Application Note

AGING & IN-CIRCUIT CHARACTERIZATION OF AL-ELECTROLYTIC CAPACITORS

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1 Overview

This paper describes the characterization of aluminum electrolytic capacitors specifically used in ac-dc power converter applications. It will be discussed why this capacitor technology is critical regarding lifetime and why it cannot be substituted simply by any another capacitor technology. Different aging effects of the capacitor will be discussed. Usage of the capacitor in different ac-dc converter topologies will be presented. Simulation circuits will be used to analyze the capacitor in more detail before suitable measurements will be performed to demonstrate a real example of a switching-mode power supply (SMPS).

After the introduction into the aluminum electrolytic capacitor basics and theory, this paper will also present all important and possible measurements of capacitor parameters, like capacitance, equivalent series resistance (ESR) and ripple current. This includes in-circuit measurement which can be performed with an oscilloscope. An LCR-bridge is used to obtain high accuracy measurements in addition. A comparison between the two measurement methods will be presented. Furthermore, the required measurement hardware for the in-circuit measurements and the bridge measurement will be discussed and presented.

Lastly, two different lifetime calculation methods are presented and a real example is used to compare the advantages and disadvantages of the different methods.

Thanks to Mr. Frank Puhane from Würth eiSos GmbH & Co. KG who provided me with all aluminum electrolytic capacitor samples including the prepared capacitor with build-in temperature sensors to perform all measurements. Furthermore, his great expertise was very beneficial and helpful to create this premium application note.

2 Aluminum Electrolytic Capacitors in AC-DC Power Converter

Power conversion is very common and required in almost every electronic circuit. However, the conversion from AC to DC is mandatory, as long as you do not want to use a battery every time you need DC. Therefore, a rectifier is required that converts AC to DC. Furthermore, a single stage rectifier only produces a rectified pulsating DC which still needs to be smoothed by a passive storage component, the bulk capacitor which is typically based on aluminum electrolytic technology.

2.1 Single Stage

In a single ac-dc stage like a flyback converter, only limited power can be converted but this topology is used in various applications. Nevertheless, the best component for smoothing the rectified pulsating DC voltage is still the aluminum electrolytic capacitor. The main reason are the following ones:

► It Provides Large Capacitance at Higher Voltage (400 V DC Is Required In AC-DC Applications).

► This Technology Is Very Price Attractive.

► The Ratio Volume Per µF Is Very Good.

All of the mentioned characteristics are mandatory for an ac-dc power supply e.g. used as charger for a mobile device. The pictures below show two examples of an offline ac-dc power supply where both circuits are based on a flyback principle.

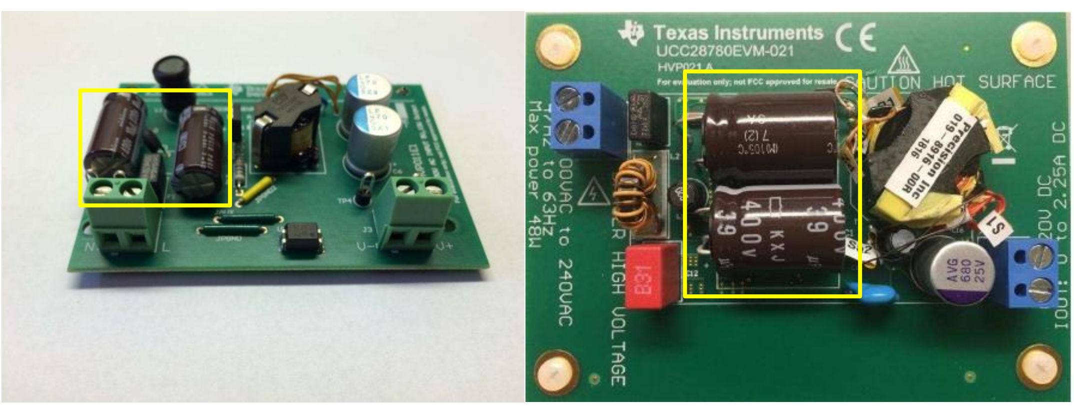

Figure 1 Standard and Extended Flyback Converters

The aluminum electrolytic capacitors are clearly visible in both designs because of the reasons mentioned before. In the application illustrated above, 2 x 400 V / 10 uF and 2 x 400 V / 39 uF capacitors are used.

2.2 Multistage Converter

In higher power levels where the power is higher than 100 W, multistage designs are often used. However, even in multistage designs, aluminum electrolytic capacitors are used for the same reasons as mentioned in the single stage design.

A boost converter with power factor correction functionality would be such an example. This converter type is typically used as frontend converter in a 2-stage design. A boost converter working as power factor correction is illustrated below:

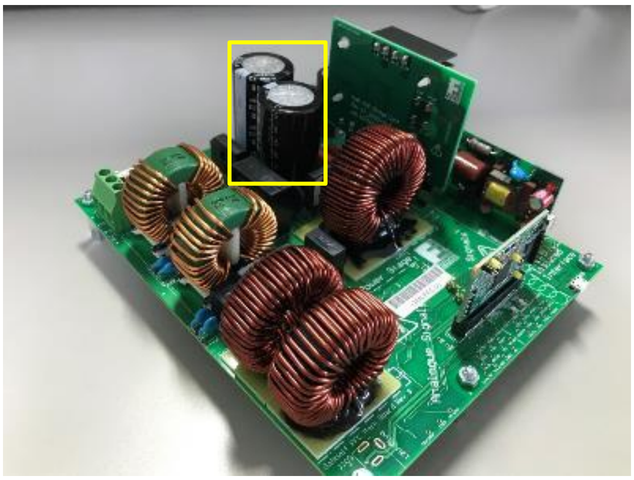

Figure 2 PFC Boost Converter

The capacitor in such application are required to smooth the line ripple (2 x 50 Hz) superimposed on the high DC output voltage (400 V DC). The best choice of capacitor are again the aluminum electrolytic capacitors. In the application illustrated above, 2 x 450 V / 100 µF capacitors at the output are used.

2.3 Limitation of Aluminum Electrolytic Capacitors

The advantages of the aluminum electrolytic capacitors are well known but this component comes along with some disadvantages. The main limitation of the component is the limited lifetime and it limits the overall lifetime of every power supply where an aluminum electrolytic capacitor is used. Therefore, a good knowledge of capacitor aging effects and using the right measurement tools are crucial to deal with these disadvantages of this component technology in the design.

3 Aging Effects of Aluminum Electrolytic Capacitors

The following effects needs to be considered within the application because they have impact on the aging of the capacitor. The main effects are the following ones:

► The Ambient Temperature.

► The RMS Ripple Current and Its Harmonic Content in The Application.

► The Applied DC-Voltage in Relation to the Maximum Specified DC-Voltage.

In general, aging effects of an aluminum electrolytic capacitor leads to a loss of capacitance and an increase of the equivalent series resistor (ESR). However, the application determines if the aging effect of the capacitor leads to an end of life condition of the power supply. For example, a loss of 20 % of the rated capacitance due to aging may not lead to an incorrect operation of the power supply. The increased ESR value will have negative impact on the ripple voltage and the design has to tolerate this ripple. This consideration needs to be validated during the system design.

3.1 Temperature Effect

The ambient temperature, where the capacitor is used leads to a loss of the electrolytic material and therefore causes a loss of capacitance. Furthermore, the temperature causes a degradation of the oxide layer within the capacitor. This leads to a higher leakage current and will influence the overall efficiency of the converter.

3.2 Ripple Current

The ripple current flowing through the capacitor produces a temperature rise within the capacitor, because of the presence of the equivalent series resistance (ESR). This increase of the core temperature of the capacitor accelerates the loss of capacitance and an increase of the ESR in as well.

3.3 Applied Voltage

The applied voltage has negative impact on the oxide layer and therefore will cause an increase of leakage current.

It is very important that all effects described above are considered and validated during the design process. Therefore, several in-circuit measurements e.g. ripple current, ESR values, temperatures, applied DC-Voltages are required to estimate lifetime of the power supply.

4 AC-DC Conversion Circuits

Several ac-dc conversion principles are regularly used in low power circuit designs. However, in all circuits presented in this paragraph, aluminum electrolytic capacitors are used.

4.1 Linear Power Supply Circuit

This principle is mainly used where the application requires very low noise. For example, a laboratory power supply is based on this circuit. The approach uses a low frequency transformer to step down the input voltage and is followed by a rectifier stage and a large storage element, the capacitor. This bulk capacitor is still required to smooth the rectified pulsating DC-voltage after the bridge rectifier.

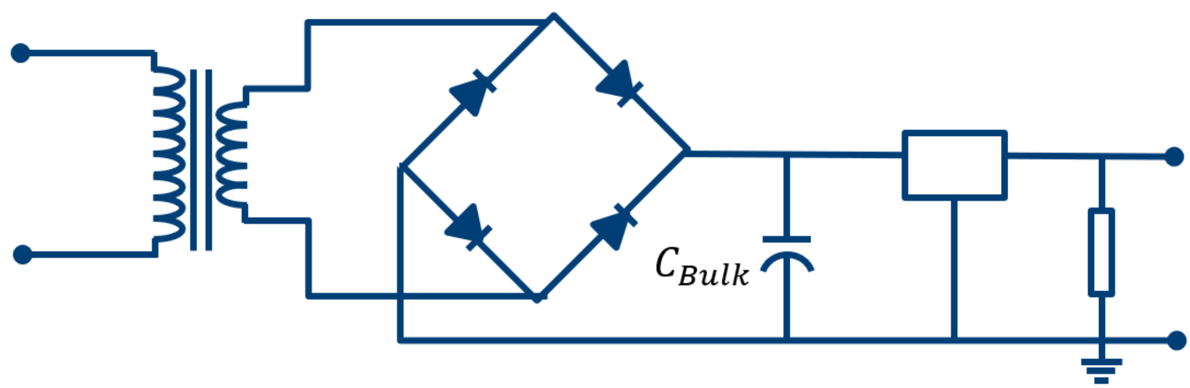

Figure 3 Linear Power Supply

The main reason for this large storage device is to filter the line frequency which is 50 Hz at the input and 100 Hz after the bridge rectifier. Therefore, the capacitor is mandatory to deliver the power to the output, while the input ac voltage crosses 0V. This is illustrated in the picture below. The blue areas indicate, that the power will be delivered only by the storage element, the bulk capacitor. In white areas, the typical charging pulse occurs.

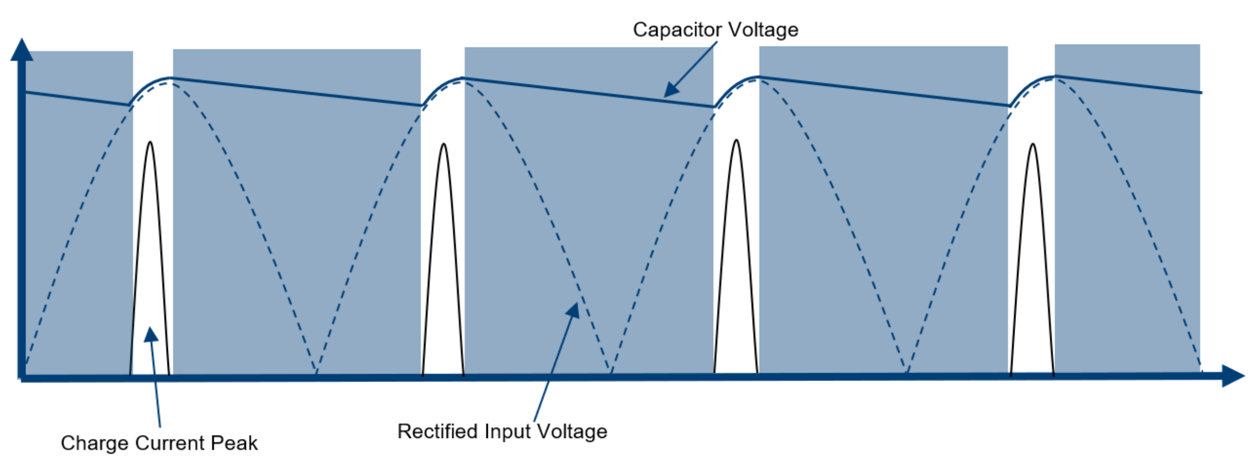

Figure 4 Voltage and Current Waveform at Bulk Capacitor

4.2 Switching-Mode Power Supply (SMPS)

An ac-dc conversion where a switching principle is applied, will have higher efficiency. Therefore, it is a very common method and is frequently used today. The converter structure is illustrated in the picture below:

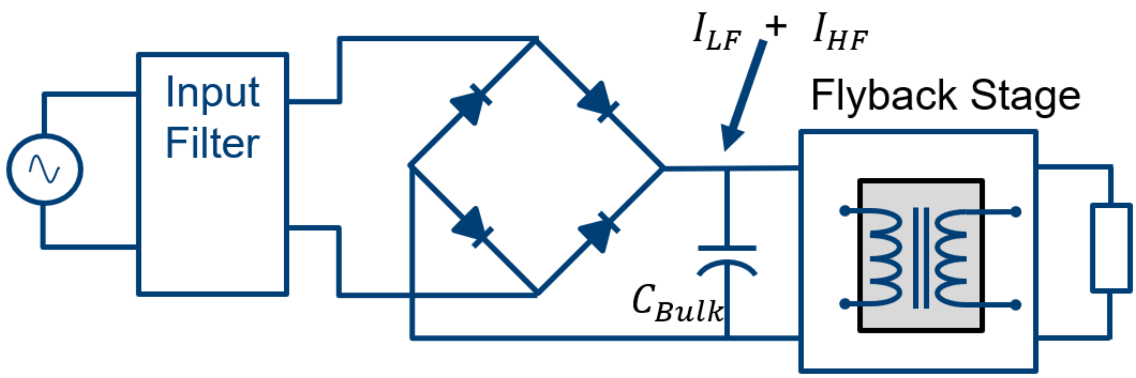

Figure 5 AC-DC Converter as SMPS

The low frequency isolation transformer and the linear circuit to control the output is substituted with the flyback stage. This will improve the overall efficiency of the converter. The rectifier stage followed by the bulk capacitor is still required as it is used for the same reason as in the linear power supply. In addition, an EMI input filter is required due to the higher frequency content created by the flyback stage.

Due to the switching element in the flyback stage, the current flowing in the bulk capacitor consists of two current frequency components as illustrated in the picture. The low frequency current content I_{LF} and the high frequency current content I_{HF}. As previously mentioned, the ripple current within the capacitor has impact on aging and needs to be considered. Furthermore, the allowed ripple current of the capacitor according to the datasheet is frequency depended.

The effective RMS ripple current is defined in the equation shown below:

$$I_{eff} = \sqrt{\frac{I_{LF}^2}{K_{LF}^2} + \frac{I_{HF}^2}{K_{HF}^2}}$$

Equation 1 Effective Ripple Current

The frequency multipliers K_{LF} and K_{HF} in the denominator are defined by the component supplier and can be found in the datasheet. Due to this frequency dependency of the ripple current, the effective ripple current I_{eff} might be higher and may increase the aging effect due to the higher core temperature of the capacitor. This equation will be used in the lifetime estimation and will be presented later in this document.

Remark: The maximum allowed ripple current is often defined at line frequency (2 x 50 Hz) but it has to be checked according to the datasheet.

4.3 Switching-Mode Power Supply (EMI Optimized)

As described in the previous section, the bulk capacitor has to deal with the low and high frequency current. Therefore, an extended approach exists where two bulk capacitors in combination with an inductor are used. The circuit is illustrated in the picture below:

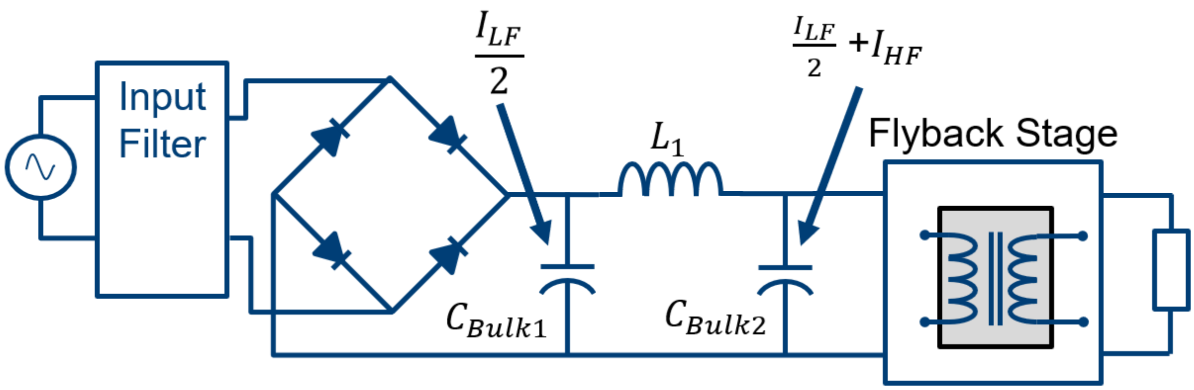

Figure 6 EMI Optimized Circuit

In this approach, an additional bulk capacitor C_{Bulk1} in combination with an inductor L_1 is used to create a pi-filter. The advantage is that the size of the input EMI filter becomes smaller because of this new added filter structure. Furthermore, the local heat created by the low frequency current in the bulk capacitor of the previous design is less because the low frequency current is shared between the two bulk capacitors. Capacitor C_{Bulk1} (named as LF-Cap in the following chapters) carries only the low frequency current, whereas the capacitor C_{Bulk2} (named as HF-Cap in the following chapters of the document) carries low and high frequency current.

However, the effective ripple current is still different in both capacitors and needs to be calculated by using Equation 1 to estimate lifetime of the capacitors.

5 In-Circuit Measurement Fundamentals

Before the in-circuit measurements can be performed, some background fundamental knowledge is essential and need to be understood.

5.1 Capacitor Fundamentals

The calculation of the charge of a capacitor is important to be known and is defined as follows:

$$Q = \int_{t1}^{t2} i(t)dt\ [As]$$

Equation 2 Charge of a Capacitor

This equation describes, that the integral of the current over time can be expressed as the charge in As. In other words, it is the area underneath the current waveform as illustrated in the picture below:

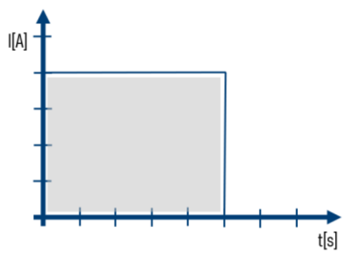

Figure 7 Charge of Capacitor

The next fundamental equation is defined as follows:

$$u(t) = \frac{1}{C} * \int_{t1}^{t2} i(t)dt\ [V]$$

Equation 3 Capacitor Voltage

This equation describes that the voltage change across any capacitor is expressed by the integral of the current over time (charge (Q)) and is multiplied with a scale factor, C (capacitance).

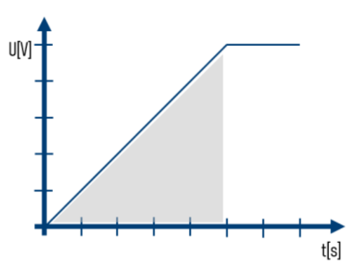

Figure 8 Voltage Change of Capacitor

After rearranging the two equations above, the following familiar equation can be derived:

$$\mathrm{C} = \frac{\mathrm{Q}}{\mathrm{U}}\ [F]$$

Equation 4 Capacitance

The capacitance can be calculated if a measurement of the charge and the related measured voltage difference can be performed.

5.2 Equivalent Series Resistance (ESR)

The simplified ESR in-circuit measurement and calculation (described in details in chapter 8) requires some basic knowledge. The equivalent sub circuit of an aluminum electrolytic capacitor consists of a capacitive part C_S, a resistive part ESR and an inductive part ESL (equivalent series inductance). Sometimes, an additional resistive part in parallel to the capacitor is shown, to represent the leakage current effect. This part is not shown in the following simplified equivalent sub circuit:

Figure 9 Simplified equivalent circuit diagram

Thus, the impedance of an aluminum electrolytic capacitor is defined as follows:

$$Z = \sqrt{ESR^2 + (X_L - X_C)^2} \; [\Omega]$$

Equation 5 Impedance

The equation consists of the ESR, the capacitive reactance X_C and the inductive reactance X_L. As the inductive part of the used component is very small at lower and mid-range frequencies (few nH), this part is neglected in the following assumptions. The graphical representation of the capacitor impedance is illustrated in the picture below.

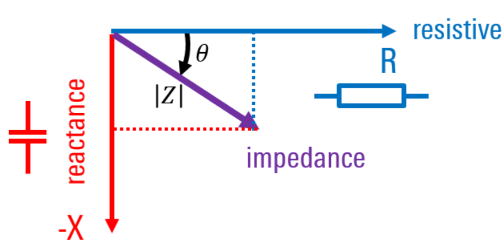

Figure 10 Impedance of A Capacitor

Using this relationship, the resistive part of the component can be derived, if the phase and the impedance values are known.

► Considerations at switching frequency (f_s~300 kHz)

The capacitive reactance X_C can be neglected as well when a higher frequency is assumed and the capacitance value of the capacitor is large enough (e.g. 47 µF). The definition of X_C is illustrated in the equation below:

$$X_C(fsw = 300\ \mathrm{kHz}; C = 47\ \mu\mathrm{F}) = \frac{1}{2*\pi*f_{sw}*C} \; [\Omega] = 11{,}3\ \mathrm{m}\Omega$$

Equation 6 Capacitive Reactance

► Calculation of the impedance

The Equation 5 can be simplified again if X_C =11 mΩ can be accepted as uncertainty at switching frequency f_{sw}.

$$Z = \sqrt{ESR_{fsw}^2 + X_{C\_fsw}^2} \cong ESR_{fsw}\ [\Omega]$$

Equation 7 Impedance Simplified at Switching Frequency

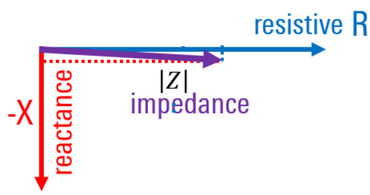

Figure 11 Impedance with Small Reactance X_C

Assuming we do not have any reactance component in the circuit, the impedance (→ESR) can be calculated just by using ohmic law. The equation is shown below:

$$Z = \frac{U_{C\_fsw}}{I_{C\_fsw}} => \frac{U_{C_{fsw}}}{I_{C_{fsw}}} => ESR_{fsw} = \frac{U_{C\_fsw\_peak}}{I_{C\_fsw\_peak}}$$

Equation 8 ESR Calculation

Therefore, the ESR can be calculated if it is possible to measure the peak to peak voltage and peak to peak current in the application.

Remark: Simplification introduces a small error but the benefit will be that no phase information is necessary.

6 Simulation - Circuits and Results

Before the real measurements will be shown, various simulations are performed to validate the calculation methods and assumptions already presented in the previous chapter 5.

6.1 Basic Simulation Circuit

6.1.1 Circuit Model

The first basic circuit which was simulated is illustrated in the picture below.

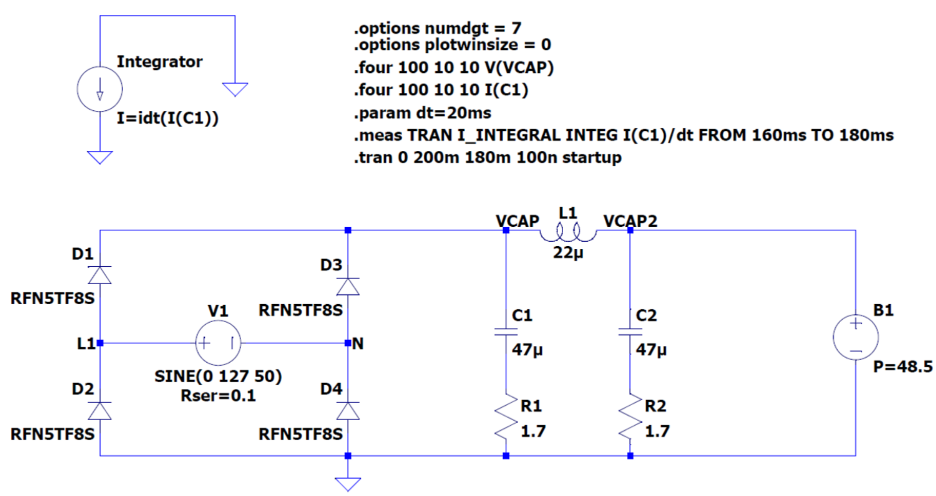

Figure 12 Basis Circuit Simulation (LF Ripple)

In this circuit simulation, the focus was to model only the ac source, the bridge rectifier, the pi-filter structure including the capacitor (C_1 & C_2) and a constant load to obtain the important voltage and current waveforms to derive the capacitance. The ESR components of C_1 & C_2 are chosen according to the datasheet of the manufacturer. The ESR component is modeled by component R_1 & R_2 and defined as 1,7 Ω resistor. The load B1 is used to act as a constant power sink. The integrator is used to obtain the charge which will be displayed as waveform.

In this basic circuit we do not consider any high frequency ripple. Therefore, the current and voltage waveforms for both capacitors will be the same because the inductor is only relevant at high frequencies. This simplifies the analysis of the results. Thus, only one capacitor (C_1) is used to display the results. The ripple voltage across the capacitor and the charge waveforms are used to calculate the capacitor value.

6.1.2 Simulation Results

The simulation created by the simulation engine (LTSpice) are illustrated in the picture below:

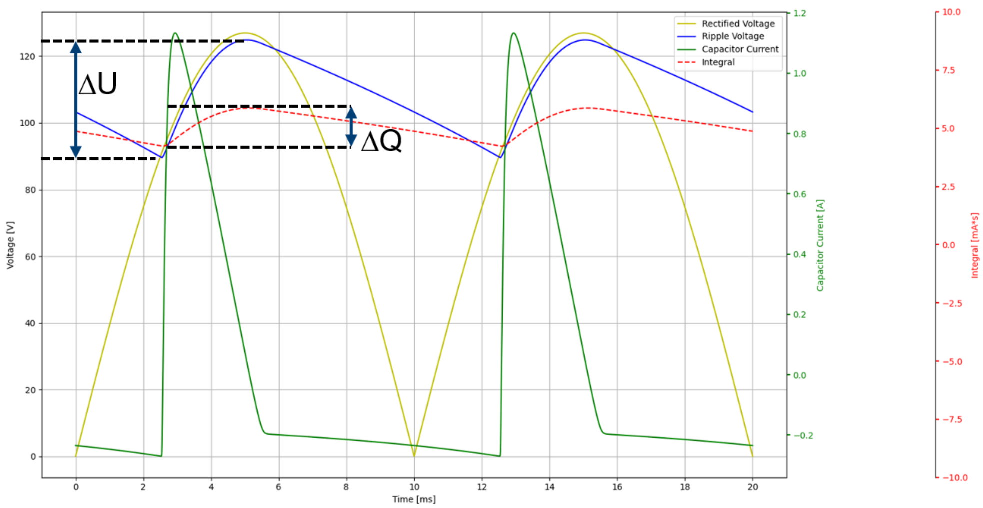

Figure 13 Basic Circuit Simulation Results

The following waveforms are visible in the graph:

► Yellow waveform = Rectified AC ripple [V] (No smoothing capacitor considered).

► Blue waveform = Smoothed voltage due to capacitor after the bridge rectifier [V].

► Green waveform = Charge/discharge current within the capacitor [A].

► Red dotted waveform = Charge of the capacitor [mA*s].

Based on the Equation 4 presented in paragraph 5.1, the calculated capacitance is:

C_1=46,5 µF

The RMS ripple current of the capacitor was derived directly form the simulation as it is offered by the circuit simulator. The result of the RMS ripple current is:

I_{C1_RMS} = 411 mA.

The calculated capacitor value and the RMS ripple current obtained from the simulation, have shown reasonable results. The 1% error is caused due to the simulation engine which was set to speed optimized.

6.2 Extended Simulation Circuit

6.2.1 Circuit Model

The second simulation model which was created is illustrated in the picture below.

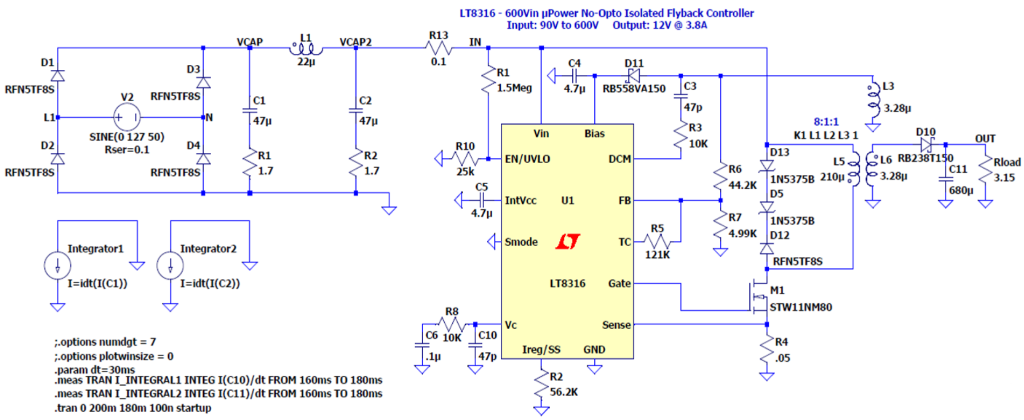

Figure 14 Extended Circuit (LF & HF Ripple)

In this circuit simulation, the focus was to extend the previous simple model to a more realistic model. Basically, the previous simple constant power load model is substituted with a switching circuit based on a flyback topology.

This extension introduces a high switching current ripple which will also have impact on the pi-filter structure. As the ripple current is different for both capacitors, an additional integrator is used to obtain the charge also for the second capacitor C_2. Therefore, the results displayed in the next chapter are presented in two steps:

► Simulation results for capacitor C_1, named in the following chapters as **LF-Cap.**

► Simulation results for capacitor C_2, named in the following chapters as **HF-Cap.**

Remark: This name convention will be also used during the measurement results.

6.2.2 Simulation Results at Low Frequency Capacitor

The first result shows the situation of the bulk capacitor C_1 which is located towards the bridge rectifier (LF-Cap).

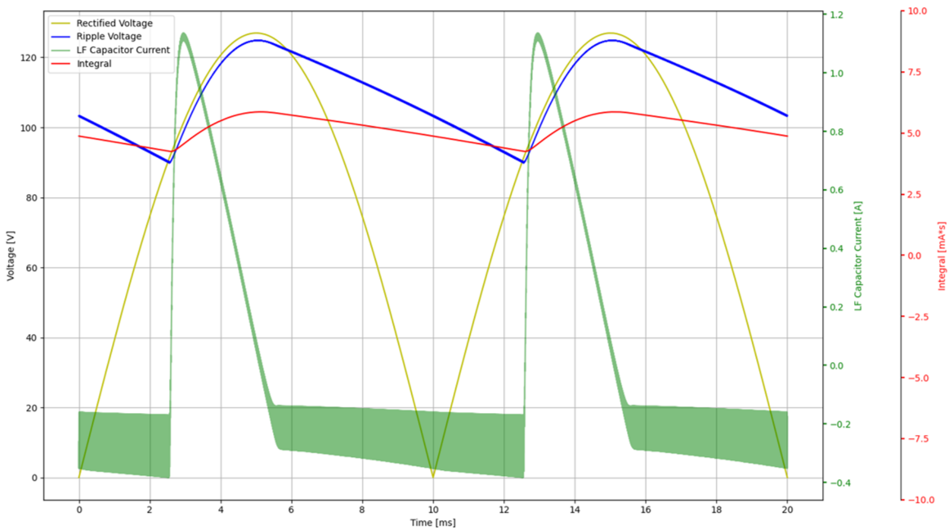

Figure 15 Extended Circuit Result (LF Capacitor)

The waveforms look pretty similar to the previous basic simulation shown in chapter 6.1.2 as the high frequency content is very low for this capacitor location. This is clearly visible in the charge current of the capacitor. Therefore, the values for the capacitor and the ripple current are very similar.

Based on the Equation 4 in paragraph 5.1, the calculated capacitance is:

C_1=46,3 µF.

The result of the RMS ripple current is:

I_{C1_RMS} = 415 mA.

The calculated capacitor value and the RMS ripple current obtained from the simulation, have shown reasonable results according to the theory.

6.2.3 Simulation Results at High Frequency Capacitor

The second result displays the waveforms of the bulk capacitor located towards the flyback stage (HF-Cap).

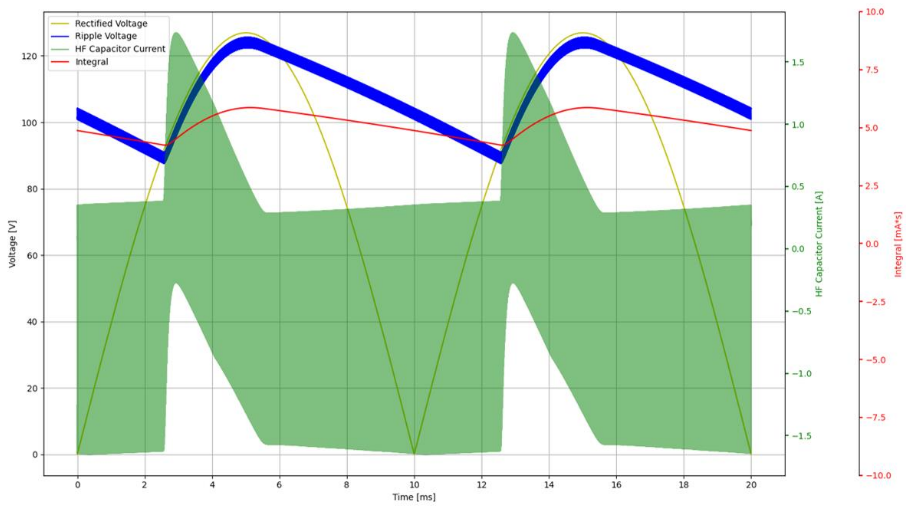

Figure 16 Extended Circuit Result (HF Capacitor)

This result shows the high frequency ripple current superimposed on the low frequency ripple current in the capacitor. Nevertheless, it was still possible to calculate the capacitance and derive the RMS ripple current from the simulation.

Based on the Equation 4 in paragraph 5.1, the calculated capacitance is:

C_2=46,3 µF.

For the result of the RMS ripple current, two RMS ripple currents need to be mentioned separately:

1. The effective RMS ripple current.

   I_{C2} = 741 mA. This RMS ripple current includes all frequency components.

2. The high frequency RMS ripple current.

   I_{C2} = 688 mA. This RMS ripple current includes only the high frequency part of the switching converter.

6.2.4 Summary

From the simulation results, the capacitor calculation matches quite good with the theory. The ripple current is different depended which capacitor position is analyzed. This becomes relevant when the life time calculation will be performed later in this paper. However, the high frequency part is dominating the overall ripple current.

6.2.5 ESR Validation Based on Simulation Data

This approach only applies for the HF-Cap. A high frequency ripple current is required to extract the ESR based on the fundamentals shown in chapter 5.2 and therefore it cannot be applied to the LF-Cap.

6.2.5.1 Filter Design

The MATLAB Filter Designer App was used to develop a suitable band pass FIR filter. The filter tool also provides the capability to extract digital filter coefficients after the filter design is fixed. The coefficients can be loaded into the oscilloscope and can be applied to any signal. The reason for this filter is to remove the low frequency content in the ripple voltage and ripple current. This enables the user to obtain the peak to peak values for calculating the ESR very easy.

The result of the designed band pass filter characteristic is illustrated in the picture below:

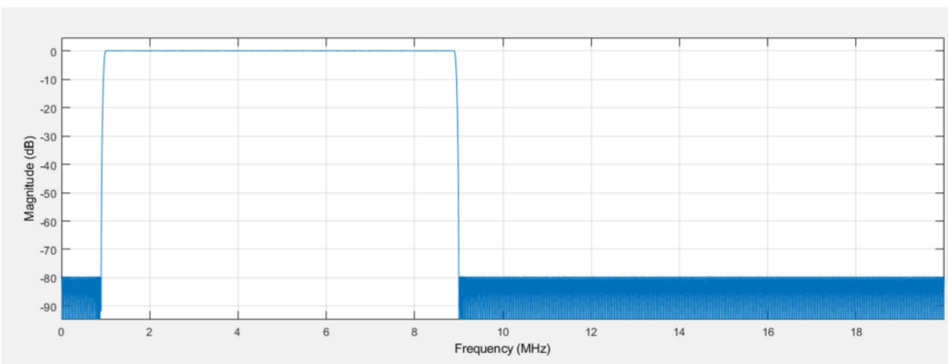

Figure 17 Bandpass Filter Design

Band pass filter (FIR) characteristics:
Fstop1 = 13 kHz
Fpass1 = 125 kHz
Fpass2 = 11 MHz
Fstop2 = 11,25 MHz

According to the stop band at the lower frequency, the low frequency amplitude is damped by 80 dB. The 80dB damping at F > 11,25 MHz ensures that no external noise will have impact on the measurements.

6.2.5.2 Filter Validation with Simulation Data

The band pass filter coefficients are validated by using the raw data derived from the simulation presented in paragraph 6.2. The result of the filter validation is illustrated in the picture below:

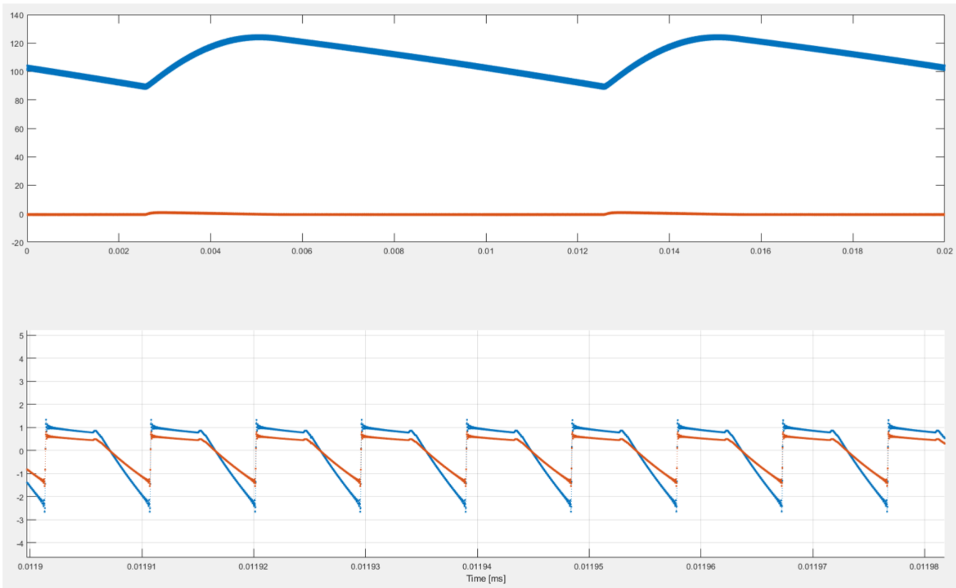

Figure 18 Filtered Simulation Data

It shows the unfiltered raw data (voltage and current) from the simulation in the top window. In the bottom window the voltage and current waveform are shown after the filter coefficient are applied.

The peak to peak values from the filtered simulation data graph (bottom window) are taken to calculate the ESR value using Equation 8, presented in chapter 5.2.

$$\mathrm{ESR_{fsw}} = \frac{\mathrm{U_{C\_fsw\_peak}}}{\mathrm{I_{C\_fsw\_peak}}} = \frac{4.133\mathrm{V}}{2.435\mathrm{A}} = 1.697\ \Omega$$

In the simulation circuit shown in chapter 6.2.1, a resistor of 1.7 Ω was used to model the ESR. Using the filter coefficient derived from the MATLAB Filter Designer, the calculation of ESR value based on the simulation waveforms have shown a very good match compared to the defined model.

7 Measurement Hardware

After presenting the theory and several circuit simulations, real measurements with the power converter will be the next step. Nevertheless, before the measurement can be performed, the required measurement hardware and their characteristics need to be evaluated.

7.1 LCR-Meter

An LCR- Meter is a very good choice to measure complex passive components like capacitors, inductors, transformers and resisters in various working points very accurately. However, it is required that the component is removed from the circuit to perform a measurement. Furthermore, the LCR-Meter applies a small sinusoidal signal to the component at a certain frequency. The LCX measurement bridge is shown in the picture below:

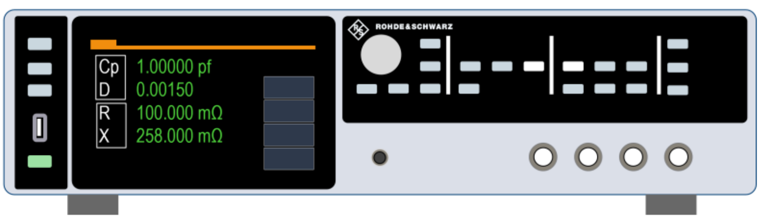

Figure 19 LCX200

The purpose of using the LCX-200 for measuring the capacitance and ESR of the electrolytic capacitors was to validate the in-circuit measurements performed with an oscilloscope presented in chapter 8.

7.1.1 Accessories

It is very important to have the correct accessory to connect the component you want measure. One possible choice of an accessory used to connect radial capacitors are the kelvin clip leads and is illustrated below:

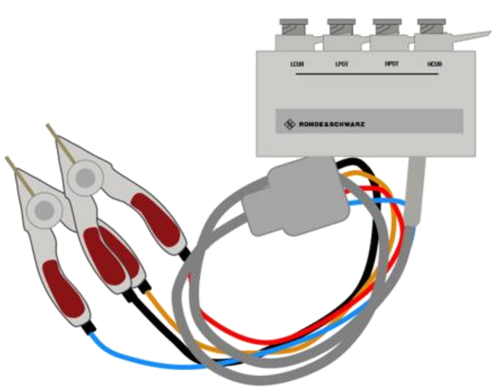

Figure 20 Kelvin Clip Leads

Beside this kelvin clip leads, another test fixture exists to connect radial or axial capacitors easily.

It is important that a calibration is performed before starting the measurement. After calibration the instrument proved high accuracy with up to 0.05 %.

7.2 Voltage and Current Probes

For the in-circuit measurements, suitable probes are required to attach the oscilloscope to the circuit. Two different probes are required to measure the voltages and currents in the circuit.

► High Voltage Differential Probe

► Current Probe

7.2.1 High Voltage Differential Probes

Differential probes were used to exclude the effect of the ground loops which improves the measurement accuracy. However, the differential probe bandwidth should be above 100 MHz and good offset capability is very beneficial, because the DC part across the capacitor can be removed easily which improves resolution. The differential probe R&S-ZHD07 covers all these needs and was used during the measurements. The probe is illustrated in the picture below:

Figure 21 R&S ZHD07

7.2.2 Current Probes

As described previously, the current flowing within the capacitor needs to measured properly. This connection is more complicated as the space to attach the probe is very limited.

7.2.2.1 Clamp-On Current Probe

One kind of suitable probe is the clamp-on probe to measure the current of the capacitor. It offers sufficient bandwidth and it is usually possible to use the capacitor lead to clamp-on the probe. If it is not possible, it is required to extend the loop with a small wire. The R&S RT-ZC20B offers 100 MHz bandwidth and can measure currents up to 30 A. The probe is illustrated in the picture below:

Figure 22 R&S RT-ZC20B

7.2.2.2 Rogowski Probe

An alternative current probe to measure the capacitor current is the so called Rogowski Probe. The advantage of this probe is that it can be attached to the circuit without breaking the loop and requires only small space.

The disadvantage of the Rogowski Probe is the limited bandwidth at lower frequency. Especially for the ripple current at line frequency the 3 dB frequency limit has to be validated against the datasheet to obtain reliable measurement results.

Remark: All in-circuit measurements presented in chapter 8 were performed with the clamp-on probe R&S RT-ZC20B to avoid inaccuracy at line frequency. Therefore, the loop to measure the current was extended by an additional wire.

7.3 Oscilloscope

The oscilloscope is the key instrument for performing the in-circuit measurements. Of course, some key features and characteristics are required or at least very helpful to perform the in-circuit measurements. The oscilloscope is illustrated in the picture below:

Figure 23 R&S RTO6

The following characteristics are required:

- At least 1 GHz of bandwidth is required.
- A possibility of loading digital filter coefficient to apply a customized filter characteristic.
- Integral function should be provided to measure the charge of a capacitor.
- General math functions like RMS, Peak to Peak and statistic information ensure reliable measurements.
- Powerful curser settings are very beneficial to read out any values from the waveform.
- High Definition Mode (HD-Mode) to extend the resolution to 16 Bits.

The R&S RTO6 is an instrument which offers all the requirements listed above and will support the user during the measurements.

8 In-Circuit Measurement Results

Within this chapter, in-circuit measurements are presented to illustrate the principle of the measurement method. For all measurements performed within this chapter the following parameters for the device under test (DUT) are used: U_{IN} = 230 V AC @ Pout = 40 W

8.1 Capacitance Evaluation

For deriving the capacitor value while the component is in the circuit, voltage and current need to be measured. In addition, an integral function enabled in the oscilloscope displays the charge Q during the charge current peak. The measurements with the oscilloscope are performed while the HD-Mode (High Definition Mode) was enabled. The HD-Mode is a method to enhance the resolution up to 16 Bits. Furthermore, it can be used to filter any signal or noise above a certain frequency without having the risk of aliasing effects during the measurements.

8.1.1 Measurement at LF-Capacitor

The measurement to derive the capacitance is shown below:

Figure 24 Capacitance Measurement @ LF-Cap

Channel 1 = AC Voltage across the capacitor (322 V offset applied to the probe to enhance resolution)

Channel 2 = Charge/discharge current peak

Math 2 = Integral of the current which is the charge Q in [µA*s]

From the measurement function, ΔQ and ΔU could be used to calculate the capacitor value as follows:

$$C = \frac{\Delta Q}{\Delta U} = \frac{603\ \mu A{*}s}{13.24\ V} = 45{,}5\ \mu F$$

8.1.2 Measurement at HF-Capacitor

The measurement at HF capacitor would have been more complicated to derive the peak values due to the superimposed high frequency signals. Refer to the simulation presented in 6.2.3. Therefore, the HD-Mode was used to remove this high frequency content to obtain only the low frequency part. The configured bandwidth of the HD-Mode was at 10 kHz. The result is illustrated in the measurement below:

Figure 25 Capacitance Measurement @ HF-Cap

Channel 1 = AC Voltage across the capacitor (322V offset applied to the probe to enhance resolution)

Channel 2 = Charge/discharge current

Math 2 = Integral of the current Q [µA*s]

From the measurement function, ΔQ and ΔU could be used to calculate the capacitor value as follows:

$$C = \frac{\Delta Q}{\Delta U} = \frac{625\ \mu A{*}s}{13.4\ V} = 46{,}7\ \mu F$$

8.1.3 Conclusion

Both capacitor values derived from the in-circuit measurement show reasonable results according to the datasheet values specified at 47 µF.

8.2 Ripple Current

The measurement of the ripple current is essential to estimate the lifetime of an aluminum electrolytic capacitor. This will be discussed in more detail in chapter 9.

8.2.1 Measurement Results at LF-Capacitor

The low frequency ripple current measurement is shown in the picture below:

Figure 26 Ripple Voltage and Current Measurement at LF Cap

Channel 1 = AC Voltage across the capacitor including DC offset.

Channel 2 = Charge/Discharge Current

For the voltage ripple measurement, the offset of 320 V DC was still applied to obtain a high resolution. Furthermore, the HD-mode with 10 kHz was enabled to remove any noise above this frequency.

The result of the RMS ripple current was defined as measurement function with the channel 2 as input and leads to:

I_{RMS_LF} = 254 mA @100 Hz. (HD-Mode with 10 kHz bandwidth)

An additional measurement with a frequency limit of 50 MHz was performed to validate that the high frequency content caused by the switching converter can be neglected for this LF-Capacitor. The result of the RMS ripple current is shown below:

I_{RMS_LF} = 255 mA @ 100Hz. (HD-Mode with 50 MHz bandwidth)

The small difference is the evidence that the high frequency content at this measurement point can be neglected.

8.2.2 Measurement Results at HF-Capacitor

The low frequency ripple current measurement is shown in the picture below:

Figure 27 Ripple Voltage and Current Measurement at HF-Cap (10 kHz Bandwidth HD-Mode)

Channel 1 = AC Voltage across the capacitor

Channel 2 = Charge/Discharge Current

Math 1 = HF Ripple Current

The result of the RMS ripple current was defined as measurement function and results in:

I_{RMS_LF} = 265 mA @ 100 Hz. (HD-Mode with 10 kHz bandwidth)

The high frequency ripple current is not measurable because of the activated 10 kHz bandwidth. In the next step the bandwidth will be changed to 50 MHz to measure the switching frequency of the converter as well.

The low frequency ripple including the superimposed high frequency ripple current measurement is shown in the picture below:

Figure 28 Ripple Voltage and Current Measurement at HF-Cap (50 MHz Bandwidth HD-Mode)

Channel 1 = AC Voltage across the capacitor

Channel 2 = Charge/Discharge Current

Math 1 = High frequency ripple current only (bandpass filter applied)

After changing the bandwidth to 50MHz and applying the filter coefficients (refer to chapter 6.2.5), it is possible to extract the high frequency RMS current content flowing within the capacitor. The result of the RMS ripple current was defined as measurement function and results in:

I_{RMS_HF} = 470 mA @ 284 kHz. (HD-Mode with 50 MHz bandwidth)

8.3 ESR In-Circuit Measurement

The last in-circuit measurement which needs to be performed is to obtain the equivalent series resistance and the result is shown in the picture below:

Figure 29 Voltage and Current Peak to Peak

Channel 1 = AC Voltage across the capacitor

Channel 2 = Charge/discharge current

Math 1 = High frequency voltage ripple (bandpass filter applied)

Math 2 = High frequency ripple current (bandpass filter applied)

After activating the bandpass filter on the voltage and on the current, it enables the user to remove the low frequency content and to focus on the high frequency. Furthermore, by using the measurement function of the oscilloscope, it is very convenient to read out the voltage and current peak to peak values. Furthermore, it was possible to obtain the frequency which is indeed the switching frequency of the converter. Statistical data provides the user detailed information about stability of the measurement.

The result for the voltage is:

U_{PP} =1,02 V @ 285kHz.

The result for the current is:

I_{PP} = 1.85 A @ 285kHz.

By using the Equation 8 shown in chapter 5.2, the ESR is:

ESR = 551 mΩ.

This is a good match as it is in the range of the specified data according to the datasheet.

8.4 Measurement Results - Comparison

All measurement results, performed for this document are summarized in the table below:

	In-Circuit Measurement		LCR-Bridge Measurement		Failure [%]	
	LF-Cap @ 100 Hz	HF-Cap @ 100 Hz	LF-Cap @ 1 kHz	HF-Cap @ 1 kHz	LF-Cap	HF-Cap
Capacitance [µF]	45,5	46,7	43,4	43,8	4,6	6,2
Capacitance [µF] (2000 h)	44,0	43,1	41,3	41,5	6,1	3,7
ESR [Ω] @ 285 kHz	X	0,55	0,710	0,628	X	-13
ESR 2000 h [Ω] @ 285 kHz	X	2,91	4,049	3,619	X	-24

Table 1 Summary of Measurements

Capacitor and equivalent series resistor results are shown where an in-circuit measurements could be performed. The ESR value for the LF-Capacitor could not be measured because no relevant ripple voltage and ripple current flow within the LF-Capacitor at switching frequency. All measurements preformed with the LCR bridge are shown in the next column. The capacitor and ESR values were measured with the LCR-Meter after the component was removed from the printed circuit board. The last column shows the calculated failure in percentage between these two measurement methods.

The first and third row (light grey) show all measurement values for a brand-new capacitor while the second and last row (dark grey) show all measurement values for a used capacitor (2000 h). The reason for using different components was to highlight the aging effect. Both phenomena described previously, loss of capacitance and the increase of the ESR due to these 2000 hours of aging, are clearly visible.

The maximum failure for the capacitor value between the in-circuit measurement and the LCR-Bridge measurement is about 6 % which a reasonable figure because the measurement methods are very different. The LCR-measurement bridge uses a bridge principle applying a small sinusoidal signal at a single frequency, whereas the in-circuit measurement has to deal with multiple frequencies. Furthermore, the LCR-Bridge is much more accurate compare to an oscilloscope in conjunction with probes attached to the circuit.

The maximum failure for the ESR measurement between the in-circuit measurement and the LCR-Bridge measurement is at least -24 % which is pretty large. The reason for this large failure is mainly caused by the temperature dependency of the ESR which was different in both measurement methods.

- ► The LCR-Bridge measurement is a small signal measurement and does not heat the capacitor or ESR during the measurement. Therefore, the ESR values were obtained at 25° Celsius ambient temperature.
- ► The in-circuit measurement is a large signal measurement and the temperature of the capacitor core will be higher due to the unavoidable ripple current. Therefore, the ESR value will drop significantly just after switch-on of the circuit.

This deviation can be minimized if the capacitor will be measured with the LCR-bridge while the component is put in a climate chamber at a similar temperature which was measured in the circuit. Only in this case, the temperature effect is the same for both methods.

8.5 Ripple Current and Temperature Result

The table shown below illustrates the overview of the RMS ripple current and the core temperature of a new capacitor while the DUT was in operation. This table is the input for the lifetime calculation explained in more detail in the next chapter.

	Current Type [mA]	In-circuit Measurement		T_{Core} [°C]		T_a [°C]
Position		LF-Cap	HF-Cap	LF- Cap	HF-Cap	
New Capacitor	I_{RMS_Total}	255	540	39,9	42,2	25,6
	I_{RMS_HF}	X	470			
	I_{RMS_LF}	254	265			

Table 2 Ripple Current and Core Temperature Summary

As already mentioned earlier, two methods exist to calculate the lifetime of a capacitor used in a dedicated application. One method is based on measuring the RMS ripple current and the other is based on core temperature.

However, it is clear that the HF-Cap where two frequency components exists, the RMS total current is higher. Therefore, the temperature rise of the core is about 2° Celsius higher because of the larger effective ripple current. The in-circuit measurement was performed at 25° Celsius.

The core temperature is only possible if you have a prepared capacitor where a thermocouple element is built in. This will be described in more detail in the next chapter.

9 Lifetime Calculation

Lifetime of an aluminum electrolytic capacitor can be calculated or at least estimated. Two common methods are supported from most of the component supplier:

9.1 Lifetime Calculation Based on Core Temperature

This method is by far the most accurate method to calculate the lifetime of an aluminum electrolytic capacitor. For this method, the temperature of the capacitor core needs to be measured while the capacitor is used in an active application. In general, it is not possible to measure the core temperature accurate easily. The typical way to solve this problem is to put a temperature sensor inside the component. This temperature sensor needs to be inserted in the capacitor during the component manufacturing process and thus the end user will need support from the component manufacturer. An example of such a prepared capacitor including a thermoelement Typ K from the supplier is illustrated in the picture below:

Figure 30 Prepared Capacitor for Core Temperature Measurement

9.1.1 Fundamental Lifetime Calculation

The equation to calculate the lifetime in hours is based on Arrhenius's law. In general, it describes the chemical reaction which depends on the temperature of the component. This rule is also well known in the industry as 10-Kelvin Rule from Arrhenius. It means when the operational temperature is reduced by 10 K, the lifetime will double. This specific equation applicable for an aluminum electrolytic capacitor is shown below:

$$\mathrm{L_x} = \mathrm{L_0} * 2^{\left[\frac{\mathrm{T_0}-\mathrm{T_a}}{10}\right]} \; [h]$$

Equation 9 Lifetime Calculation Al-Electrolytic Capacitor

L_0 = Lifetime at upper category temperature and according to the datasheet.

T_0 = Maximum rated operating temperature of the capacitor according to the datasheet.

T_a= Actual operating temperature where the capacitor is used.

9.1.2 Calculation

The prepared capacitor shown in the picture above was used during the measurements and is specified according to the datasheet as follows:

L_0 = 10000h

T_0 = 105°C

Using Equation 9 for lifetime calculation and considering a measured core temperature (refer to Table 2) of 39,9°C for the low frequency capacitor and 42,2° C for the high frequency capacitor in the application, the results are as follows:

$$\mathrm{L}_{\mathrm{x}_{\mathrm{LF}}} = 10000\ h * 2^{\left[\frac{105-39{,}9}{10}\right]} = 911392\ h$$

$$\mathrm{L}_{\mathrm{x}_{\mathrm{HF}}} = 10000\ h * 2^{\left[\frac{105-42{,}2}{10}\right]} = 777084\ h$$

It is obvious, that the temperature rise of the high frequency capacitor is higher due to the high frequency content within the effective ripple current. Therefore, the expected lifetime of the high frequency capacitor is significantly lower.

9.2 Lifetime Estimation Based on Ripple Current

The method based on the ripple current is not as accurate as the core temperature method described previously. Nevertheless, this method is much easier to perform and no support from the component supplier is required. Therefore, this approach is by far the most used method to estimate the lifetime of an aluminum electrolytic capacitor.

9.2.1 Fundamentals

► Ripple Current

As already defined in Equation 1, the effective ripple current need to be calculated using the frequency multipliers. The frequency multipliers are defined by the component supplier in their datasheet. For the used capacitor, the following multipliers are defined:

	Frequency Point 1 [Hz]	Frequency Point 2 [kHz]	Frequency Point 3 [kHz]	Frequency Point 4 [kHz]
Frequency	120	1	10	>100
Multiplier	0,5	0,8	0,85	1,0

Table 3 Frequency Multiplier

For the LF-Capacitors and HF-Capacitor, to different calculations need to be performed.

► Temperature Rise

As soon as the effective ripple current is calculated, the expected temperature rise caused by the ripple current can be calculated as defined in the equation below:

$$\Delta \mathrm{T} = \Delta \mathrm{T}_{\mathrm{max}} * \left(\frac{\mathrm{I}_{\mathrm{eff}}^2}{\mathrm{I}_{\mathrm{Rated}}^2}\right)\ [K]$$

Equation 10 Core Temperature Rise Produced by Ripple Current

ΔT_{max} = Inside temperature increase of capacitor by permissible ripple current at the maximum operating temperature. This specific parameter is defined by the component supplier

ΔT= An increase in core temperature produced by internal heating due to actual operating ripple current.

► Ripple Current Factor

After the temperature rise caused by the applied ripple current, the ripple current factor can be calculated according the following equation:

$$\mathrm{K}_{\mathrm{Ripple}} = 2^{\left[\frac{\Delta \mathrm{T}_{\mathrm{max}} - \Delta \mathrm{T}}{5}\right]}$$

Equation 11 Ripple Current Factor

► Estimated Lifetime including ripple current factor

The last step is to calculate the estimated lifetime according to the equation shown below:

$$\mathrm{L}_{\mathrm{x}} = \mathrm{L}_0 * 2^{\left[\frac{\mathrm{T}_0 - \mathrm{T}_{\mathrm{a}}}{10}\right]} * \mathrm{K}_{\mathrm{Ripple}}\ [h]$$

Equation 12 Lifetime Calculation (Ripple Current)

It is important that T_a in the equation above is the actual temperature in the application and not the core temperature as presented in the previous paragraph.

9.2.2 Calculation

► Ripple Current

Calculate the effective ripple current in both capacitors using the measured values listed in Table 2. Using Equation 1 for effective ripple current calculation for the low frequency capacitor and for the high frequency capacitor, the results are as follows:

$$I_{eff\_LF\_Cap} = \sqrt{\frac{255\ mA^2}{0.5^2}} = 510\ mA$$

$$I_{eff\_HF\_Cap} = \sqrt{\frac{255\ mA^2}{0.5^2} + \frac{470\ mA^2}{1^2}} = 756\ mA$$

The effective ripple current of the high frequency capacitor is significantly higher due to the HF current content.

► Temperature Rise

Next Step is to calculate the temperature rise due to the effective ripple current. The equation is shown below:

$$\Delta T_{LF} = 5\mathrm{K} * \left(\frac{510\ mA}{1050\ mA}\right)^2\ [K] = 1{,}2\ K$$

$$\Delta T_{HF} = 5\mathrm{K} * \left(\frac{756\ mA}{1050\ mA}\right)^2\ [K] = 2{,}6\ K$$

with maximum rated ripple current I_{Rated} = 1050 mA

with ΔT_{max} = 5 K

► Ripple Current Factor

Calculate the ripple current factor or acceleration factor by using the temperature rise values.

$$\mathrm{K_{Ripple\_LF}} = 2^{\left[\frac{5\mathrm{K}-1{,}2\mathrm{K}}{5}\right]} = 1{,}693$$

$$\mathrm{K_{Ripple\_HF}} = 2^{\left[\frac{5\mathrm{K}-2{,}6\mathrm{K}}{5}\right]} = 1{,}454$$

► Estimated Lifetime including ripple current factor

Calculate the lifetime hours with K_{Ripple} and ambient temperature

with L_0 = 10000h, T_0 = 105° C and Ta=40° C

$$\mathrm{L_{x\_LF}} = 10000 * 2^{\left[\frac{105-40}{10}\right]} * 1{,}693 = 1532328\ h$$

$$\mathrm{L_{x\_HF}} = 10000 * 2^{\left[\frac{105-40}{10}\right]} * 1{,}454 = 1316010\ h$$

10 Conclusion

These days, the aluminum electrolytic capacitor technology is still the best solution for most ac-dc converter. This is particularly true, if your design needs to be compact and cost-optimized. AC converter connected directly to mains also require a capacitor technology, which is capable to withstand higher voltage. Aging of this component due to the technology is the biggest disadvantage and need to be controlled by the designer. This can be achieved if the converter design process will include the lifetime estimation of the capacitor. This requires detailed knowledge of aging effects of the capacitor technology and specific measurements performed with the running application. Finally, it requires some calculation. This approach was covered in this paper.

However, although technical information and simulations can provide many details, real measurements are still required to estimate the aging of an aluminum electrolytic capacitor. In-circuit measurements are in some cases mandatory to estimate end of lifetime used in a specific application. Especially, ripple current measurements are mandatory to estimate end of lifetime of an aluminum electrolytic capacitor, if no temperature sensor is available to measure the core temperature. Furthermore, deriving the capacitance value and the equivalent series resistance may be valuable to characterize the capacitor directly used in the application circuit. In-circuit measurements are closer to the real application and can be performed in addition to the standard LCR-Bridge measurements. An LCR-Bridge will provide the highest accuracy, but the measurement method is very different form the real application.

Using a prepared capacitor with build-in thermocouple element, the accuracy of the lifetime calculation would be the highest. However, this component needs to be prepared by the component manufacturer during the production of the capacitor.

The aluminum electrolytic capacitor technology is still used in many converters for good reasons and therefore, the aging of the single component will define the overall lifetime of a power supply unit. Therefore, in-circuit measurements should be performed to obtain a product to sustain over its whole lifetime.

11 Literature

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12 Ordering Information

Designation	Type	Order No.
Oscilloscope, 4 Channels	R&S®RTO64	1802.0001.04
High Voltage Differential Probe	R&S®RT-ZHD07	1800.2307.02
Current Probe	R&S®RT-ZC20B	1409.8233.02
LCR-Meter	R&S®LCX200	3629.8856.03
Test Fixture for axial/radial lead type devices	R&S®LCX-Z1	3639.2296.02
Kelvin Clip Lead	R&S®LCX-Z2	3638.6446.02
Power Deskew Fixture	R&S®RT-ZF20	1800.0004.02

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Application Note | Aging & In-circuit Characterization of AL-Electrolytic Capacitors
Data without tolerance limits is not binding | Subject to change