THE CLEMSON UNIVERSITY VEHICULAR ELECTRONICS LABORATORY

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Investigating the Contribution of Non-linear Behavior to Losses in Multi-layer Ceramic Capacitors

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Abstract

Multi-layer ceramic capacitors can exhibit a non-linear response when subjected to a sinusoidal stimulus. This non-linear response shifts energy from the fundamental frequency to harmonics of the fundamental. The loss of energy at the fundamental frequency may be interpreted by a measuring system as a resistive loss and might contribute to an increase in the apparent equivalent series resistance (ESR) of the capacitor at that frequency. The non-linear behavior of X7R and NP0 capacitors is investigated and compared to SPICE models of linear and non-linear capacitors. It is determined that the non-linearity does not contribute significantly to the measured ESR under most practical circumstances, but in some cases may be non-negligible.

1. Introduction

Multi-layer ceramic capacitors (MLCCs) are known to exhibit non-linear behavior, where the capacitance is a function of the applied voltage. Some MLCC dielectrics are more non-linear than others. Dielectric losses are the dominant losses in MLCCs at lower frequencies [1]. At high frequencies, the dominant losses of the capacitor are due to skin effect losses in the electrodes [1].

Fig. 1 shows typical ESR curves for 10-nF X7R and NP0 capacitors [1]. Because the X7R dielectric is lossier than the NP0 dielectric, the ESR of the NP0 capacitor is generally lower than that of the X7R capacitor.

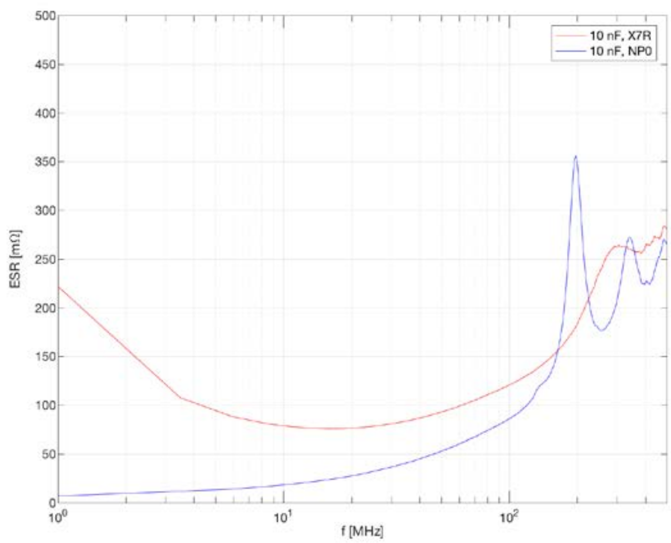

Fig. 1. ESR of 10-nF X7R and NP0 capacitors

Some MLC dielectrics are known to demonstrate non-linear behavior. These capacitors exhibit a capacitance that varies with the applied DC voltage [2]. If this nonlinear behavior flattens out a sinusoidal waveform in the time-domain, that affects the harmonics of the waveform in the frequency domain. This paper seeks to investigate whether non-linear behavior of MLCCs causes energy to shift from a fundamental frequency to its harmonics, and whether that energy shift contributes to the apparent ESR of the capacitor at the fundamental frequency.

2. Contribution of Frequency Conversion to Apparent Losses

When a multi-layer ceramic capacitor is excited by a sinusoidal source with a given fundamental frequency, power can be shifted into harmonics of the fundamental by the non-linear response of the dielectric. The stronger the excitation, the more non-linear the behavior and the more power that is shifted into the harmonics. This effect is dependent upon not only the strength of the excitation but of the dielectric of the MLCC. Some dielectrics like X7R exhibit more non-linear behavior than others. Damage to a capacitor may also increase the non-linearity of the capacitor [3]. A thinner dielectric layer will exhibit more non-linearity due to the higher electric field strength for a given applied voltage. The thickness of the dielectric layer is related to the voltage rating of the capacitor.

To investigate this, a test setup is created in which the capacitor under test (CUT) is subjected to a sinusoidal source of 2 MHz and 30 dBm. Using a special coaxial cable with a break in the middle, the CUT is soldered between the center conductor and shield of the cable. At the other end of the coaxial cable is a spectrum analyzer. Thus, the capacitor forms a low-pass filter between the function generator and the spectrum analyzer. Fig. 2 shows a picture of the test setup, and Fig. 3 shows the special coaxial cable and an 0603-size CUT.

Fig. 2. Test setup used to measure capacitor response

Fig. 3. Special coaxial cable fixture used for measuring capacitor response

The power at the fundamental frequency and its harmonics are measured with a spectrum analyzer using the special cable both with and without the shunt capacitor. The expected attenuation of the CUT at each frequency is calculated and compared to the measured attenuation. Fig. 4 illustrates the equivalent circuit of the test setup.

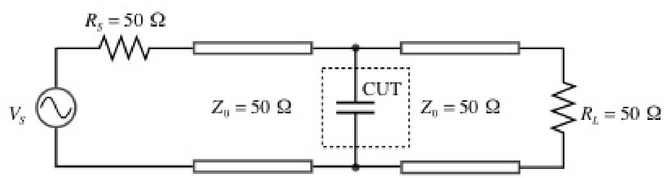

Fig. 4. Equivalent circuit of measurement setup

From [4] and Fig. 4, the expected attenuation at a given frequency, *f*, due to a shunt 10-nF capacitor in a 50-Ω system is determined by

$$\alpha\ (\mathrm{dB}) = 20\log_{10}\left(\sqrt{1+\left(\pi f \cdot 50\ \Omega \cdot 10\ \mathrm{nF}\right)^2}\right) \tag{1}$$

Using the special coaxial cable without a CUT, Fig. 5 shows the through measurement, which characterizes the standard response of the test setup shown in Figs. 2 and 3.

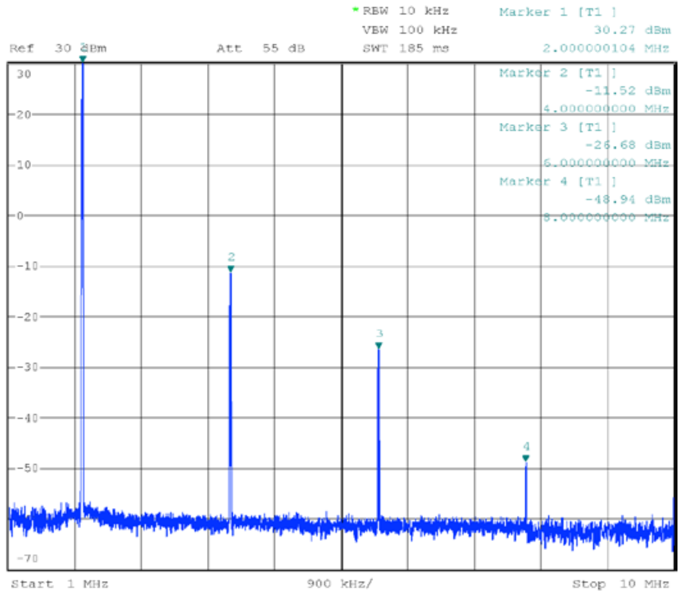

Fig. 5. Through measurement with test setup

It should be noted that Fig. 5 shows harmonics of the fundamental that are produced by the source itself; however, the highest of these harmonics is approximately 40 dB down from the fundamental, which is negligibly small for the purposes of this investigation.

Fig. 6 shows a measurement of the response of a 10-nF X7R capacitor using the test setup shown in Figs. 2 and 3.

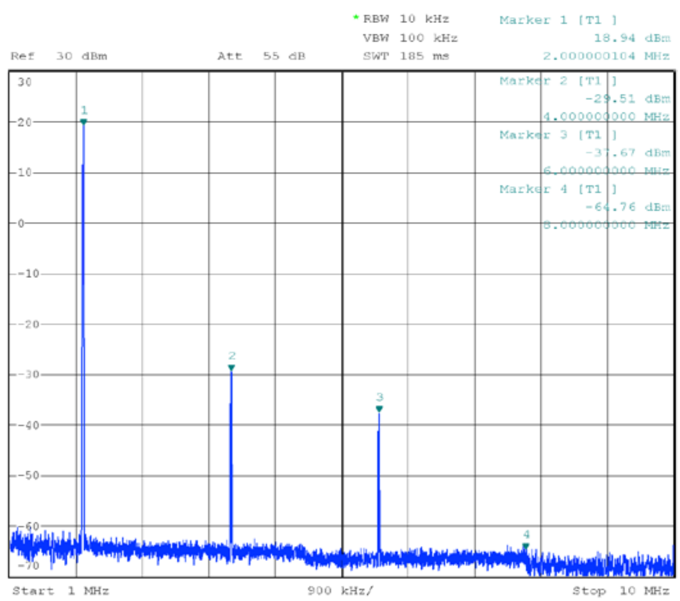

Fig.6. Measurement of 10-nF X7R capacitor with test setup

After measuring the attenuation of a 10-nF X7R capacitor, the same is done for 10-nF, 50-V NP0 capacitor. This is shown in Fig. 7.

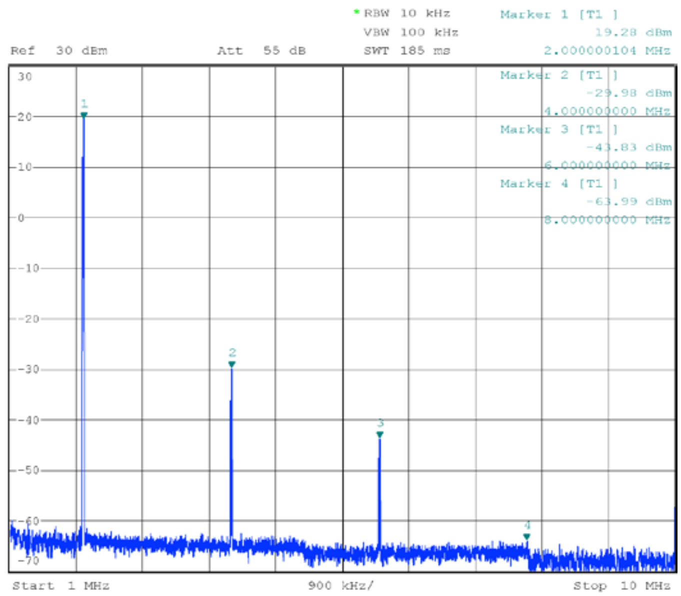

Fig. 7. Measurement of 10-nF NP0 capacitor with test setup

Both the X7R and NP0 capacitors are expected to have the same attenuation, since (1) does not take into account the dielectric of the capacitor. In the case of the 10-nF X7R capacitor, the strength at the fundamental frequency of 2 MHz is within 0.1 dB of the expected value; however, the third harmonic, 6 MHz, is 9 dB higher than expected. The expected value at each frequency was determined by evaluating (1) at that particular frequency.

For the 10-nF NP0 capacitor, the strength at the fundamental is 1 dB lower than expected, but the strength at the third harmonic is 3 dB higher than expected. This indicates that some power is shifted from the fundamental frequency to the third harmonic for both dielectrics. The effect is not as perceptible with the NP0 capacitor.

To determine if the apparent losses at the fundamental due to this shift in power are appreciable compared to the overall ESR of the capacitor, the ESR required to dissipate the same amount of power that was shifted to the third harmonic is calculated. From Fig. 6, the power measured with the spectrum analyzer at the fundamental frequency is 18.9 dBm, or approximately 78 mW. This corresponds to a voltage of

$$P_L = \frac{V_L^2}{50\,\Omega} \quad \rightarrow \quad V_L = \sqrt{50\,\Omega \cdot 78\,mW} \cong 2.0\,V \tag{2}$$

The current through the CUT at the fundamental frequency is then found by

$$\begin{aligned} I_C &= \frac{V_L}{X_C} = 2\pi \cdot V_L \cdot f \cdot C \\ &= 2\pi \cdot (2.0\text{ V}) \cdot (2\text{ MHz}) \cdot (10\text{ nF}) \cong 250\text{ mA} \end{aligned} \tag{3}$$

A worst-case approximation would assume that all of the power at the third harmonic was shifted from the fundamental due to the non-linear response of the capacitor. This power could be equated to an apparent resistance at the fundamental frequency. Thus, the value of this apparent ESR may be determined by dividing the power of the third harmonic by the square of the current through the capacitor at the fundamental frequency. Harmonics higher than the third are neglected due to their negligible contribution. From Fig. 6, the power at the third harmonic is -37.7 dBm, or approximately 170 nW. The apparent ESR caused by non-linear effects of the capacitor is then approximated by

$$P_{ESR} = I_C^2 \cdot ESR \quad \rightarrow \quad ESR = \frac{170\ nW}{(250\ mA)^2} \cong 2.7\ \mu\Omega \quad . \tag{4}$$

From this result, the amount of apparent ESR caused by non-linearity in the capacitor under these circumstances is negligibly small in comparison to the actual measured ESR at the fundamental, which is approximately 100 mΩ as determined by Fig. 1.

3. Using SPICE to Investigate the Apparent Losses of Linear and Non-linear MLCCs

SPICE models of both linear and non-linear capacitors can be used to determine if a non-linear capacitor with no additional modeled resistance will have an effective resistance in comparison with a linear capacitor model. To do so, a 10-nF capacitor is modeled with dependent sources in PSPICE as shown in [5]. By modeling a capacitor in this manner, non-linearity is created by varying the device capacitance with the voltage across the capacitor. One difference from the example in [5] is that non-linear behavior is extended to include negative bias voltages.

To model a non-linear capacitor, the SPICE model for the non-linear capacitor loses half of its nominal capacitance at a ±10-V bias with linear interpolation of the device capacitance between the 0-V and ±10-V bias points. An extreme case, referred to as a “very non-linear” capacitor, was also evaluated in which the capacitor loses 90% of its nominal capacitance at a ±10-V bias. A linear capacitor is simulated with the same model, but the capacitance does not depend on the voltage across the capacitor.

These capacitor models are placed in parallel with a 50-Ω load and driven by a 50-Ω sinusoidal source. The source is characterized by a 40-V amplitude and a 2-MHz frequency. This circuit simulates the equivalent circuit of the physical measurement shown in Fig. 4. Fig. 8 shows a time-domain comparison of the voltage across the parallel combination of the CUT and load resistor for one linear and two non-linear cases.

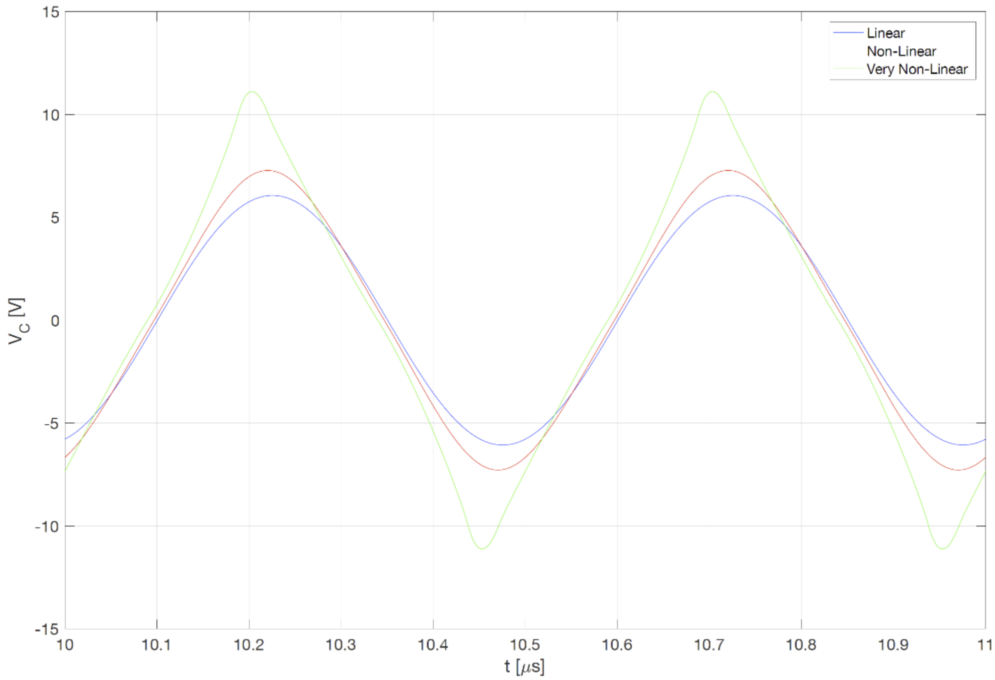

Fig. 8. Time-domain comparison of linear and non-linear 10-nF capacitors.

The voltage across the linear capacitor appears to demonstrate a perfect sinusoidal waveform. As nonlinearity increases, the waveform becomes more distorted. For the very non-linear case, the waveform is clearly no longer a pure sine wave. The voltage waveforms of Fig. 8 are transformed with an FFT and plotted as power to provide a comparison in the frequency domain. This power is plotted in dBm in Fig. 9.

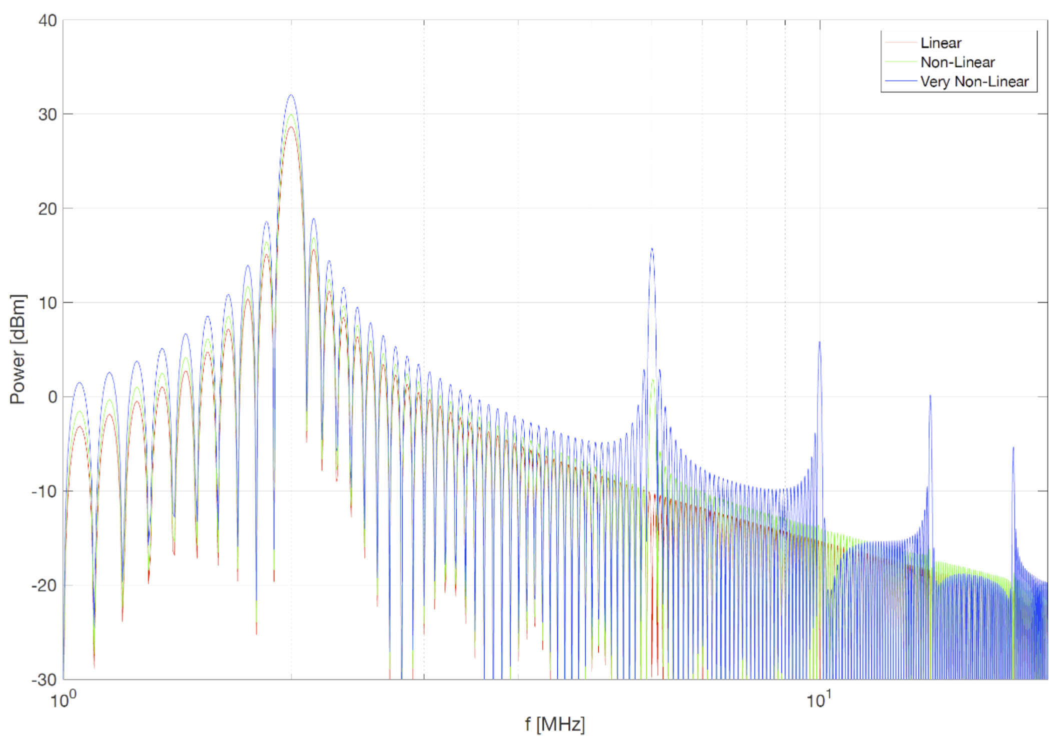

Fig. 9. Frequency-domain comparison of linear and non-linear 10-nF capacitors.

The linear capacitor shows a strong response at the fundamental frequency, but displays no harmonic content beyond that. This is characteristic of a pure sine wave. The non-linear capacitor demonstrates a third harmonic that has become significant, but no appreciable harmonics exist beyond the third harmonic. As non-linearity increases further, the very non-linear case shows odd harmonics up to the ninth harmonic that are non-negligible. The increase in harmonic amplitudes as non-linearity increases corresponds to increased distortion in the time-domain waveform. The strength of the harmonics shown in Fig. 9 is inversely proportional to frequency squared, so harmonic contribution becomes negligible at the higher harmonics.

Using the power displayed in Fig. 9, the calculations from Section 2 are performed for the worst-case, very non-linear capacitor SPICE model:

$$\text{At 2 MHz, } P_L = 32.06\ \text{dBm} \cong 1.6\ \text{W}$$

$$\mathrm{P}_L = \frac{V_L^2}{50\ \Omega} \;\rightarrow\; V_L = \sqrt{50\ \Omega \cdot 1.6\,\text{W}} \cong 9.0\ \text{V}$$

$$I_C = \frac{V_L}{X_C} = 2\pi \cdot V_L \cdot f \cdot C$$

$$= 2\pi \cdot (9.0\ \text{V}) \cdot (2\ \text{MHz}) \cdot (10\ \text{nF}) \cong 1.1\ \text{A}$$

$$\text{At 6 MHz, } P_L = 15.75\ \text{dBm} \cong 38\ \text{mW}$$
$$\text{At 10 MHz, } P_L = 5.851\ \text{dBm} \cong 3.8\ \text{mW}$$
$$\text{At 14 MHz, } P_L = 0.1848\ \text{dBm} \cong 1.0\ \text{mW}$$
$$\text{At 18 MHz, } P_L = \text{-}5.339\ \text{dBm} \cong 0.29\ \text{mW}$$

$$\text{Thus, } \mathrm{P}_{ESR} = 38\ \text{mW} + 3.8\ \text{mW} + 1.0\ \text{mW} + 0.29\ \text{mW} = 43\ \text{mW}$$

$$\mathrm{P}_{ESR} = I_C^2 \cdot ESR \;\rightarrow\; ESR = \frac{43\text{mW}}{(1.1\,\text{A})^2} \cong 39\ \text{m}\Omega$$

From these calculations performed on the worst-case non-linear SPICE model, the extreme non-linear behavior contributed 39 mΩ of apparent ESR to the capacitor. In this case, the apparent losses caused by non-linear behavior are comparable to typical ESRs of MLCCs at 2 MHz.

4. Conclusion

It has been shown that, while non-linear behavior in X7R and NP0 capacitors will shift some power from a fundamental frequency to its harmonics, the effective contribution to ESR due to this non-linear behavior under most practical circumstances is negligible. The magnitude of the non-linear effects depends on the voltage rating of the capacitor, which determines the thickness of the dielectric layers, and the strength of the applied voltage. For an applied voltage that is small relative to the voltage rating of the capacitor, non-linear effects will make a negligible contribution to the apparent ESR of the capacitor.

Under extreme circumstances, a very non-linear capacitor may exhibit a capacitance that is strongly dependent upon the applied voltage. If such a capacitor is driven with a signal that is large relative to its voltage rating, the capacitor may show a non-negligible contribution to the capacitor ESR due to the non-linear behavior of the capacitor.

References

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