AGING AND IN-CIRCUIT CHARACTERIZATION OF ALUMINUM ELECTROLYTIC CAPACITORS

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Make ideas real

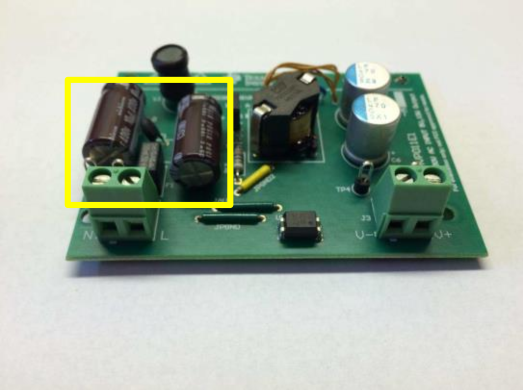
CONTENT

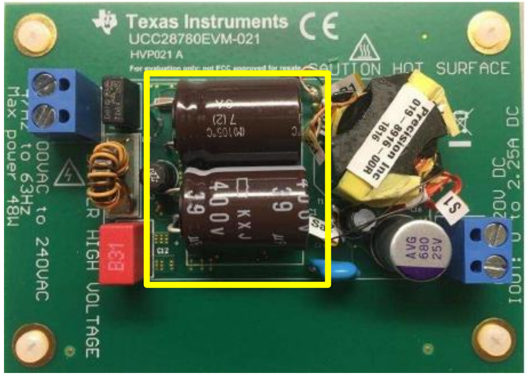
- Aluminum Electrolytic Capacitors In AC-DC Power Converter
- Common Circuits For Offline AC-DC Power Supplies
- Capacitance Calculation And Equivalent Series Resistance Fundamentals
- Basic and Extended Circuit Simulation

- Measurement Hardware
- Demonstration
- In-Circuit Measurement And Results – Capacitance, ESR and Current Ripple
- Lifetime Prediction
- Conclusion

AL-ELECTROLYTIC CAPACITORS IN AC-DC POWER SUPPLIES

- It Is Still The Key Component In Power Supplies For Several Reasons
  - Provide Large Capacitance At Higher Voltage
  - Very Price Attractive
  - Volume Per µF Is Very Good





- Aluminum Electrolytic Capacitor Is The Relevant Component Of The Overall PSU Life Time!!!!

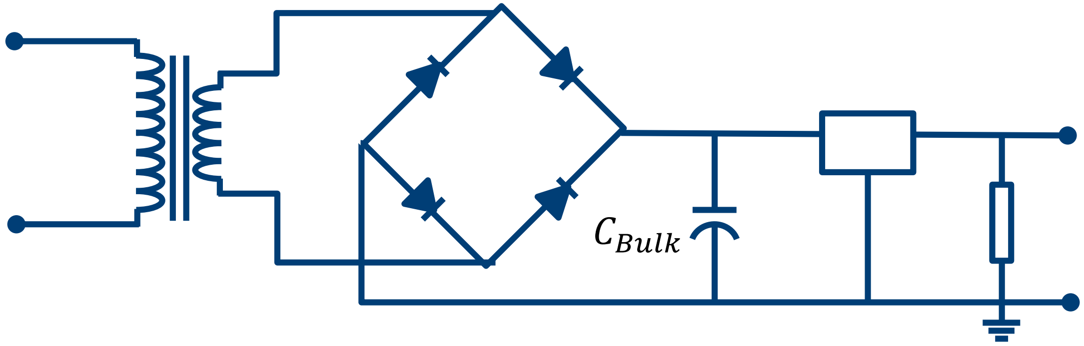
AGING EFFECTS OF AL-ELECTROLYTIC CAPACITOR

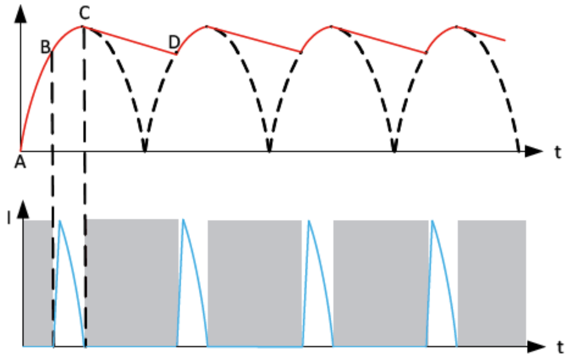
- Impacts On Aging Of Aluminum Electrolytic Capacitors Are:
  - **Temperature**
    - Loss Of Electrolytic
    - Leakage Current >> Oxide Degradation
  - **Ripple Current**
    - Local Heating >> Loss Of Electrolytic
  - **Voltage**
    - Leakage Current

Loss Of Capacitance And An Increasing Equivalent Series Resistors (ESR)

LINEAR POWER SUPPLY CIRCUIT

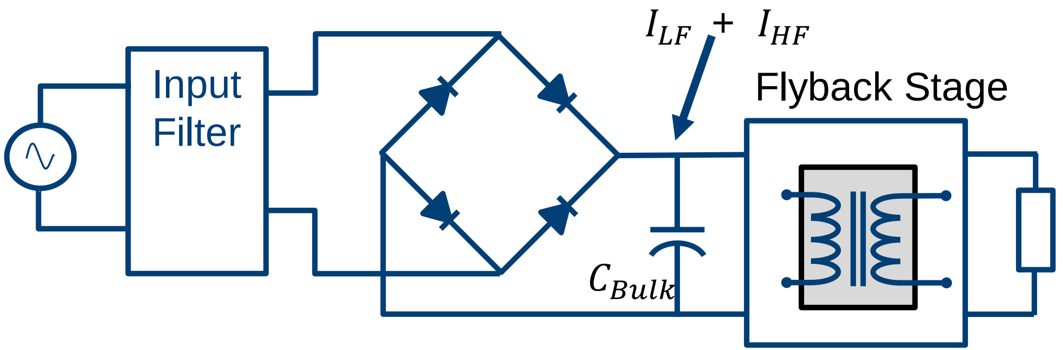
- They Still Need A Storage Element To Smooth The Rectified Pulsating Voltage (Low frequency) After The Bridge Rectifier
- Use Of The Large Bulk Capacitor Based On Aluminum Electrolytic Technology Is The Preferred Choice





SWITCHING-MODE POWER SUPPLY CIRCUIT

- In Many Applications, Overall Efficiency Requires The Use Of Power Supplies Based on SMPS principle
  - The Bulk Capacitor Is Still Required For Smoothing The Pulsating DC Voltage
  - An Additional HF Current Component Has To Be Considered

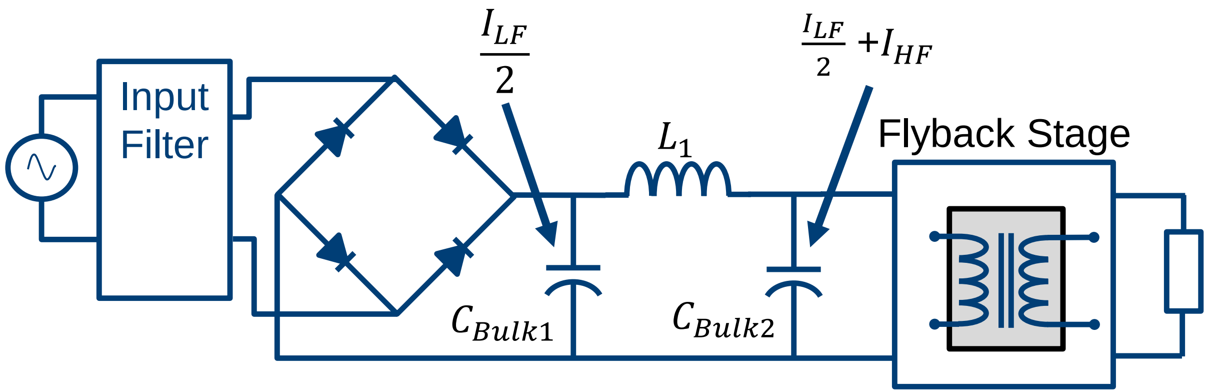


$$I_{eff} = \sqrt{\frac{I_{LF}^2}{K_{LF}^2} + \frac{I_{HF}^2}{K_{HF}^2}}$$

The Maximum Current Ripple Is Typically Defined At Line Frequency (100Hz)

EMI OPTIMIZED POWER SUPPLY CIRCUIT

- A Small Change In The Previous Setup May Solve EMI Challenges
  - An Additional Bulk Capacitor And Filter Inductor Is Used To Create A PI Filter
  - Low Frequency Content Will Flow In Both Capacitors
  - Low And High Frequency Content Will Flow Only In C_{bulk2}



Lifetime Of Bulk Capacitors Are Different!!

HOW TO CALCULATE CAPACITANCE FROM MEASURED CURRENT AND VOLTAGE

▶ Basic Math Fundamentals

The Integral Of The Current Over Time Can Be Expressed As The Charge

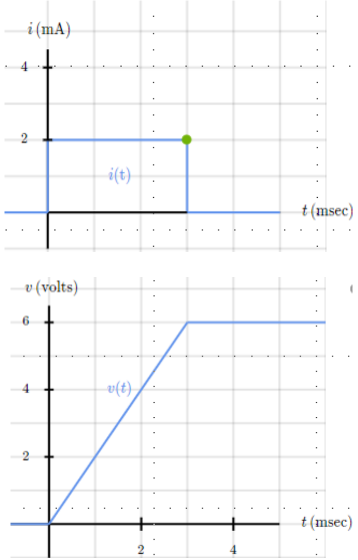
$$Q = \int_{t1}^{t2} i(t)dt \; [As]$$

The Voltage Across The Capacitor Is Expressed By The Integral And The Scale Factor C (Capacitance)

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

The Capacitance Can Be Expressed Using The Formulas Above

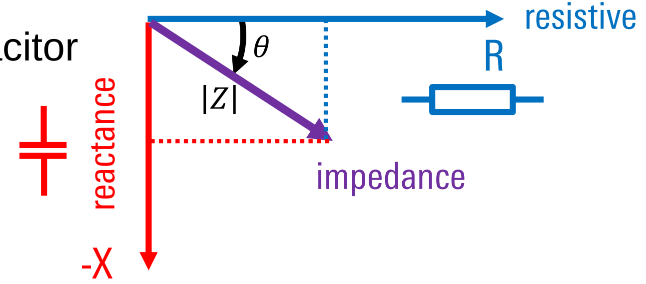
$$C = \frac{\Delta Q}{\Delta U}$$



ESR CALCULATION AT SWITCHING FREQUENCY

- Impedance Of Electrolytic Capacitor

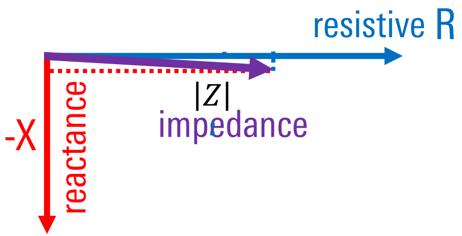
$$Z = \sqrt{ESR^2 + X_C^2}$$



- Capacitive Reactive Can Be Neglected At Switching Frequency

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

$$X_{C\_fsw} = \frac{1}{2*\pi*f_{sw}*C}$$

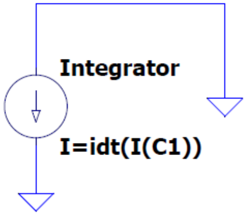


- ESR Can Be Calculated From Voltage And Current Switching Peak To Peak

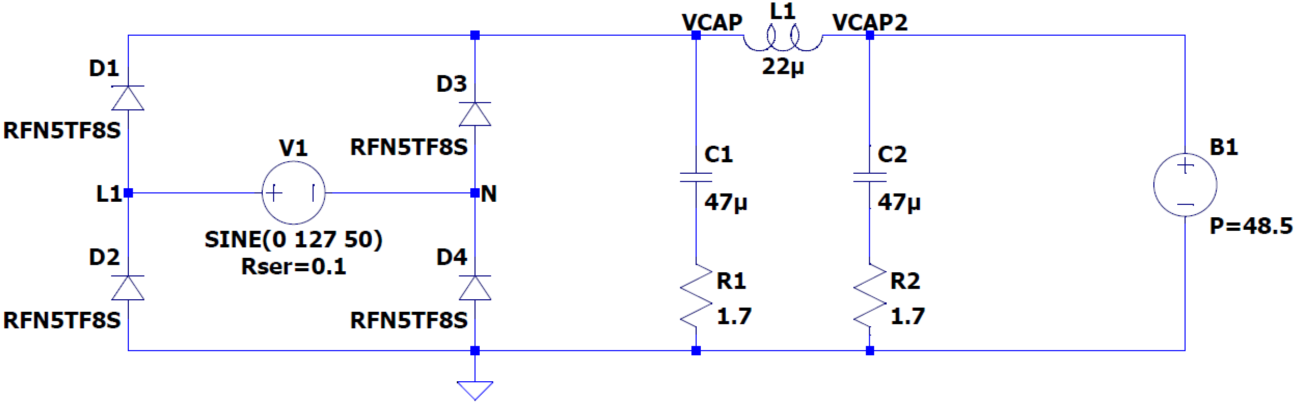
$$Z = \frac{U_{C\_fsw}}{I_{C\_fsw}}$$

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

BASIC CIRCUIT SIMULATION – LF RIPPLE

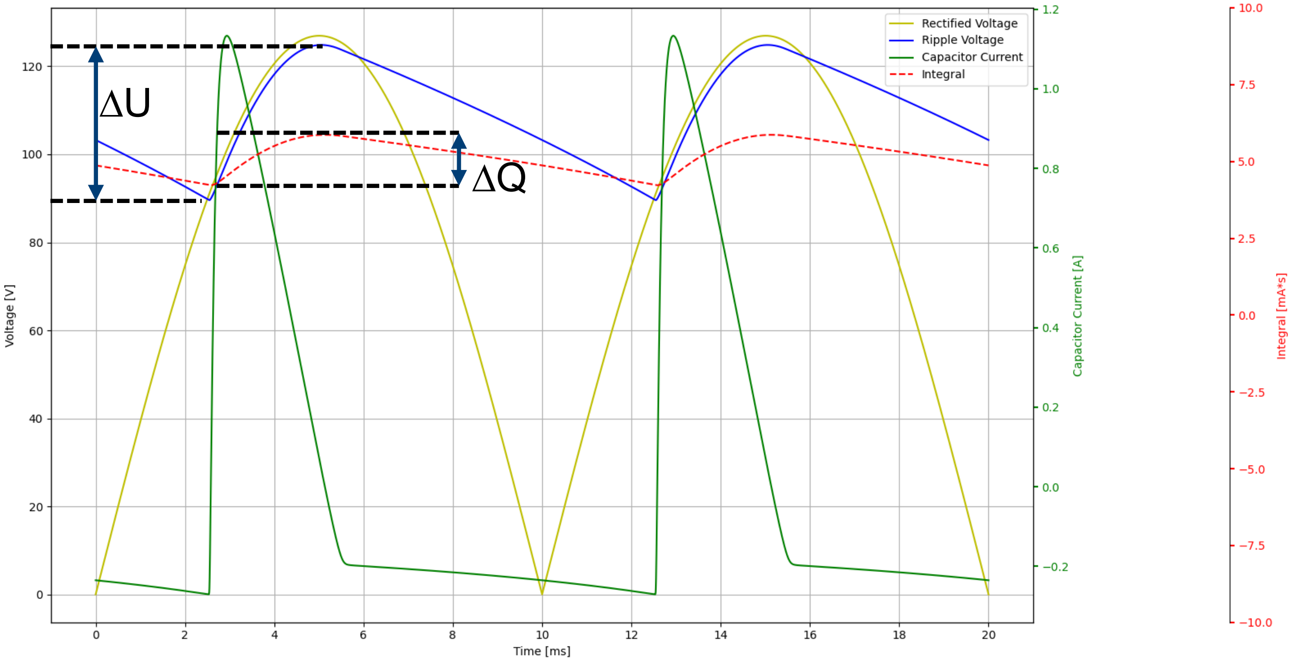



```
.options numdgt = 7
.options plotwinsize = 0
.four 100 10 10 V(VCAP)
.four 100 10 10 I(C1)
.param dt=20ms
.meas TRAN I_INTEGRAL INTEG I(C1)/dt FROM 160ms TO 180ms
.tran 0 200m 180m 100n startup
```



SIMULATION RESULTS

► LF Ripple Simulation Is Used To Derive RMS Current And Capacitance

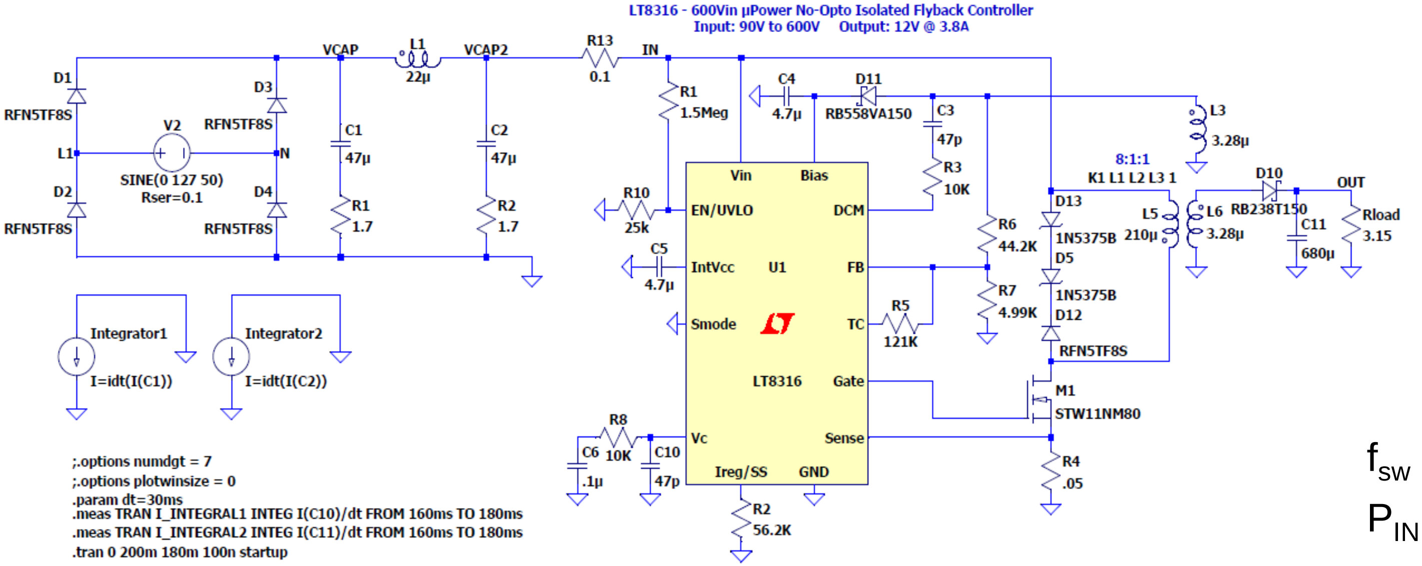


$$C = \frac{\Delta Q}{\Delta U} = 46{,}5\mu F$$

$$I_{C\_RMS} = 411mA$$

EXTENDED SIMULATION CIRCUIT

- Contribution Of The Flyback Converter Has To Be Taken Into Account For Lifetime Calculation

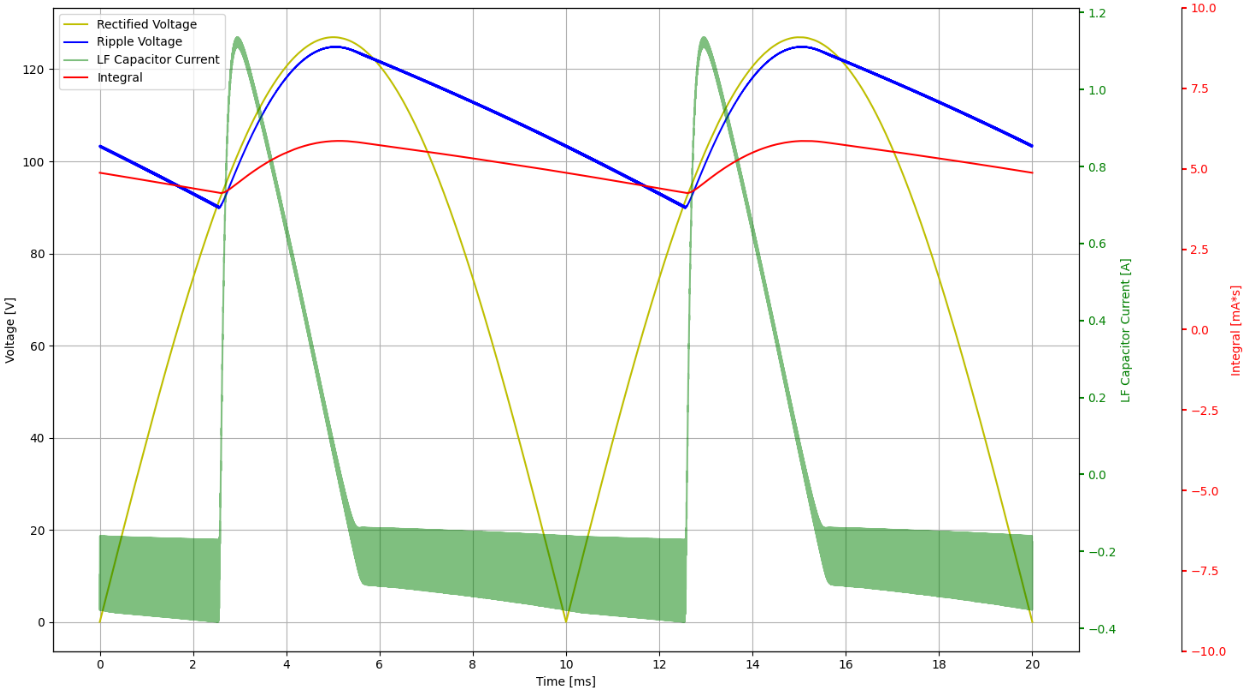


f_{sw} = 100kHz .. 110kHz

P_{IN} = 47,6W

SIMULATION RESULTS @ LF CAPACITOR

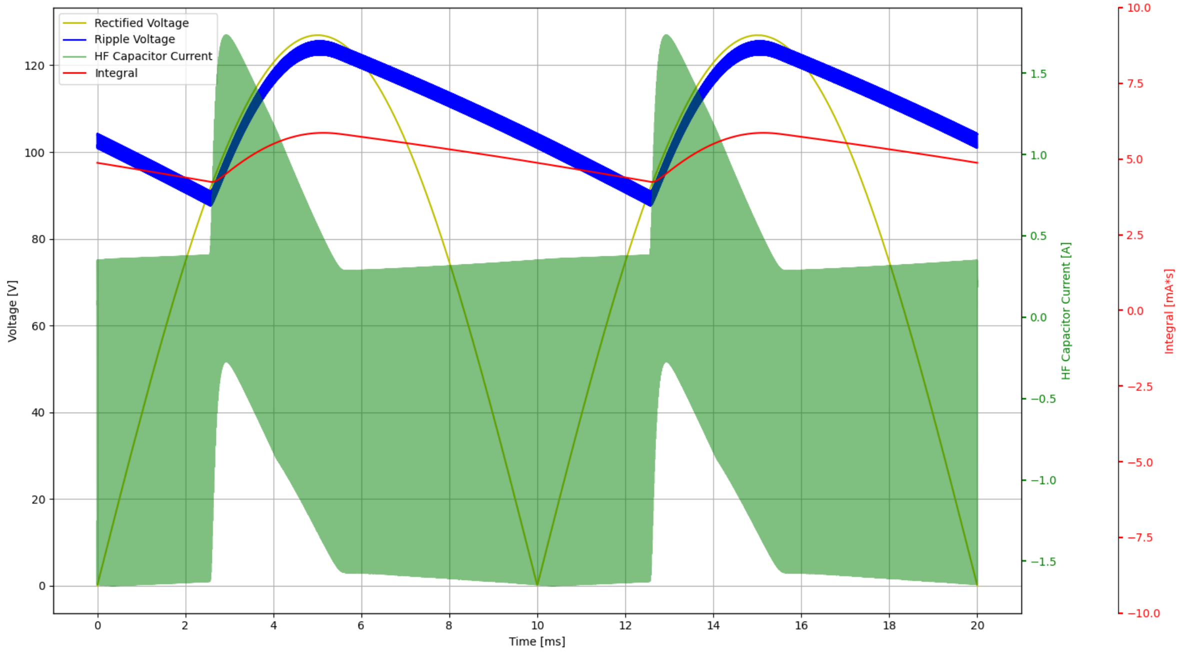
► LF Ripple Simulation To Derive RMS Current And Capacitance



C_{LF} = 46,3µF

I_{C_RMS} = 415mA

SIMULATION RESULTS @ HF CAPACITOR



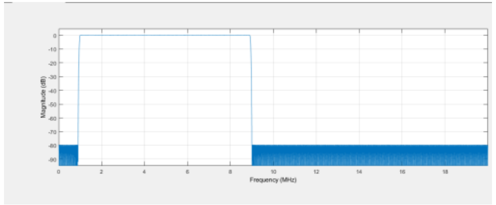
C_{HF} = 46,4µF

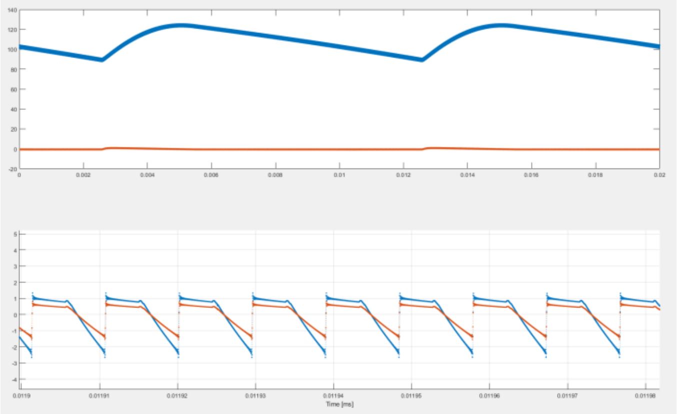
$I_{RMS\_Effective}$ = 741mA

I_{RMS_HF} = 688 mA

ESR ESTIMATION BASED ON SIMULATION DATA

- Digital FIR Filter (Band Pass Filter) Can Be Used To Measure Peak To Peak At Switching Frequency
- Filter Design Is Based On Matlab Filter Designer
- ESR Calculation Within Matlab





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

Very Close To The Simulation Model!!

PROBING

- ► What Kind Of Hardware Is Required To Derive The Capacitance, Ripple Current And ESR Value Within The Circuit Operation.

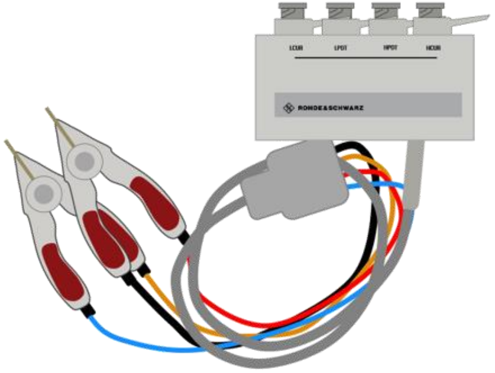
  – *High Voltage Differential Probe*
    – R&S ZHD07 - Offset Capability And Sufficient Bandwidth

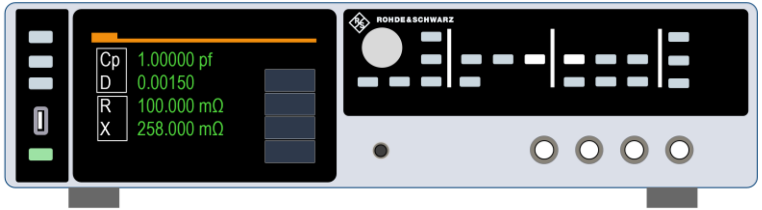
  – *Current Probe*
    – Current Clamp Probe or Rogowski Probe
    – R&S RT-ZC20B Offers Very Good Bandwidth
    – Rogowski Probe Is easy To

  Attach To The Circuit (AC Current Only)

LCR-METER

- ► It Was Used To Validate The In-Circuit Measurements
  - R&S LCX100/LCX200 LCR Meter Provides High Accuracy
    - Basic Accuracy Up To 0.05%
  - It provides Many Different Impedance Measurement Functions
    - ESR, ESL And Capacitance Is Needed





LCR-METER DEMONSTRATION

OSCILLOSCOPE

- An Device With The Following Characteristic Is Essential:
  - Bandwidth Of At Least 1GHz Is Required
  - Use Of Customized Digital Filter
  - Integral Math Function Should Be Used To Calculate Q Charge
  - Measurement Function Like RMS, Peak to Peak, etc.
  - Powerful Curser Setting Supports The User To Extract The Capacitance

The RTO6 Is The Perfect Choice To Perform The Challenging Task

CAPACITANCE EVALUATION PART I

► Capacitance Measurement At Line Frequency

HD Mode with BW Limit 10kHz (16Bit)

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

DUT Parameter:

230VAC @ Iout = 20V/2A

CAPACITANCE EVALUATION PART II

► A Combination Of Low and High Frequency Content Is Present

HD Mode With BW Limit 10kHz (16Bit)

(Switching Frequency Rejection)

$$C = \frac{\Delta Q}{\Delta U} = \frac{625\ \mu A*s}{13{,}4\ V} = 46{,}7\mu F$$

DUT

230VAC @ Iout = 20V/2A

RIPPLE CURRENT MEASUREMENT PART1

► Ripple Current Measurement At Line Frequency

HD Mode with BW Limit 50MHz (16Bit)

I_{RMS_LF} = 254 mA

I_{RMS_Total} = 255 mA

DUT

230VAC @ Iout = 20V/2A

RIPPLE CURRENT MEASUREMENT PART II

► Ripple Current Measurement At Line Frequency, Switching Ripple And The Total Ripple

HD Mode with BW Limit 50MHz (16Bit)

I_{RMS_LF} = 265 mA

I_{RMS_Total} = 540 mA

I_{RMS_HF} = 470 mA

DUT

230VAC @ Iout = 20V/2A

ESR IN-CIRCUIT MEASUREMENT @ SWITCHING FREQUENCY

► Ripple Voltage And Current Measurement At Switching Frequency

Results (@25°)

U_{PP} = 1,02 V

I_{PP} = 1,85 A

ESR = 551 mΩ

F_{sw} = 285 kHz

Bandpassfilter (FIR)

F_{stop1} = 13 kHz

F_{pass1} = 125 kHz

F_{pass2} = 11 MHz

F_{stop2} = 11,25 MHz

CAPACITANCE AND ESR COMPARISON

	In-Circuit Measurement		LCR-Bridge Measurement		Failure [%]	
	LF-Cap @ 100Hz	HF-Cap @ 100Hz	LF-Cap @ 1kHz	HF-Cap @ 1kHz	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_{2000h} [Ω] @ 285 kHz	X	2,91	4,049	3,619	X	-24

RIPPLE CURRENT AND TEMPERATURE RESULTS

	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			

LIFETIME CALCULATION

► Based On Core Temperature Measurement

Lifetime Calculation (Law of Arrhenius)

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

L_0 =10000h

T_0 =105°C

Lifetime Calculation With New Device

$L_{x\_LF} = 911\,392\ h$

$L_{x\_HF} = 777\,084\ h$

Lifetime Calculation With Accelerated Aging

$L_{x\_LF} = 530\,764\ h$

$L_{x\_HF} = 458\,865\ h$

Most Accurate Calculation But It Requires A Built-In Thermocouple Element

LIFETIME ESTIMATION

► Based On Ripple Current Measurement

Current Ripple Including Frequency Multiplier

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

$$K_{LF} = 0{,}5$$

$$K_{HF} = 1$$

$$I_{eff\_LF\_Cap} = 510mA$$

$$I_{eff\_HF\_Cap} = 756\,mA$$

Frequency [Hz]	120	1000	10000	≥ 100000
Multiplier	0.50	0.80	0.85	1.0

Temperature Rise And Lifetime Estimation

$$\Delta T = \Delta T_{max} * \left(\frac{I_{eff}^2}{I_{Rated}^2}\right)$$

$$I_{Rated} = 1050\,mA$$

$$\Delta T_{LF} = 1{,}2\,K$$

$$\Delta T_{HF} = 2{,}6\text{ K}$$

$$K_{Ripple} = 2^{\left[\frac{\Delta T_{max} - \Delta T}{5}\right]}$$

$$\Delta T_{Max} = 5K$$

$$K_{Ripple\_LF} = 1{,}693$$

$$K_{Ripple\_HF} = 1{,}454$$

$$L_x = L_0 * 2^{\left[\frac{T_0 - T_a}{10}\right]} * K_{Ripple}$$

$$T_0 = 105°C$$

$$L_{x\_LF} = 1\,532\,328\,h$$

$$L_{x\_HF} = 1\,316\,010\,h$$

40°C Should Be Considered For Ta, If The Ambient Temperature Is Below 40°C

CONCLUSION

- ► Smart Circuit Simulation Will Provide The First Insight Of Key Values But Cannot Avoid Real Measurements

- ► In-Circuit Measurement Supports The Designer With RMS Ripple Current Measurement To Estimate Lifetime Of An Capacitor In An Easy Way But Is Limited In Accuracy
- ► A Core Temperature Measurement Of The Capacitors Operating In The Application Provides Best Accuracy But Requires More Effort

- ► In-Circuit Measurement Provide Capacitance and ESR Values Within the Application
- ► LCR-Bridge Measurement Provides Highest Accuracy For Capacitance And ESR Measurements

- ► Lifetime Calculation Of Aluminum Electrolytic Capacitor Is Essential To Estimate The Overall Power Converter Lifetime

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