Coupling Capacitor Evaluation

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Coupling Capacitor Application:

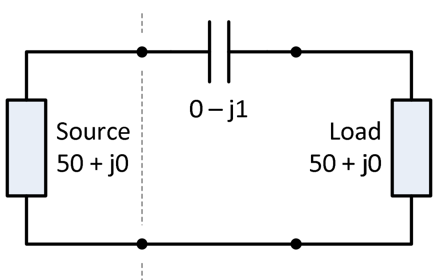
Coupling capacitors isolate components, such as RF switches, attenuators and RF amplifiers, from undesired dc voltages. Ideally, a coupling capacitor has reactance that decreases with frequency throughout the desired frequency range according to $1/2\pi fC$ where C is the capacitance and f is the frequency. However, practical capacitors have equivalent series resistance (ESR), equivalent series inductance (ESL), and a self-resonant frequency (SRF). The SRF is the frequency at which the capacitive reactance equals (and cancels) the inductive reactance. At the SRF, the capacitor's impedance equals the ESR and above the SRF, the capacitor has inductive reactance.

ARX Rev. G and Rev. H Coupling Capacitors:

For reference, the coupling capacitors used in the Rev. G ARX are 1000 pF (1 nF) whereas in the Rev. H ARX they are 0.1 µF (100 nF).

ARX Rev. I Requirements:

The design frequency range of the ARX is 3 to 100 MHz. The coupling capacitors are chosen to have ≤ 1 ohm impedance (≤ 2% of 50 ohms system impedance) at 3 MHz. The 1 ohm impedance is a tradeoff between large capacitors that have higher ESR and lower SRF and small capacitors with relatively high capacitive reactance that would introduce impedance mismatching at the lower frequencies.



The simple circuit shown left has 50 + j0 ohms source and load impedances and a capacitor with 0 – j1 ohms impedance (at 3 MHz) connecting them. The impedance seen by the source is 50 – J1 ohms and |Z| = 50.01 ohms. The return loss seen by the source at the junction of the source and capacitor is 40 dB, indicating that the capacitor introduces negligible impedance mismatch. If the capacitor impedance is increased to 0 – j3 ohms, |Z| = 50.09 ohms and the return loss reduces to 30.5 dB.

At higher frequencies, the capacitive reactance is (theoretically) lower and the return loss is higher. However, practical capacitors have an SRF and inductive component at higher frequencies as shown below. Ideally, for the ARX application, the capacitor SRF would be ≥ 100 MHz but this is not achievable with ordinary ceramic capacitors in the values required. The actual capacitors selected for the ARX are discussed in the next section.

<u>Selected Capacitors</u>: The theoretical reactance at 3 MHz of a 0.047 µF (47 nF) capacitor is 1.1 ohms, slightly higher than the maximum given above; therefore, a value of 0.068 µF (68 nF) is selected, which has theoretical reactance of 0.78 ohms at 3 MHz. To protect the GALI-74+ amplifiers outputs from possible transient voltage damage, 5X to 10X larger capacitors are used on the amplifier outputs as recommended in the Mini-Circuits (MCL) application note *Transient Protection of Darlington Gain Block Amplifiers*, page 10 (see References); note that these recommendations are dated 2015 and MCL did not provide a definitive answer to inquiries about the applicability of this recommendation to current GALI-74+ products. Therefore, a conservative approach is taken

to ensure there are no problems. The selected value for the amplifier output coupling capacitors is 0.47 µF (7X the input capacitor value).

Refer to the master system block diagram in the Reports folder. The Rev. I ARX RF path contains 14 coupling capacitors, 11 with 0.068 µF capacitance and 3 with 0.47 µF capacitance. The goal is to find multi-layer ceramic capacitors (MLCC) that meet the reactance requirements from 3 to 100 MHz. All capacitors are size 0805, and a tolerance of ±10% and X7R dielectric are acceptable (capacitance variation due to applied voltage is not expected to be important).

Manufacturers Evaluated:

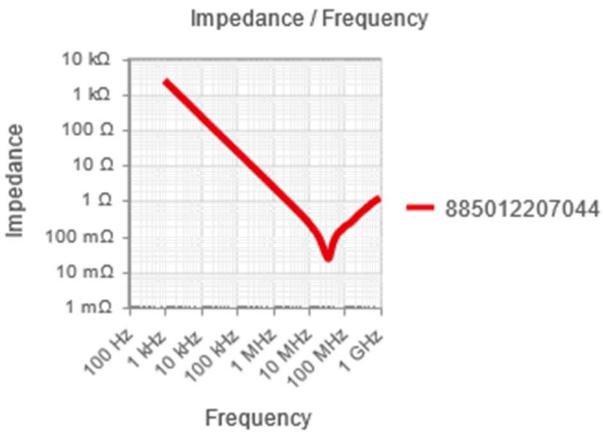
Investigation of Kemet, Kyocera, Murata, TDK and Wurth showed that all ordinary ceramic capacitors in the desired capacitance ranges have SRF far below 100 MHz. However, these capacitors still are usable if the reactance throughout the frequency range 3 to 100 MHz meets the 1 ohm requirement mentioned above; in other words, the 2% impedance requirement must be achieved throughout the entire operating frequency range even though the SRF requirement cannot be met by available parts. It is noted that if the impedance requirement is met at the 3 and 100 MHz endpoints, it will be met at all frequencies in between because the transition from capacitive to inductive reactance, and minimum impedance, occurs between the two endpoints for the capacitors being considered.

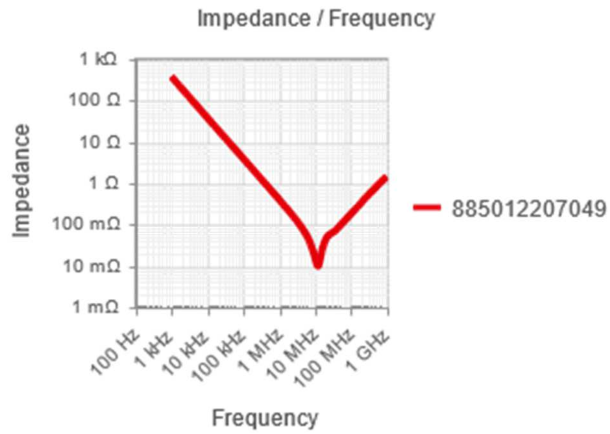
Silicon RF capacitors were investigated and rejected because of their extremely high costs. Detailed frequency-dependent data for MLCCs are available from capacitor manufacturers but, for most of them, the data are not readily accessible. TDK and Wurth Elektronik are exceptions. Wurth data, including SRF plots and other data, were the easiest to access and use through their REDEXPERT online software (see References). The analysis below is based on Wurth capacitors.

Wurth Capacitors:

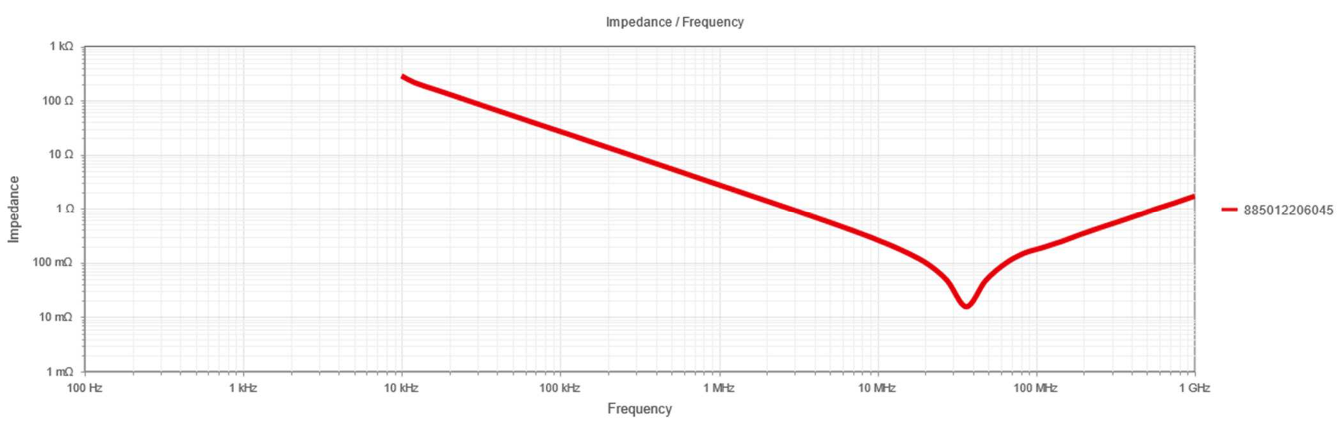
Wurth manufacturers several types of MLCCs. Its line of WCAP-CSRF High Frequency capacitors is specifically designed for RF applications but are available with a maximum value of only 33 pF. However, its line of WCAP-CSGP General Purpose capacitors reaches 47 µF in a voltage rating of 16 Vdc and a temperature rating of –55 to +125 °C.

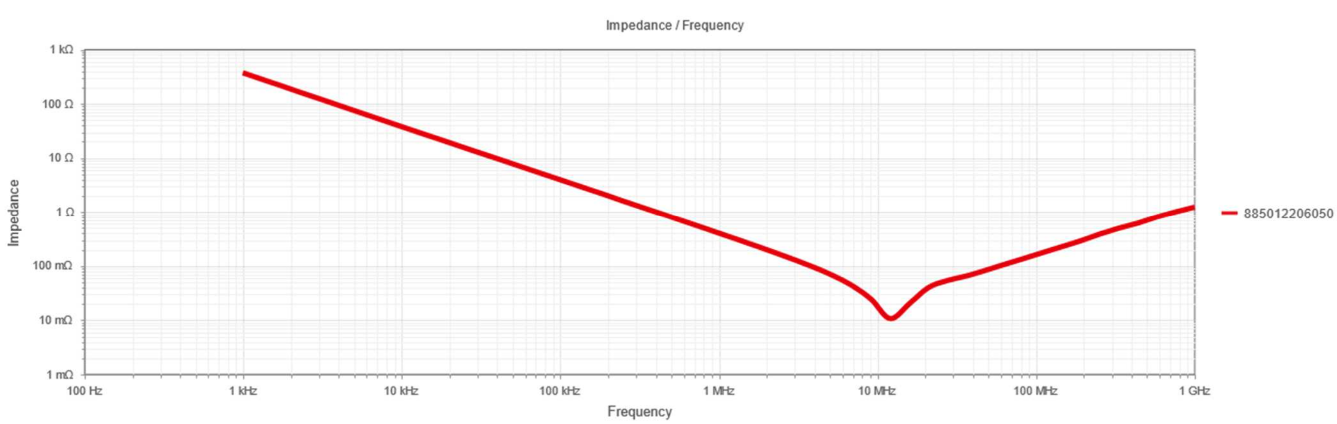
For the 0.068 µF capacitor, Wurth p/n 885012207044, the plotted impedance (below-left) is 0.845 ohms at 3 MHz and 0.181 ohms at 100 MHz. For the 0.47 µF capacitor, p/n 885012207049, the plotted impedance (below-right) is 0.129 ohms at 3 MHz and 0.176 ohms at 100 MHz. These two capacitors meet the requirements previously stated.





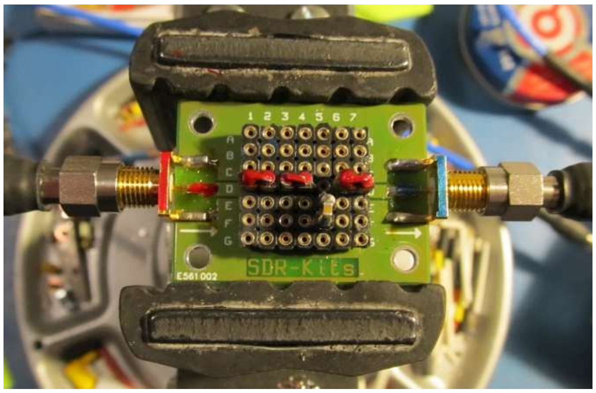
The Wurth capacitors in 0603, 16 Vdc, X7R and ±10% tolerance also were examined. These capacitors have a smaller footprint and less pad capacitance than the 0805 sizes. The plotted impedance for the 0.068 µF capacitor in 0603, p/n 885012206045 (upper image below) is 0.851 ohms at 3 MHz and 0.180 ohms at 100 MHz. For the 0.47 µF capacitor in 0603, p/n 885012206050, the plotted impedance (lower image below) is 0.124 ohms at 3 MHz and 0.165 ohms at 100 MHz. These two capacitors meet the requirements previously stated.

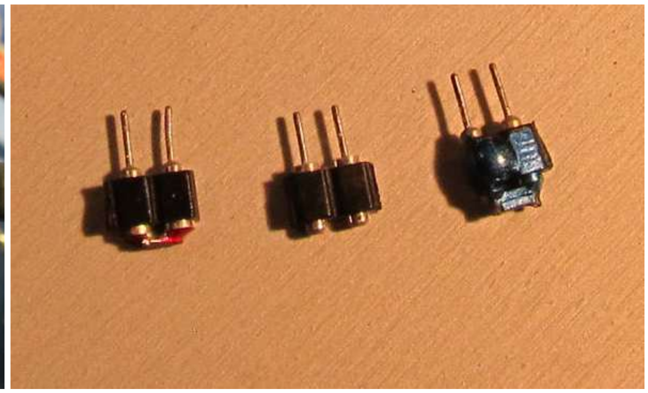




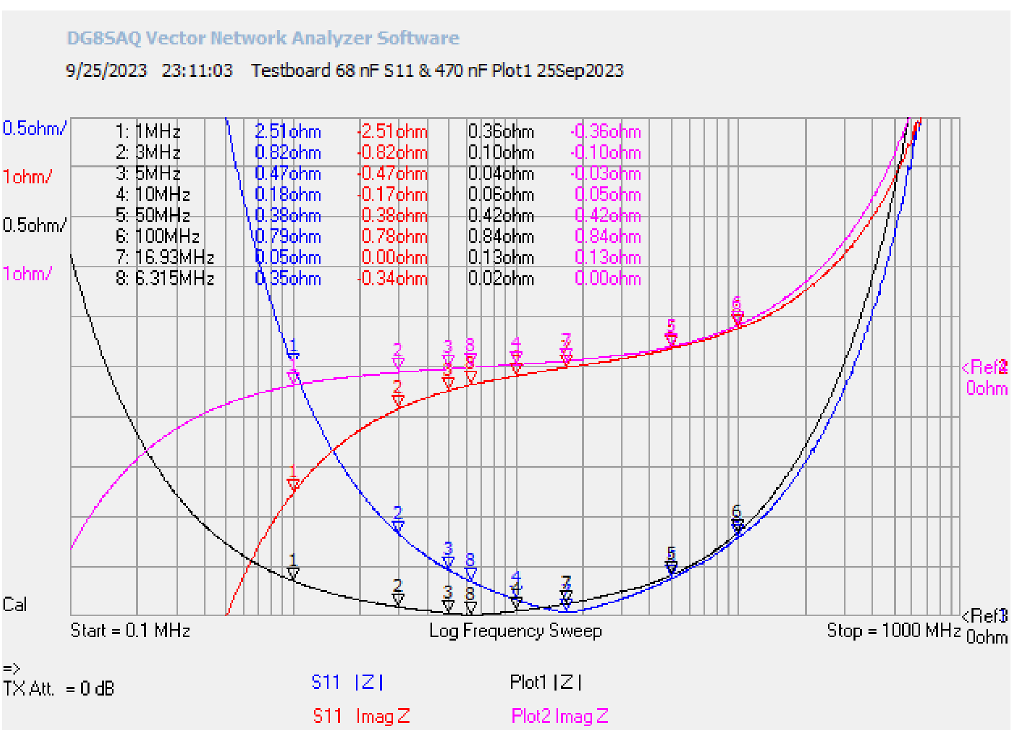
Measurements: Samples of the 0.068 and 0.47 µF capacitors in size 0805 were obtained and measured in a simple shop-built test fixture with a DG8SAQ VNWA vector network analyzer. S-parameter and equivalent impedance measurements and insertion loss were made over the frequency range 100 kHz to 1000 MHz.

The test fixture was made from a PCB with SMA connectors and 0.1 inch pitch socket strips (below-left with a capacitor under test). A plug-in fixture like this has some inherent variability but does provide sufficient accuracy for the comparisons with factory capacitor measurements. The calibration components (Short, Open, Load, Thru) and capacitors were soldered to 2-pin pin strips (below-right).

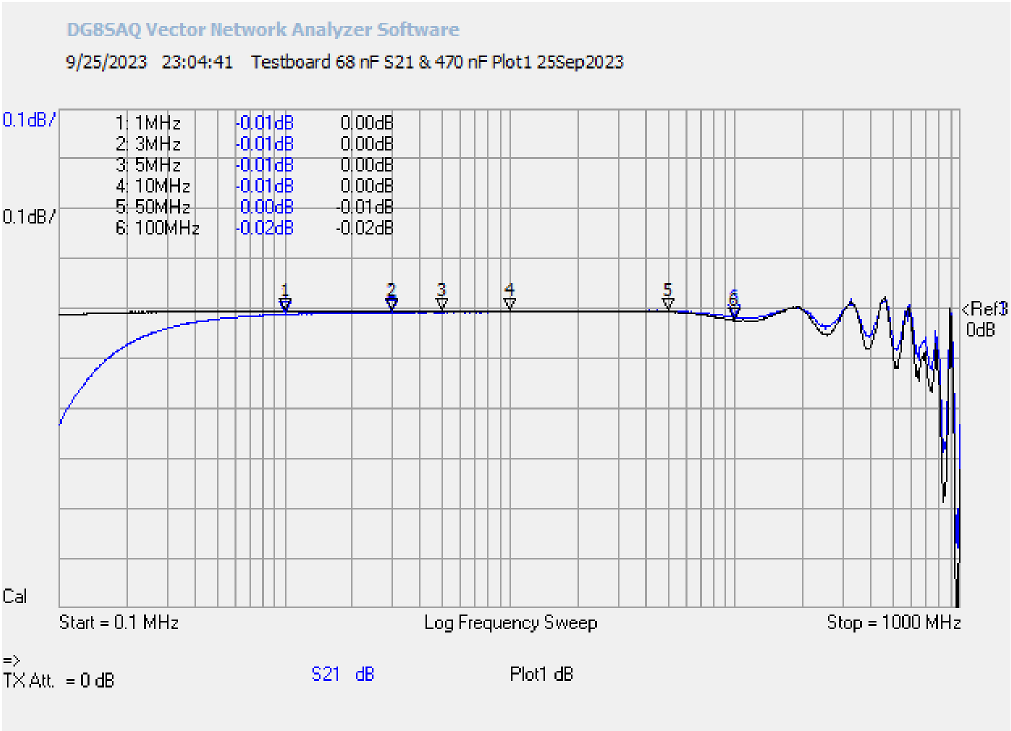




The sockets and pin strips allow easy calibration and the capacitors to be installed in both shunt and series configurations. In the shunt configuration, the primary measurement was S11 reflection coefficient displayed as impedance magnitude |Z| and imaginary impedance ImagZ in ohms. In the series configuration, the primary measurement was S21 transmission coefficient displayed in dB. The plots below show |Z| and ImagZ in the upper plot and S21 in the lower plot.



The blue trace in the is the impedance magnitude |Z| and the red trace is the reactance ImagZ of the 68 nF capacitor and the black and magenta traces are of the 470 nF capacitor.



The blue and black traces are the transmission coefficients (S21) in dB of the 68 nF and 470 nF capacitors, respectively.

The vertical scale *per division* for each trace is shown along the upper-left edge. The frequency range is shown along the bottom horizontal scale as Start and Stop frequencies. Note that the Wurth plots in the previous section use a logarithmic vertical scale whereas the measurements use a linear vertical scale.

The transitions from capacitive to inductive reactance for both capacitors are clearly seen at the center of the dips in |Z| and zero values for ImagZ. The SRF of the 68 nF capacitor is approximately 16.9 MHz (marker 7) and of the 470 nF cap is approximately 6.3 MHz (marker 8), very similar to the Wurth data. The measured reactance of the Wurth 68 nF capacitor at 1 MHz is –j2.51 ohms (red marker 1), equivalent to a capacitance of 63.4 nF, and comparable to –j2.58 ohms from the Wurth data. Similarly, the measured reactance of the Wurth 470 nF capacitor is –j0.36 ohms (magenta marker 1) at 1 MHz, equivalent to a capacitance of 44.2 nF and comparable to –j0.38 ohms from the Wurth data.

References:

- Mini-Circuits, APPLICATION NOTE: Transient Protection of Darlington Gain Block Amplifiers, AN-60-034 Rev. : A M150261 (04/14/15) File: AN60034.DOC
- Wurth Elektronik REDEXPERT website: https://redexpert.we-online.com/we-redexpert/en/#/redexpert-embedded

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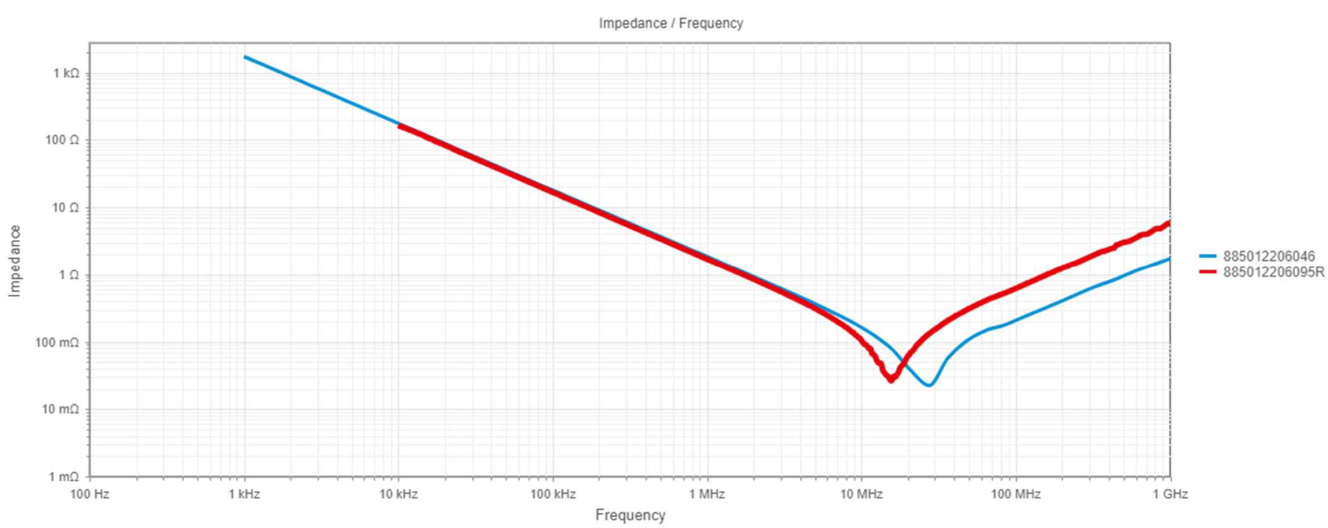
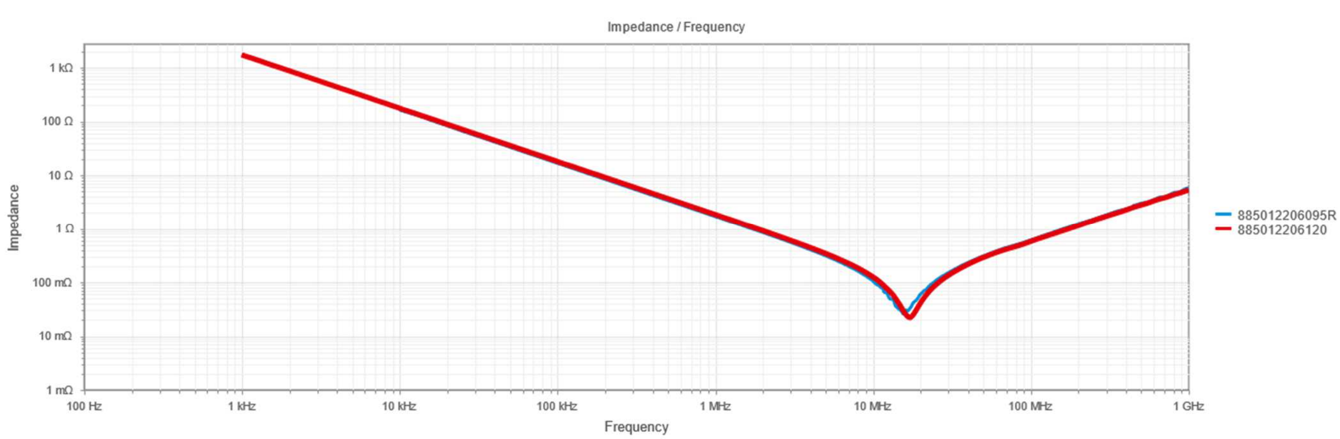
Addendum ~ 17 September 2024:

Increasing the input coupling capacitors from 0.068 to 0.100 µF was considered during Prototype testing to determine if the original capacitors affected the input impedance. Three Wurth capacitors were considered with voltage ratings of 16 V, 50 V and 100 V as follows:
p/n 885012206046: 0.100 µF, 0603, 16 Vdc, X7R, ±10% tolerance
p/n 885012206095R: 0.100 µF, 0603, 50 Vdc, X7R, ±10% tolerance
p/n 885012206120: 0.100 µF, 0603, 100 V, X7R, ±10% tolerance.

Note that all X7R capacitors are subject to capacitance change due to their operating environment – particularly bias voltage and temperature – but this is not considered a factor in their application here.

The plotted impedance of the 16 V 0.100 µF capacitor (blue trace in image directly below) is approximately 0.538 ohms at 3 MHz and 0.195 ohms at 100 MHz. The plotted impedance of the 50 V 0.100 µF capacitor (red trace in image directly below) is approximately 0.538 ohms at 3 MHz and 0.647 ohms at 100 MHz. The plotted impedance of the 100 V 0.100 µF capacitor(red trace in the bottom image) is approximately the same at both frequencies.





All three capacitors meet the requirements previously stated (≤ 1 ohm impedance at high and low frequencies). The 100 V part is recommended for the input circuit because it is exposed to the 15 Vdc FEE voltage and transients from the outside plant; the 100 V rating provides additional margin.

Document Information

Author: Whitham D. Reeve

Revisions: 0.0 (Original draft started, 05 Sep 2023)
0.1 (Added Wurth capacitor data, 07 Sep 2023)
0.2 (Corrected p/n for the Wurth 0.068 µF capacitor, 15 Sep 2023)
0.3 (Added measurements, 25 Sep 2023)
0.4 (Added test fixture images & description, 26 Sep 2023)
0.5 (Distribution, 29 Sep 2023)
0.6 (Added plots and impedances for 0603 Wurth capacitors, 5 Dec 2023)
0.7 (Addendum for 0.100 µF capacitors, 17 Sep 2024)

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