TECHNICAL PAPER

Ripple Current: An Increasingly Relevant Test to Complement Design Considerations

Vincent Mao
Joe Hock
Caleb Winfrey
KYOCERA AVX Components Corporation
One AVX Boulevard
Fountain Inn, S.C. 29644 USA

Abstract

The world is shifting towards electrification with electric vehicles (EVs), renewable energy, and smaller, more powerful, but efficient, system-on-chips (SOCs) as both signal and power integrity across different environments become a concern. The ripple current test is usually required to assess device performance up to 20°C above room temperature. This overview focuses on the test setups used to cover three ESR tiers (low, medium, high, respectively) for applications from signal integrity to microwave/RF. We present initial results and procedures to collect and analyze data as well as considerations for performance impacts with mounted parts. Ongoing challenges are also discussed.

INTRODUCTION

Ripple current is part of the design consideration that has traditionally been more of an issue in CPU design and cooling in computer systems. As more embedded systems enable computing technology to become more ubiquitous, this phenomenon is becoming more relevant across other industries that historically were less susceptible to its effects (automotive being one recent example). As such, physical properties and design choices for capacitors and other passive elements are now of interest.

We present a test to characterize ripple current across our three different product lines as it is related to the equivalent series resistance (ESR) that affects the amount of heat generated per part. In volume and mounted on boards for various applications and more varied environments, performance of these parts can be significantly impacted. Because ESR is frequency-dependent, ripple current becomes of interest to microwave and RF applications in addition to signal integrity applications.

The ripple current test setup includes a signal generator, a power amplifier, an impedance matching component, a fixture that supports both unmounted and mounted DUT configurations, and data collection instruments such as power meters, oscilloscopes, a thermal imaging and temperature monitoring apparatus, and a load. The power and frequency capabilities of the setup depend on the form factor as well as capacitance and energy requirements.

RIPPLE CURRENT BACKGROUND

Ripple current is the AC current provided by a power source that features high amplitude and narrow bandwidth pulses. It also coincides with or is close to the AC voltage applied across capacitors. Because of this dependency, ripple current is a test best suited to provide insights into how the part will respond to it across a frequency range without exceeding the rated voltage. This informs both the circuit design and the type of capacitor to use in potential applications that measuring the ESR alone does not.

The power and heat generated by the part is dependent on the ripple current as well as the ESR of the capacitor through the following expression:

$$P_{generated} = I_{Ripple}^{2} ESR$$

In addition, the ESR varies with the frequency of the applied voltage. Since the maximum power transfer occurs when the amplifier output impedance matches the impedance of the capacitor (i.e., the conductive and inductive properties are cancelled out due to resonance). To this end, applications below the resonance frequency minimize ripple current are recommended to avoid damaging the part due to unmitigated power delivery.

As ripple current is dependent on the ESR, different types of capacitors will have different levels of heating (i.e., the higher the ESR, the lower the ripple current tolerance). NP0 parts have the highest tolerance, followed by X7R capacitors, with tantalum having the lowest tolerance. As far as capacitance values are concerned, there is a negative correlation between it and the resonance frequency as characterized by the following expression:

$$F_r = \frac{1}{2\pi\sqrt{LC}}$$

As the capacitance is a fixed value, the only factor that can be used to adjust the resonance frequency is the inductance. Decreasing this value can be achieved by minimizing air gaps when mounting the part on a printed circuit board (PCB) while increasing it requires the addition of inductors in series with a capacitor. These modifications depend on the application as well as the frequencies needed for characterizing the ripple current.

A typical ripple current test setup requires two parts: 1) a means to provide the signal, and 2) a means to measure the temperature as well as the voltage and current.

RIPPLE CURRENT BACKGROUND

For the first portion of the setup, a function generator provides the sinusoidal AC voltage signal. The waveform is then delivered to a power amplifier, followed by a transformer apparatus for impedance matching to deliver maximum power at the specific frequency. The final optimized waveform is sent to a fixture securing the device under test (DUT). Depending on the magnitude of the ESR, the part is either mounted on a board or clamped between two metal bars.

Voltage and current are measured using an oscilloscope to monitor voltage with a probe and a current monitor attached to the instrument. A thermal imaging camera is suspended from above to monitor both the temperature of the part and the ambient temperature. All data is recorded using a desktop computer.

For cases where a higher ambient temperature is required to simulate operational environments, the test fixture sits on a water-cooled platform with a temperature control unit that includes a water tank and water pumps to provide circulating water for rapid cooling. Temperature control is needed for tests that require the part to reach a stable temperature above room temperature in cases for simulating a different operating environment.

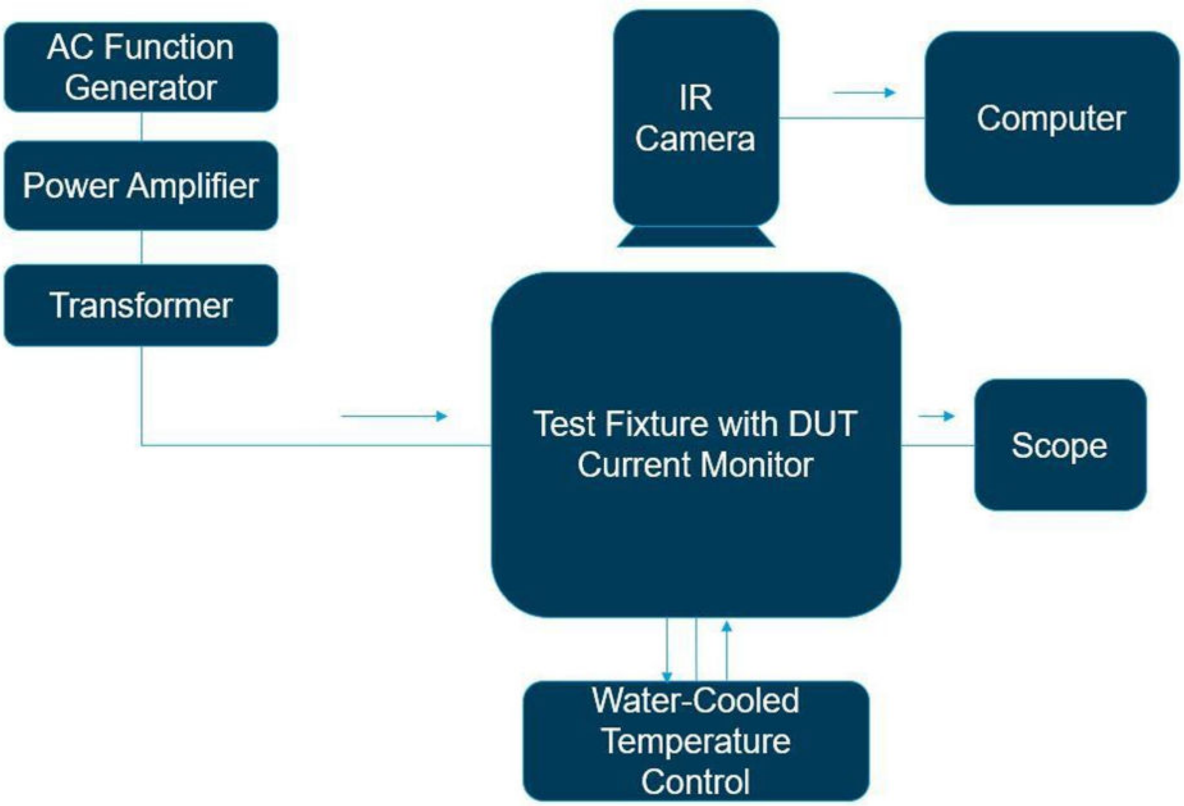


Figure 1. Block diagram of the ripple current test apparatus for low frequency ranges up to 12 MHz.

Figure 1 presents a block diagram layout of the ripple current test as described above. An AC function generator provides a voltage signal that is amplified and impedance matched through the power amplifier and transformer, respectively. The signal is then delivered to the DUT on the test fixture. The oscilloscope captures the voltage and current signals while the thermal camera measures temperature and relays it to the desktop computer.

While the basic setup is sufficient for frequencies

RIPPLE CURRENT BACKGROUND

up to 12 MHz, parts that require higher power or frequencies up to 1 GHz use a higher power amplifier, as well as a separately coupled power meter to monitor the power with a dedicated dummy load.

There are optional modifications to the setup for temperature control as well as power measurements are also included. These become essential at higher test frequencies that are beyond the operational range of the current monitor and the transformer components of the setup. In this case, the block diagram simplifies to the one presented in Figure 2.

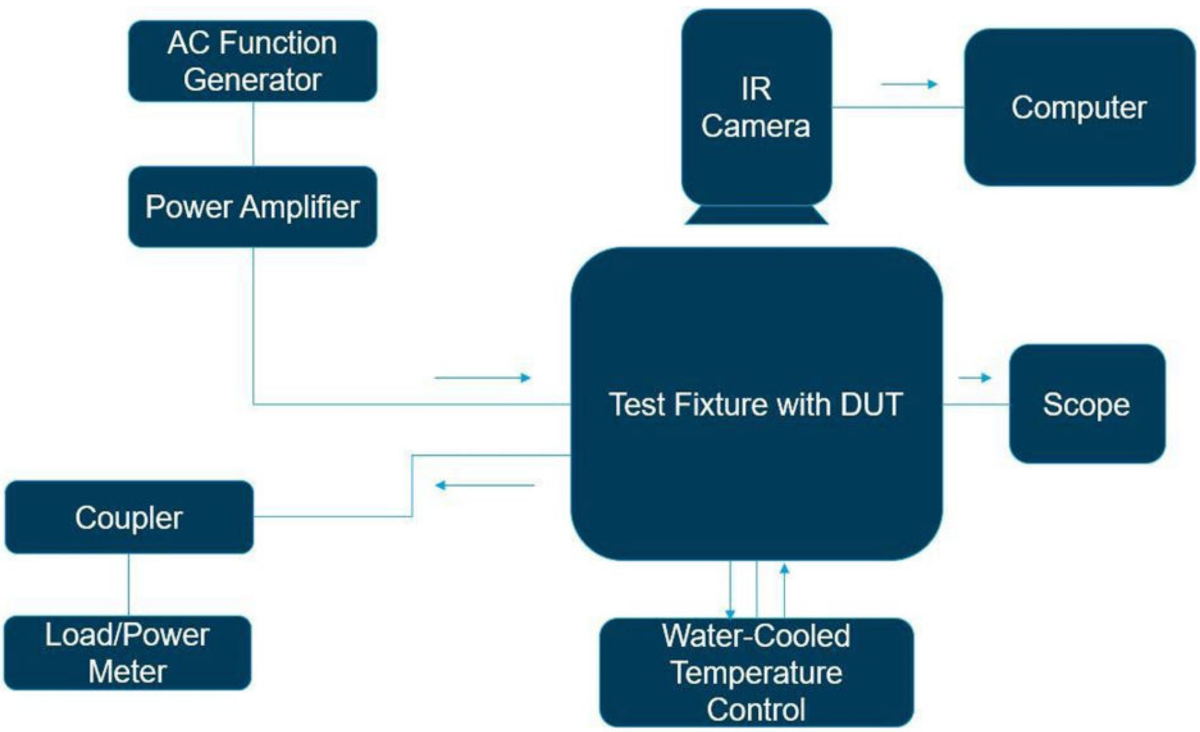


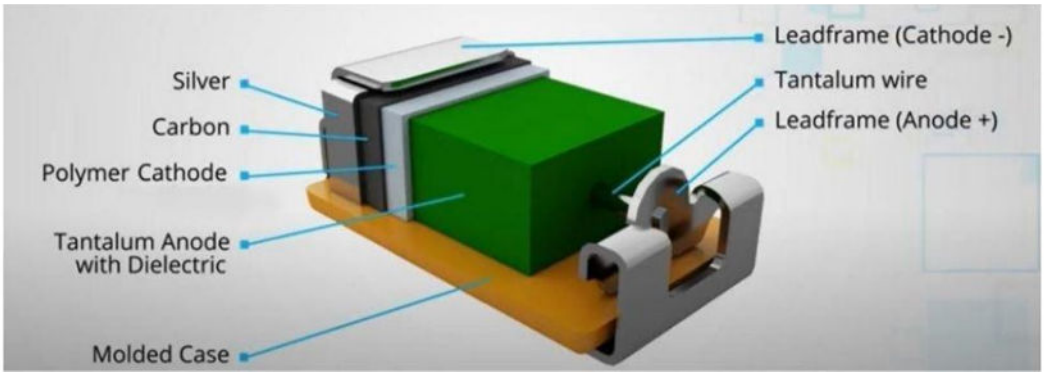
Figure 2. Block diagram of the ripple current test apparatus for high frequency ranges up to 1 GHz.

TANTALUM CAPACITOR BACKGROUND

Tantalum capacitors generally are marketed with low ESR, but they have the highest ESR of the three categories used for this study with values ranging in the high 100's of milliOhms. The value is largely dependent on the dielectric at the low frequency range and on the oxide material at higher frequencies, solid electrolytic capacitors for automotive applications are composed of manganese oxide (MnO2) and feature long lifetime operation with high temperature tolerance, ideal for ripple current characterization studies. In addition, this material is easier to manage than aluminum electrolytics that are sensitive to heat during PCB mounting [1].

The layout for this type of capacitor features a polarized orientation. The tantalum wire connects between the anode and the dielectric followed by the polymer cathode and the cathode. A molded case surrounds the entire tantalum material. Figure 3 shows the cross section of a typical solid electrolytic capacitor along with a typical part below.

TANTALUM CAPACITOR BACKGROUND



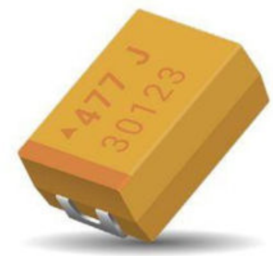


*Figure 3. **Left** Cross section of a solid electrolytic tantalum capacitor. **Right** External tantalum surface mount capacitor case. [2]*

Tantalum capacitors, while higher in ESR, feature a higher stability in maintaining their capacitive properties across a wider applied DC voltage. Another interesting property of this type of capacitor is its self-healing mechanism. When damage to the dielectric occurs, it causes the polymer material to evaporate or carbonize to surround the point of failure. Since the polymer layer is non-conductive and is also non-flammable, tantalum capacitors are more resistant to current spikes and have higher ripple current limits.

X7R CAPACITOR BACKGROUND

X7R capacitors feature more stable behavior across a wide temperature range. The "X" indicates that the device is capable of operating down to -55°C while the "7" indicates it can operate up to 125°C. Finally, the "R" indicates the potential change in capacitance over this temperature range, in this case +/- 15%. An X7R ceramic falls in the Class 2 category and is one of the more common ones used in a wide variety of applications due to its high dielectric constant (i.e., higher capacitive capability), a trade-off for the stability of the operating capacitance.

Due to its design specifications, X7R capacitors have a wide ESR range, generally in the low 100's of milliOhms for lower capacitor values and 10's of milliOhms for higher values. The form factors for this type of capacitor offer more flexibility in its application in addition to its wider capacitive capabilities (100 pF to 22 µF). Figure 4 depicts a typical X7R capacitor.

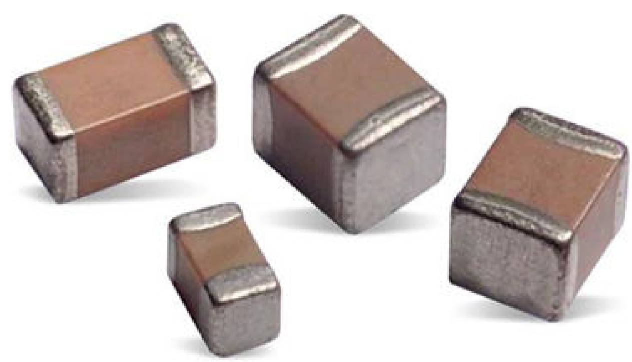


Figure 4. Image of typical KYOCERA AVX X7R capacitors of varying sizes. [3]

As opposed to the tantalum design shown in Figure 3, the design of X7R capacitors is a standard design of alternating layers of metallic electrodes and dielectric ceramic material. Variations in layout such as the position, terminal contact, and number of layers vary among competitors and can affect the ESR as well as the inductive properties of the part.

NP0 CAPACITOR BACKGROUND

NP0 capacitors feature the lowest ESR of the three types used in this study as it ranges in the tens of milliOhms. The name indicates that there is little deviation (0 parts per million or ppm) in the capacitance due to negative or positive shifts in temperature. These capacitors are the most stable across a wide temperature range as a tradeoff for the low efficiency of form factor design (i.e., the size of the parts due to permittivity of the materials used). As such, these capacitors are used for filter networks, tuning and timing circuits, and frequency drift in environments with high temperature variation [4].

Since the size to capacitance ratio is worse for this category of capacitors, it ranges from 0.5 pF to 100 pF. However, this limitation combined with the temperature stability enables much smaller form factors for this capacitance range relative to the previous two products for the applications previously mentioned.

The layout of these capacitors is of similar design with alternating electrode and dielectric layers described for X7R designs. Again, manufacturers vary in configurations for electrode length, position, and type of terminal contacts. The ceramic material used for them falls into the Class 1 category due to its temperature stability regardless of voltage applied over its long lifetime as Figure 5 illustrates.

As can be observed in the plot, the sensitivity of different classes of dielectrics determines their resilience to temperature variation. Illustrating these dependencies serves to emphasize the importance of ripple current over the lifetime of operation for the three capacitor types described in this section.

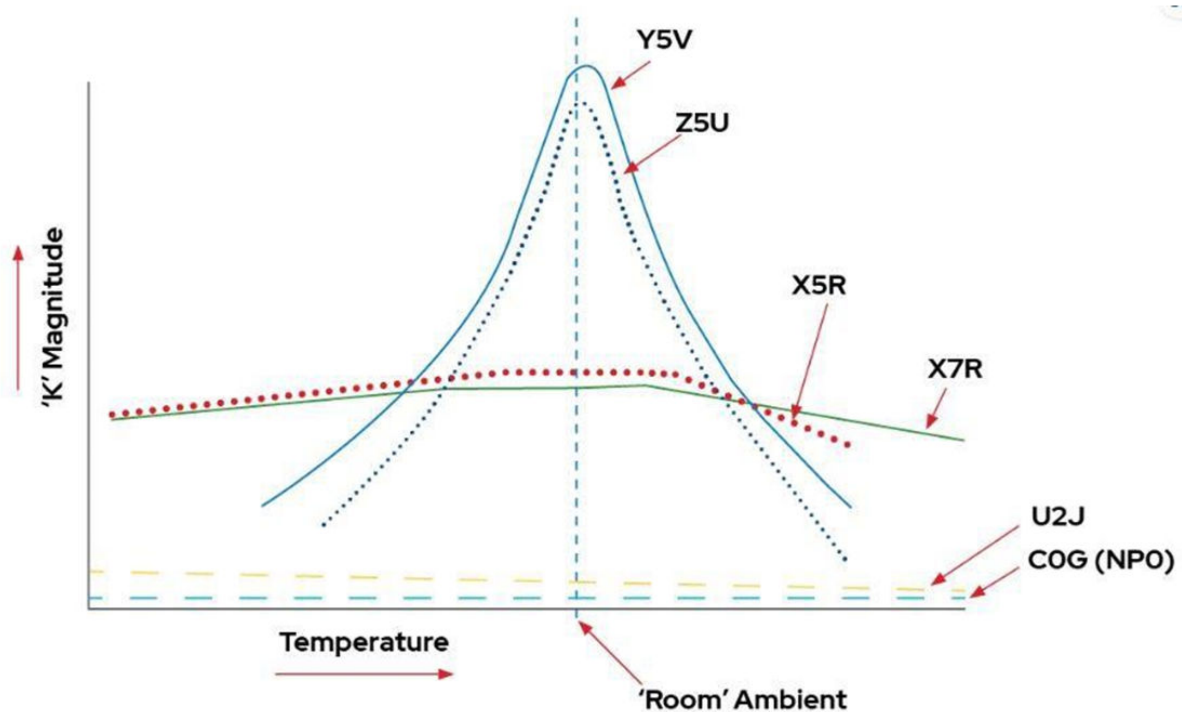


Figure 5. Dielectric permittivity (K') vs. temperature stability comparison for Class 1, Class 2, and Class 3 dielectrics on a linear scale for both axes. [5]

METHODS AND PROCEDURES: DATA COLLECTION FOR NP0, X7R, AND TANTALUM CAPACITORS

A typical ripple current test has three stages: 1) impedance (Z) and ESR characterization, 2) data collection, and 3) data analysis and post-processing. The most time-consuming portion of this process is generally the third stage as this is where assessment of follow-up actions and recollection of data takes place.

Z AND ESR CHARACTERIZATION

In the first stage of the test, the Z and ESR frequency sweeps are collected using an impedance analyzer of an appropriate frequency range. The range must be wide enough to capture the capacitive (negative slope), resistive (i.e., the resonance point where Z = ESR), and inductive (positive slope) responses of the capacitor. This characterization is required to assess the best frequencies to test for ripple current. Up to four frequencies are selected in the capacitive frequency response range. Figure 6 shows an example.

Test frequencies are selected based on the proximity to the resonance frequency. Both tantalum and X7R parts use frequencies that range as low as 25 kHz up to 5 MHz. While NP0 parts also have this range, inductors are also needed for improved impedance matching. Mounting

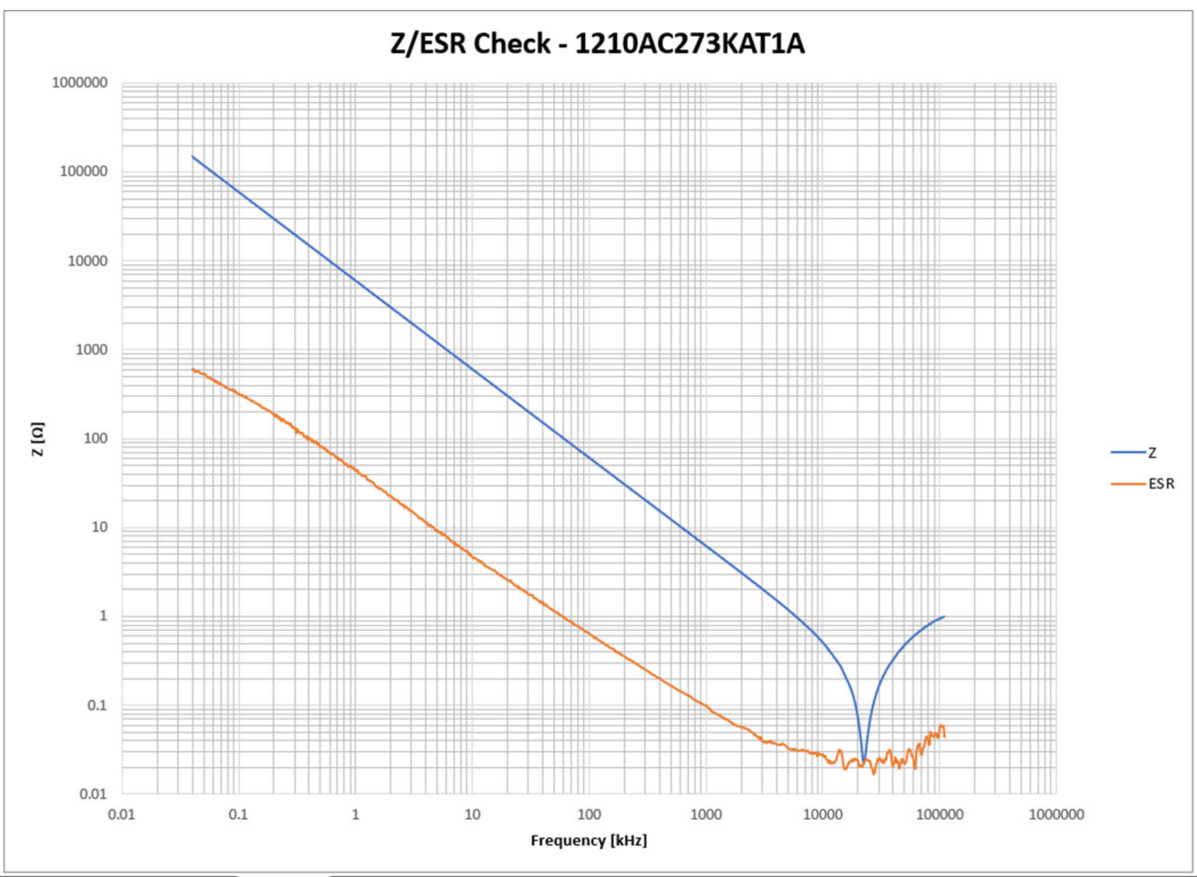


Figure 6. Typical Z ESR frequency response for a 1210 size 27 nF X7R KYOCERA AVX capacitor with a 22 MHz resonance frequency.

Z AND ESR CHARACTERIZATION

these devices on a test board also improves characterization as this also adds inductance for testing. However, since the amplified voltage signal is directly applied across the device, the calculated impedance is not affected.

Two instruments are used for collecting impedance and ESR data: 1) Agilent 4294A 40 Hz – 110 MHz Precision Impedance Analyzer and 2) Agilent E4991A 1 MHz – 3 GHz RF Impedance/ Material Analyzer. Depending on the device and whether inductor coils were needed for resonance frequency adjustments, the following four test fixtures were used: 1) Agilent 16192A (up to 2 GHz), 2) Agilent 16047E (for impedance matching), 3) HP 16034H (up to 110 MHz), and 4) HP 16034E (up to 2 GHz).

Once the appropriate target frequencies are determined, the part is ready for the data collection phase of the test.

RIPPLE CURRENT DATA COLLECTION

The data collection process is designed to progressively increase the voltage across the part until the part meets or exceeds the standard temperature rise of 20°C above ambient temperature. Special test cases requested by the customer can be accommodated on a case-by-case basis. With each amplified voltage signal applied, the RMS voltage and current values are recorded from the oscilloscope signal. The temperature of the part is also recorded relative to the ambient temperature from the thermal camera. Figure 7 presents the test setup.

As can be seen in the figure below, the following instruments are used for the ripple current test apparatus: signal generator – Keysight Function Generator, matching network – T&C Power Transformer, power amplifier – EIN Model 2100L RF, thermal camera – FLIR A320, current monitor – Pearson 410, oscilloscope – Tektronix MDO3022, and temperature control – Instec water-cooled fixture. The DUT fixture is a custom mount fixture with copper bars for the unmounted device. The mounted devices are clamped on the platform to

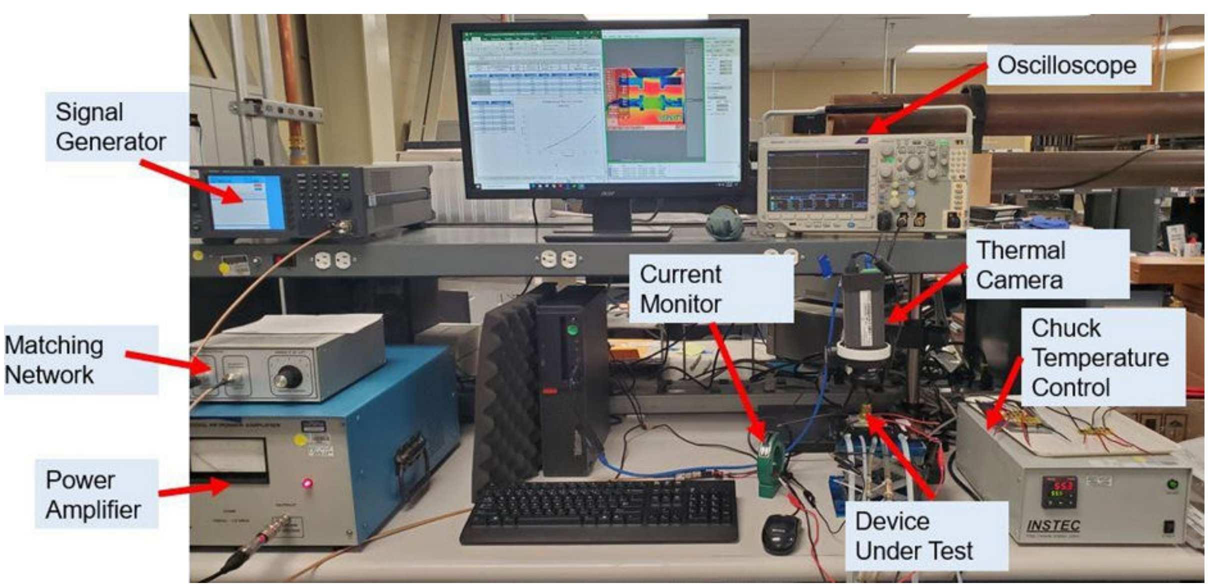


Figure 7. Ripple current test apparatus.

RIPPLE CURRENT DATA COLLECTION

hold it in place with inductors connected in series using leads with alligator clips.

Data collection for X7R and NP0 parts use four frequencies while the tantalum parts focus on one frequency at a 45°C base temperature. Once the data collection process is complete, the final phase of the ripple current measurement begins.

DATA ANALYSIS AND POST-PROCESSING

Impedance sweep data from the first phase of the procedure is used to verify that the second phase provides reasonable results. Ohm's Law states that impedance is the voltage divided by the current, and the spreadsheet used to collect the RMS voltage and current calculates the resulting impedance at the specific frequency. The calculated impedance from the data is required to be in the same order of magnitude as the data collected from the impedance analyzer. Deviations from it are due to additional resistance from the fixture depending on the frequency applied to the part.

Interpolation is used to approximate the ripple current needed to achieve the 20°C rise above ambient temperature. For frequencies where the maximum voltage was insufficient to achieve the target temperature, some extrapolation is done

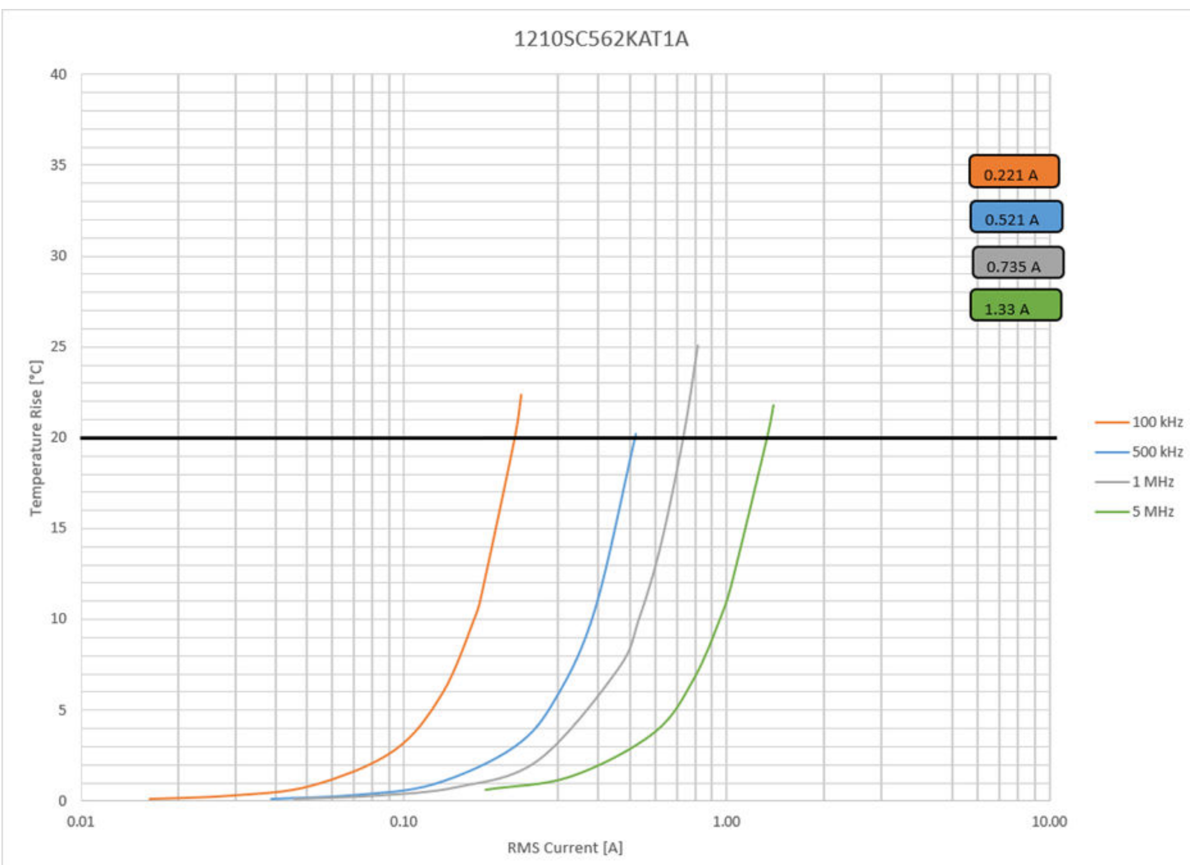


Figure 8. Ripple current data set for a 1210 X7R 5.6 nF KYOCERA AVX part.

DATA ANALYSIS AND POST-PROCESSING

using fourth order polynomial fitting. For these data sets, more data up to the voltage limit on the apparatus is collected for best fit, provided that the rise in temperature is at least 10°C – 15°C. If this is not possible, a lower frequency is selected for further data collection for the part.

Once the limit is determined for each frequency, the entire data set is assembled into one plot. This plot is used to determine if the part is suitable for the intended application. Figure 8 presents an example of a set of data ranging from 100 kHz to 5 MHz.

Due to the time-intensive nature of the entire process, two parts from a lot are used for each test. If the results of the two parts are not within 15% of each other for each frequency, a third part is used for data collection. Typical data values are planned to be determined as test volume increases.

RESULTS: DATA ANALYSIS AND FUTURE MODIFICATIONS

Data from the three capacitor types was collected across multiple lots ranging from 100 pF to 470 µF across a variety of form factors from 0603 to 2220. X7R parts yielded ripple current values from the tens of mA to as high as 3A with a positive correlation with capacitance value. NP0 parts ranged from hundreds of mA up to 6A. Tantalum capacitor data was collected for 100 kHz for repeatability with currents ranging between 3A and 8A with a standard deviation of between 100 and 400 mA.

To illustrate further the overall visible trend for each part, the following sections provide a breakdown of each capacitor type tested as well as the frequency and corresponding ripple current value for each. Only the four most common tested frequencies (100, 500, 1000, and 5000 kHz) are provided for convenience.

X7R DATA ANALYSIS

Data collection was completed for 35 lots ranging from 100 pF to 47 µF over three different form factors (1206, 1210, and 1808 sizes). Figure 9 presents the log-log capacitance vs. ripple current plot.

From the data presented below, a clear positive correlation can be observed that can be used to interpolate ripple current values for capacitors that fall within this range. Over this capacitance range, equations for the best fit can be determined for each frequency value using the power trendline. The R2 values for are ~0.96, with the exponents of the fit being ~0.5, meaning there is a possible square root relation for the capacitance with a scaling term. Further data collection is needed to verify whether this trend will be consistent.

X7R DATA ANALYSIS

Figure 9. Capacitance vs. ripple current data for X7R parts for 100 kHz, 500 kHz, 1000 kHz, and 5000 kHz frequencies.

NP0 DATA ANALYSIS

Data collection for this class of capacitor proved to be more challenging due to lower ESR values and higher impedance. The process included multiple characterizations for inductors in series to search for the appropriate resonance frequencies needed to achieve the target ripple current criterion of 20°C. In addition, the size range of these parts from 0402 to 1210 meant that these parts needed to be mounted on a PCB, further affecting the resonance frequency.

Current data is not enough for any discernable trend to emerge. A power trend is expected based on the results observed in X7R. However, there are several differences between the data collection process as previously described. The need for mounting the parts as well as placing inductors in series could affect the results. Further investigation is needed to determine additional post-processing steps to remove these effects. Figure 10 presents the results available.

NP0 DATA ANALYSIS

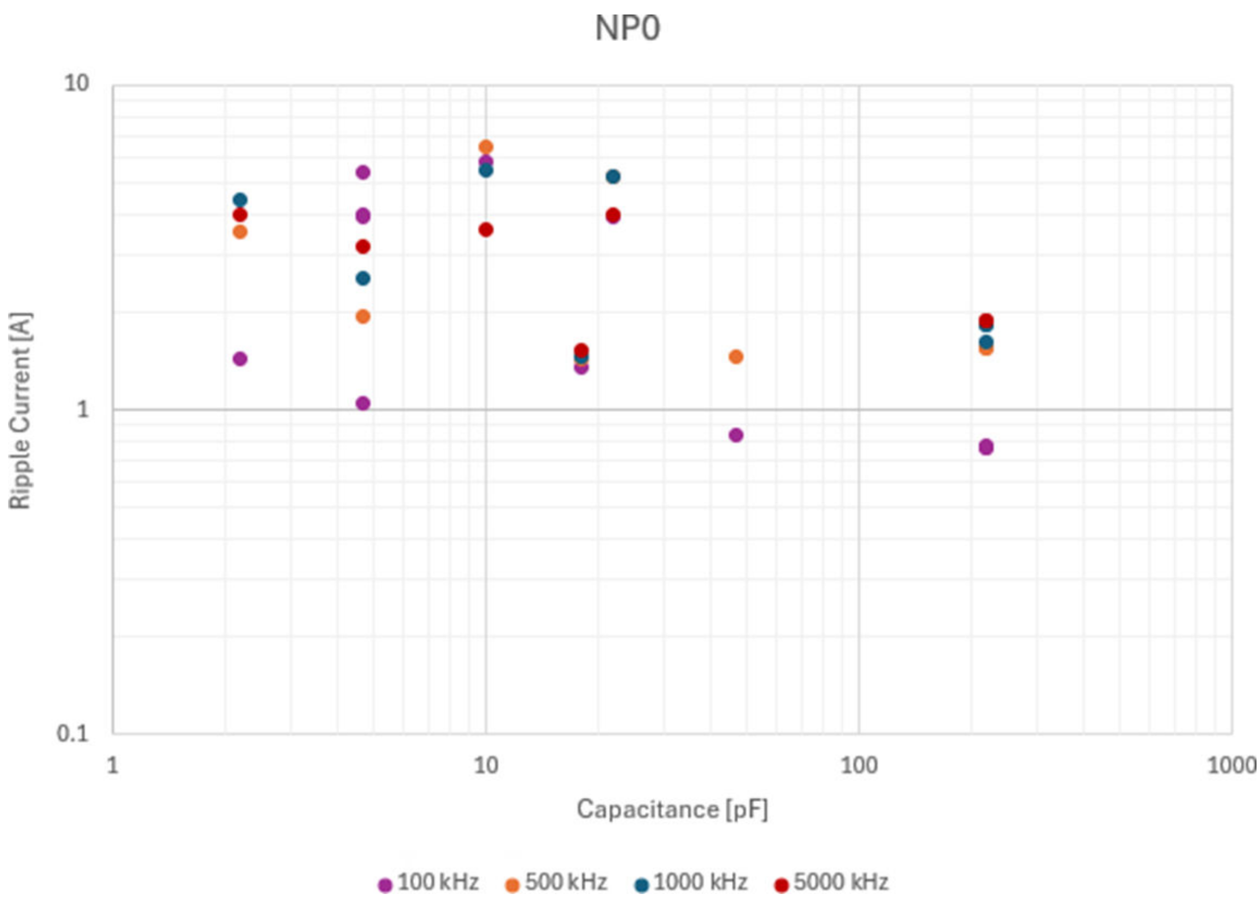


Figure 10. Capacitance vs. ripple current data for NP0 parts for 100 kHz, 500 kHz, 1000 kHz, and 5000 kHz frequencies.

TANTALUM DATA ANALYSIS

Due to the high ESR for these types of capacitors, they are ideal for repeatability studies as the response time for them is rapid since they do not require mounting or impedance matching steps that the previous two required. A total of 6 lots ranging from 10 μF to 470 μF using 10 parts each were measured and analyzed. The minimum, maximum, and standard deviation of the ripple current values were determined for each set of data. Figure 11 presents the results in a plot.

For this set of data, there appears to be a positive trend, but as with the NP0 data, there is not enough data from multiple capacitor values to make accurate predictions for interpolation. Additional frequency data like the previous two capacitor types will be needed. Repeatability of the data ranges in standard deviation from 0.121A to 0.405A, within 5% of the ripple current values of most of the lots. However, the variation in the ranges from lot-to-lot is from 0.41A to 1.21A among these 6 lots. The spread is due to the tolerance range from these lots that can affect the ESR tolerance range.

TANTALUM DATA ANALYSIS

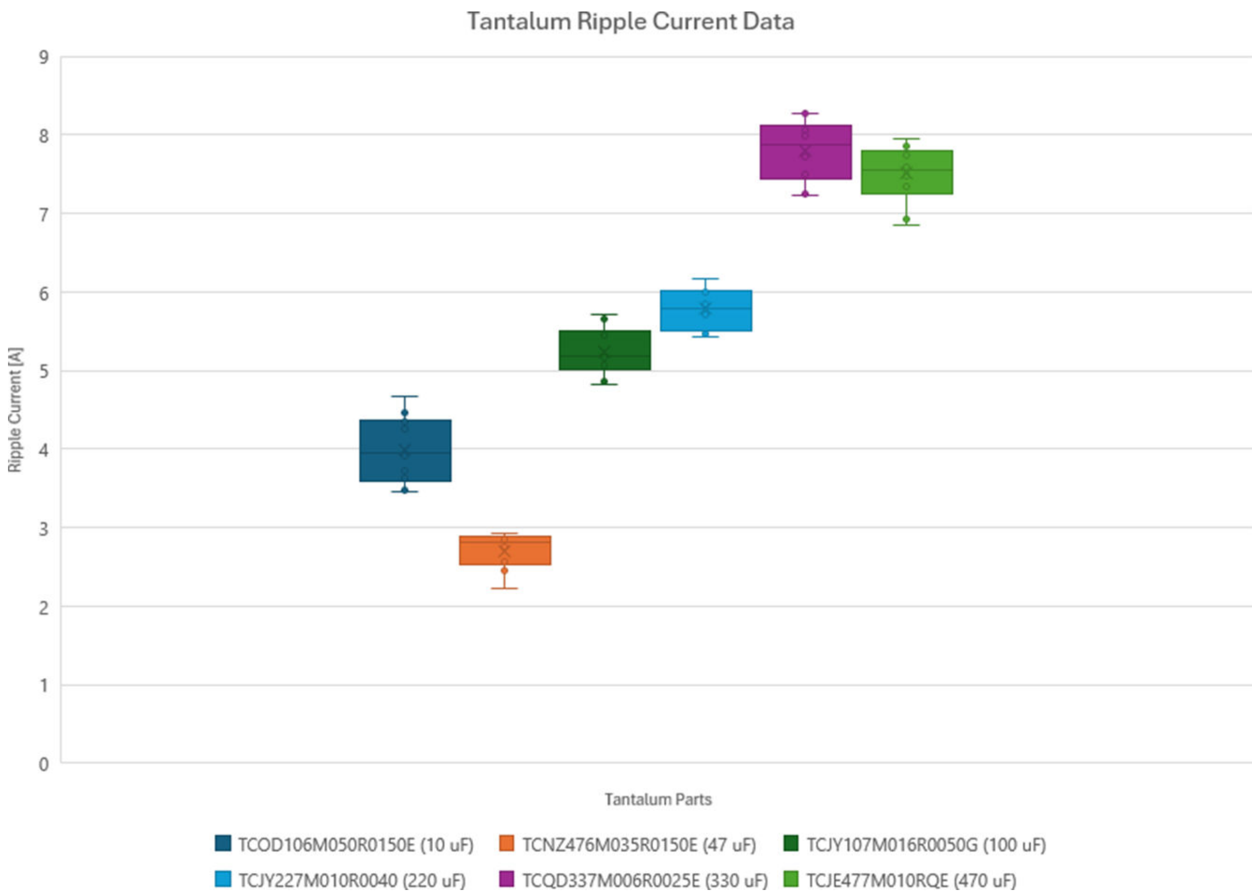


Figure 11. Capacitance vs. ripple current data for tantalum parts for 100 kHz frequency at 45°C baseline temperature.

FUTURE MODIFICATIONS FOR DATA ANALYSIS

The analysis of these three capacitor categories indicates several improvements that can be made. The development and refinement of the ripple current test can benefit from higher frequency data collection as well as more parts tested per lot. With sufficient data volume, similar log-log plots presented for X7R can be used to observe a correlation between the frequency and the ripple current in both NP0 and Tantalum parts. Another potential trend to present in future analysis is one that plots the frequency vs ripple current for each capacitor type. As was seen in Figure 9, the scaling term could be used to see if there is a predictable trend.

Another aspect of the ripple current test that can be improved is dependent on the design of the test setup. While the power amplifier can deliver 250W, the instruments used to monitor the applied voltage are sensitive to frequencies higher than 10 MHz.

Modifications to the setup will include methods to shield them from interference.

Further analysis and characterization such as providing plots for VI curves that are dependent on frequency are in progress as well. Because the ripple current is dependent on the ESR value, it is possible to make reasonably accurate estimates

FUTURE MODIFICATIONS FOR DATA ANALYSIS

from this perspective. Figure 12 presents a work-in-progress.

The figure below presents an example that is based on scaling the ripple current based on the ESR at the resonance point of the part but is only accurate based on the maximum ripple current measured near the resonance frequency. Accuracy of the plots continues to be a challenge since the predicted ripple current values do not match well with the measured values at other frequencies.

Overall, there is a negative correlation between ESR ranges for NP0 to X7R to Tantalum type capacitors. Lower ESR results in higher ripple current values as expected from the data collection. Design considerations for each type in the future will take into consideration the amount of power that can be dissipated as well as the amount of current that can be tolerated for each part. These insights will be useful for applications that require consistent power delivery across different environments. As the volume of data collected increases over time, more insights will be revealed with different correlations and models. A combination of real data and extrapolation models can aid in EV charging circuit design, low-loss power delivery efficiency, and higher frequency operation applications.

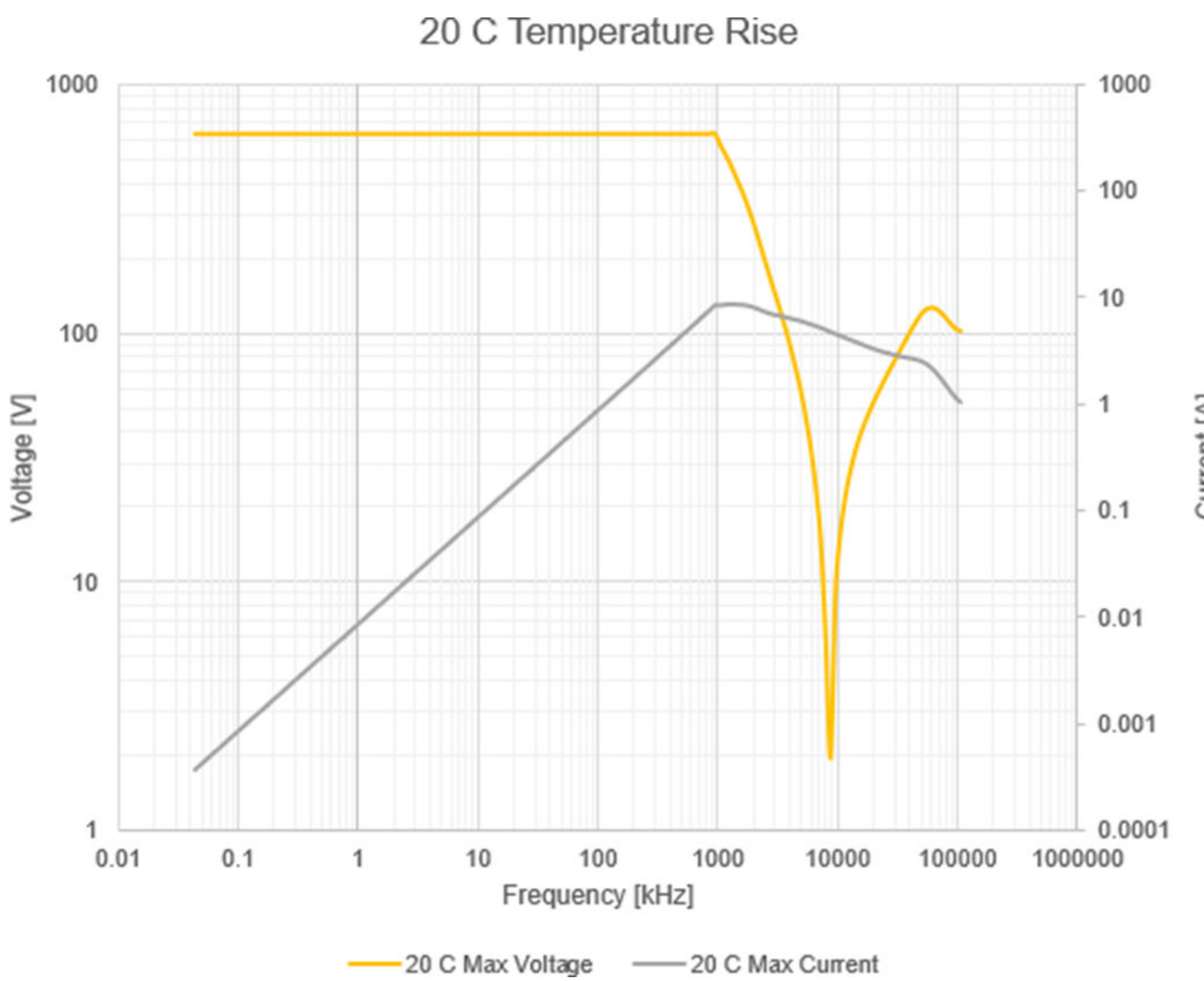


Figure 12. Max voltage and current plots for a high capacitor value NP0 part with a 630V rating.

SUMMARY

Ripple current is a test that becoming increasingly relevant for embedded systems. Theory, the test setup, data collection methods, and data analysis were presented in this study for three product lines. While the concept of ripple current is nothing new, the comprehensive approach we take to cover the space across several different capacitor products aid to predict its behavior and characterization. The test is tedious and time intensive, but our approach enables us to connect its dependence on the capacitance value and frequency that can aid in applications like signal integrity and microwave/ RF circuit designs.

REFERENCES

[1] KYOCERA AVX, "Basic_Tantalum_Capacitor_ Technology.pdf," KYOCERA AVX, [Online]. Available: https://www.kyocera-avx.com/docs/techinfo/Basic_Tantalum_Capacitor_Technology.pdf. [Accessed 11 October 2024].

[2] KYOCERA AVX, "polymer-caps-automotive-applications.pdf," KYOCERA AVX, [Online]. Available: https://www.kyocera-avx.com/docs/techinfo/Tantalum-NiobiumCapacitor/polymer-caps-automotive-applications.pdf. [Accessed 11 October 2024].

[3] Mouser, KYOCERA AVX X7R Multilayer Ceramic Capacitors – KYOCERA AVX, [Online]. Available: https://www.mouser.com/new/kyocera-avx/avx-x7r-mlcc/ [Accessed 11 October 2024].

[4] Learning About Circuits, “What is a NP0 Ceramic Capacitor”, [Online]. Available: http://www.learningaboutelectronics.com/Articles/What-is-a-NPO-ceramic-capacitor [Accessed 14 October 2024].

[5] Yageo Kemet Group, “Here’s What Makes MLCC Dielectrics Different”, [Online]. Available: https://www.kemet.com/en/us/technical-resources/heres-what-makes-mlcc-dielectrics-different.html [Accessed 14 October 2024]

First Published at DESIGNCON 2025

www.designcon.com

NORTH AMERICA
Tel: +1 864-967-2150

ASIA
Tel: +65 6286-7555

CENTRAL AMERICA
Tel: +55 11-46881960

EUROPE
Tel: +44 1276-697000

JAPAN
Tel: +81 740-321250

WWW.KYOCERA-AVX.COM