	28
Average capacitance (nF)	34.4	31.9	24.5
Average length (inches)	0.1262	0.1261	0.1256
Average length (mm)	3.21	3.20	3.19
Average width (inches)	0.0643	0.0644	0.0682
Average width (mm)	1.63	1.64	1.73
Average thickness (inches)	0.0603	0.0620	0.0636
Average thickness (mm)	1.53	1.57	1.62

Table 2. 1206 X7R MLCC designs and properties

All of these MLCCs are made with the same advanced X7R Vishay dielectric system and have the same active thickness. The reliability of each of the MLCC designs was determined by life testing at elevated voltage levels. The test was conducted on samples for 1000 hours at +125 °C with 1000 VDC applied. For each of the three MLCC designs, an 80-piece sample was mounted by reflow soldering onto FR4 test boards and then coated with a conformal coating. Another 80-piece sample for each design was placed in spring-loaded mountings with no conformal coating. A summary of test results at 500 hours and 1000 hours is shown in Figure 6.

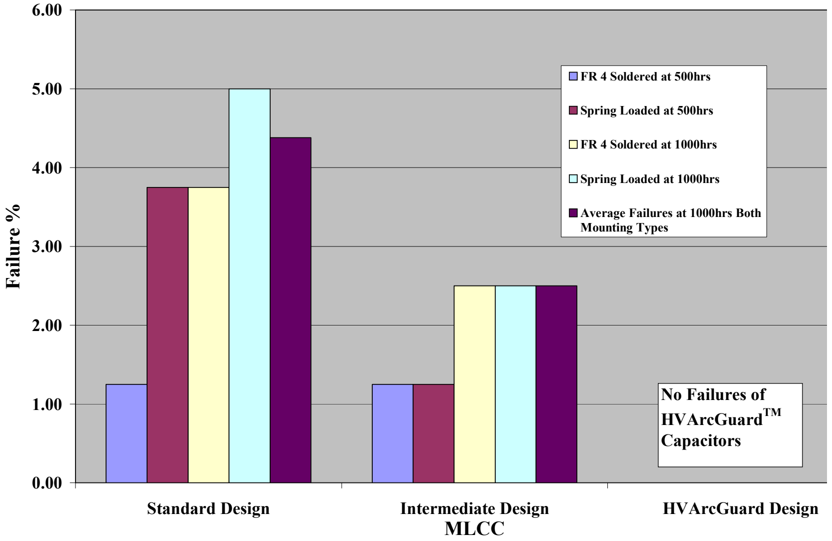

Figure 6. Results of life tests

The failure rate of the spring-loaded standard MLCCs is slightly higher than the FR4 mounted capacitors, but this is not statistically significant. There was no difference in the failure rates for the different mounting used in the test of the intermediate design. However, in both the standard and intermediate designs, the failure rates increased from 500 hours to 1000 hours. Since these failures continue with time, it is not possible to develop a screening procedure to remove infant mortality from the population. There were no failures for the HVArc Guard capacitor samples tested at an equivalent to 18 years of normal operation at 1000 VDC.

The Impedance (Z) and ESR of the standard and HVArc Guard capacitors are quite similar (Figure 7). At higher frequencies the HVArc Guard capacitors have slightly higher ESR.

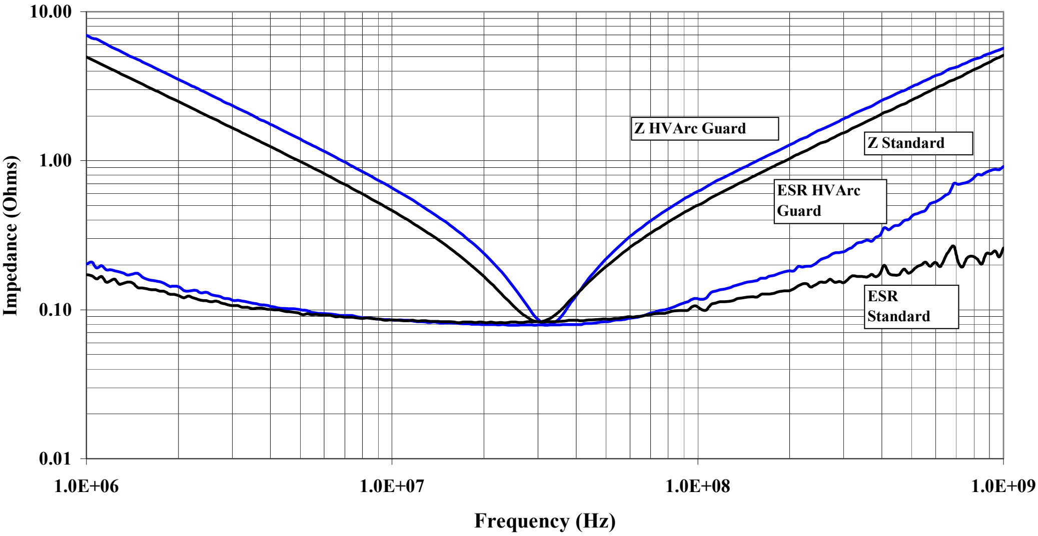

Figure 7. ESR and Z vs. frequencies for the standard 1206, 500-V X7R, and the HVArc Guard capacitor

Development of Class-I (NP0) HVArc Guard MLCCs

Current high-voltage MLCCs made with NP0 type dielectrics have no voltage coefficient of capacitance (VCC) by virtue of the paraelectric nature of these dielectric systems, whereas the capacitance of ferroelectric X7R (and X5R) MLCCs can be lowered by as much as 90 % of the original capacitance at rated voltages, depending on the design and material.

Since the initial development work identified reliable HVArc Guard X7R MLCCs for use at 1000 VDC, this goal was applied to the development of NP0 HVArc Guard capacitors. In addition to no appreciable VCC, the more temperature-stable, Class-I NP0 type dielectrics have some advantages compared to the Class-II X7R systems. In this section the properties of the initial HVArc Guard NP0 MLCCs will be reviewed and compared to X7R.

MLCCs of a 1206, 1000-pF, HVArc Guard NP0 capacitor were manufactured and the voltage breakdown of samples measured in air and inert fluid are shown in Figure 8.

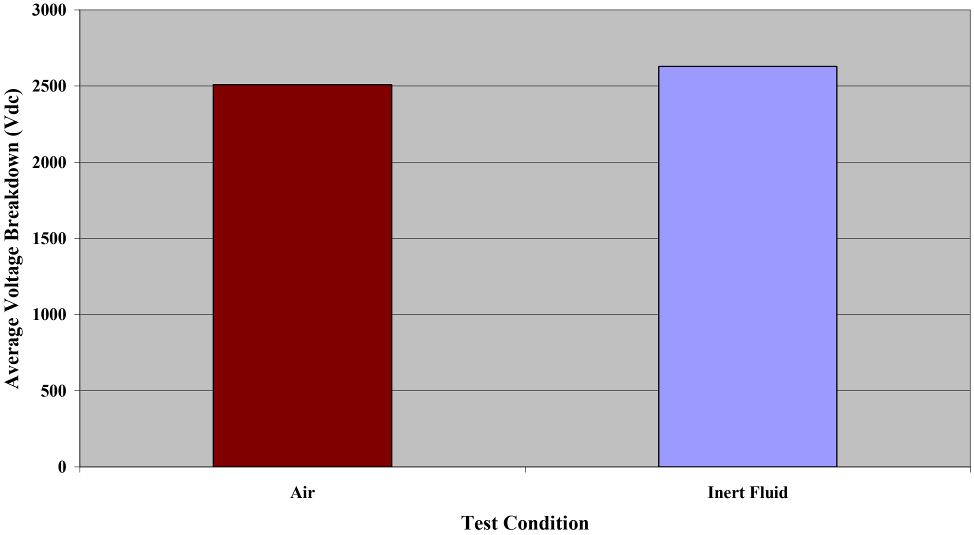

Figure 8. Voltage breakdown of a 1206, 1000-pF, NP0 HVArc Guard MLCC capacitor in air and inert fluid

The voltage breakdown in air and inert fluid are very similar, indicating the absence of surface arc over in air.

To confirm their reliability, samples of these 1206, 1000-pF, NP0 HVArc Guard MLCCs were life tested on FR4 boards as previously described, at 1000 VDC and +125 ^{o}C, with no failures observed after 1000 hours. This test is currently being repeated at 1500 VDC. It should be noted that our current high-voltage 1206 NPO MLCCs are qualified to a maximum capacitance value of 120pF for 1000-VDC rating. This 1206, 1000-pF, NP0 HVArc Guard MLCC therefore represents an eight-fold increase in available capacitance in this case size. Additionally, a 1500pF design representing a 12-fold increase in capacitance had an average voltage breakdown of 2645 VDC.

Lightning Surge Capability

HVArc Guard NP0 MLCCs have significantly improved surge capability compared to the aforementioned HVArc Guard X7R MLCCs. The FCC and telecom surge tests of table 3 were performed using a CDI 1000 surge tester per the wave shape shown in Figure 9.

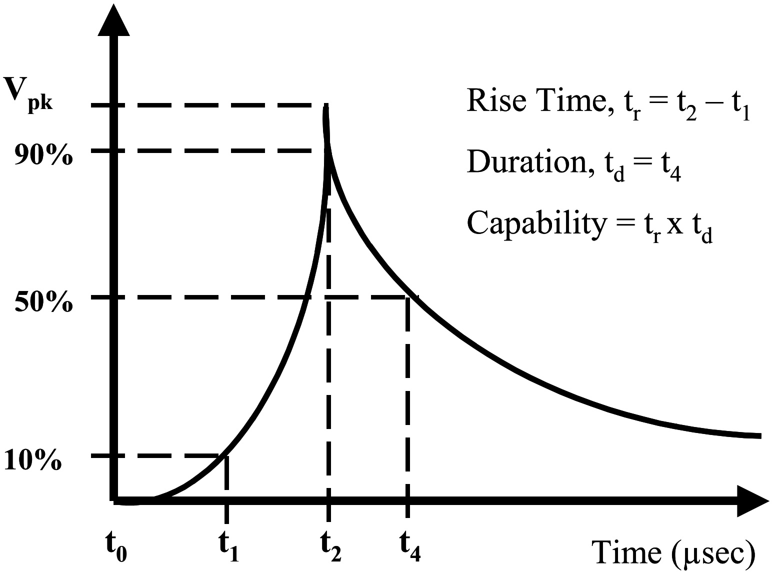

Figure 9. Surge test waveform definition

The results of surge testing the X7R and NP0 HVArc Guard capacitors show that the NP0 has greater surge voltage handling capability than that of the X7R.

Waveform	NP0 HVArc Guard	X7R HVArc Guard
1.2 µsec x 50 µsec	1650 V	500 V
10 µsec x 700 µsec	1800 V	1200 V
10 µsec x 160 µsec	>1500 V	1200 V

Table 3. Surge capability of NPO and X7R HVArc Guard capacitors

NPO Impedance Characteristics

The impedance and ESR of two 1206 NPO HVArc Guard capacitors were measured using the Agilent 4291A impedance analyzer. Both designs, and others tested, have an interesting second-order parallel resonance occurring above the series resonant frequency. The 1206 1000pF and the 1206 1500pF HVArc Guard capacitor designs have parallel resonant frequency points at 575 MHz and 455 MHz respectively, as shown in Figure 10.

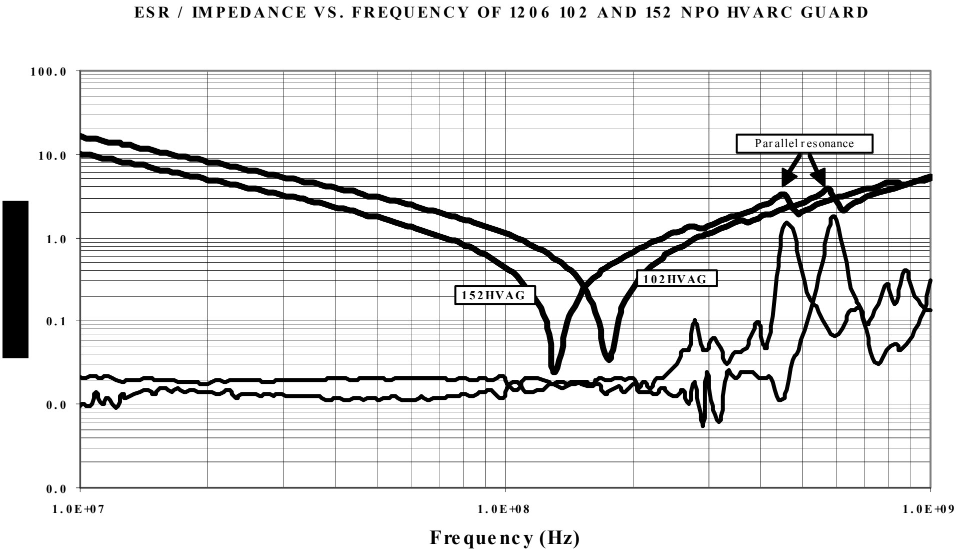

Figure 10. ESR and impedance vs. frequency for 1206 NP0 1000pF and 1500pF HVArc Guard capacitors.

Particular measurements of interest for the parts tested in figures 7 and 10 are summarized below in Table 4.

Part	Capacitance	Series Inductance	Series Resistance @ SRF (ESR)	Self Resonant Frequency
1206, 500-V, X7R standard design	33 nF	.813 nH	82.6 mOhms	30.5 MHz
1206, 1000-V, X7R HVArc Guard	22 nF	.950 nH	79.4 mOhms	32.8 MHz
1206, 1000-V, NPO HVArc Guard	1 nF	.825 nH	34.1 mOhms	177.8 MHz
1206, 1000-V, NPO HVArc Guard	1.5 nF	.900 nH	25.2 mOhms	134.2 MHz

Table 4. High-frequency characteristics of HVArc Guard NP0 and X7R designs compared to standard design MLCCs.

Summary of HVArc Guard Capacitor Range Extension

Since the initial development work identified reliable capacitor designs for use at 1000 VDC, further modifications were made to increase the available capacitance. The properties of a selection of these HVArc Guard capacitors compared to standard capacitors are summarized in Table 5.

Case size	0805 NPO	1206 NPO	0805 X7R	1812 X7R
Current standard design maximum capacitance (nF)	N/A	.120	N/A	27.0
HVArc Guard average capacitance (nF)	.435	1.57	7.7	145.8
Average DF (%)	.07	.035	1.27	1.07
Average VBD in air (Vdc)	2712	2645	2949	3090
Self resonance (MHz)	298.8	134.2	75.2	12.4
ESR (ohms)	.025	.025	.094	.040
Inductance (nH)	.628	.900	.622	1.1

Table 5. Properties of 1000V HVArc Guard Capacitors compared to standard capacitors

In addition to capacitance range extension, HVArc Guard capacitor down-sizing to smaller case sizes, such as 1210 or 0805 sizes, in both the X7R and NP0 dielectric systems can be achieved.

Applications

High-voltage capacitors are used in voltage multipliers, dc-to-dc converters, transmitters, receivers, medical, and X-ray equipment to name a few. For proper operation, power sources for electronic devices need to be accurately controlled and regulated for each function that the device must perform. The power source for the electronic device could be DC or AC power. Any residual pulsation, called ripple noise, in the output of the power source is undesirable. High-voltage capacitors are used in these circuits to reduce ripple, and to contain potentially unsafe transients due to noise generated by the switching regulator.

The HVArc Guard 1-kv, 470pf capacitor is suitable for use as a snubber capacitor in a Ballast circuit.

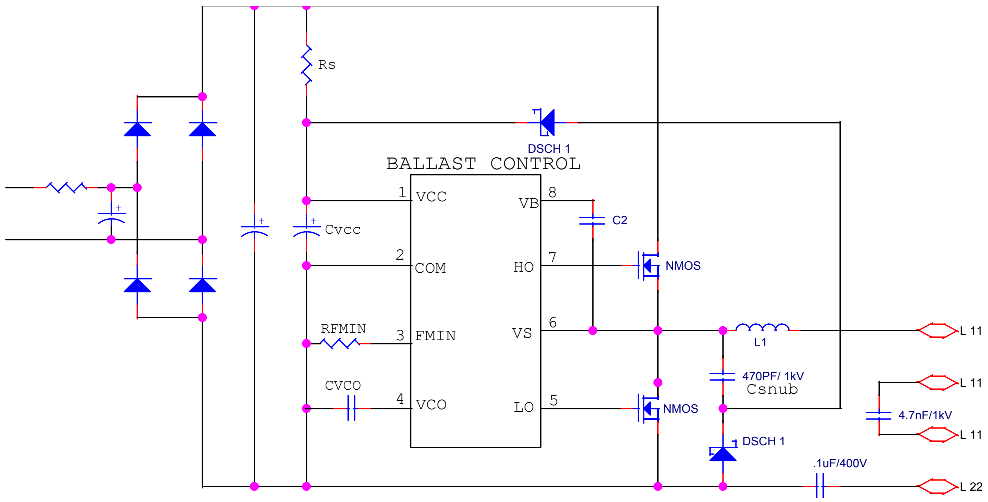

Figure 11. HVArc Guard capacitors used in Ballast circuit.

Series-connected HVArc Guard capacitors can be used in high-voltage, low-power voltage multipliers such as the circuit displayed in Figure 12. Usually these high-voltage module boards are potted or conformably coated. The output voltage increases as the number of stages increase.

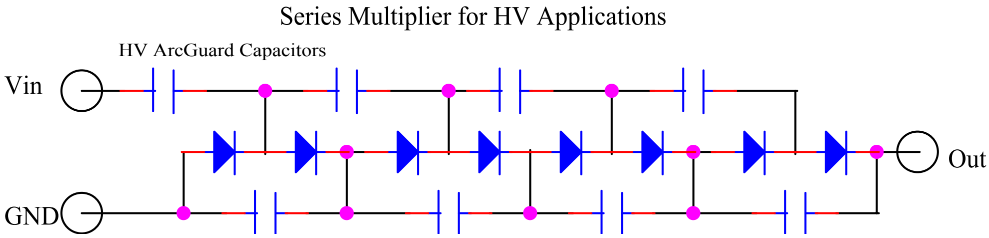

Figure 12. HVArc Guard capacitors used in voltage multiplier circuits

Conclusion

Arc-over-resistant MLCCs have been manufactured that have reliable performance at 1000 VDC. These HVArc Guard capacitors can be made with higher capacitances and in smaller case sizes to reduce board space and component cost (patents pending). Their reliable performance has also been demonstrated without the use of conformal coatings, further reducing assembly costs. Some applications have been identified and extensive testing is underway to confirm performance.

References

1. UL Specification 746C, “Polymeric Materials - Use in Electrical Evaluations;” UL Specification 810, “Capacitors”
2. Electronic Industries Association document ANSI/EIA-198-1F-2002

3. Bultitude, J., Gormally, P., Rogers, J., and Jiang, J., “Surface Mount Multilayer Ceramic Capacitors for High Voltage Medical Applications,” SMTA Medical Symposium, May 2006