AGING AND IN-CIRCUIT CHARACTERIZATION OF ALUMINUM ELECTROLYTIC CAPACITORS

Marcus Sonst
Application Engineer Power Management

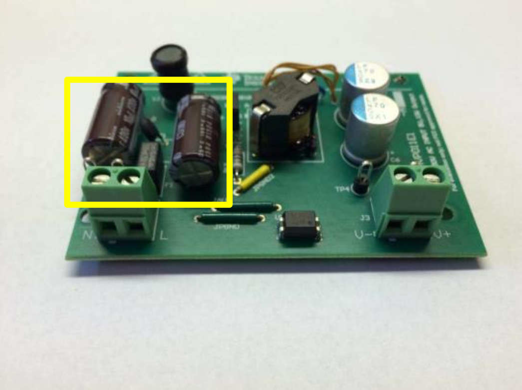
ROHDE&SCHWARZ

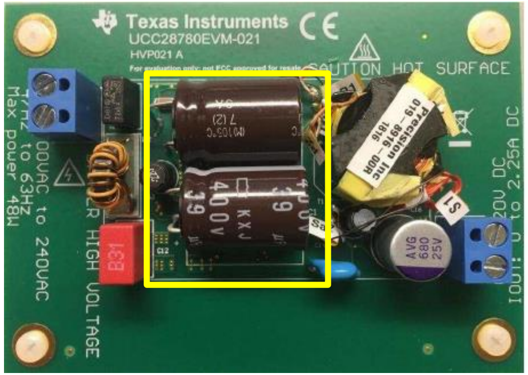
Make ideas real

CONTENT

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!!!!

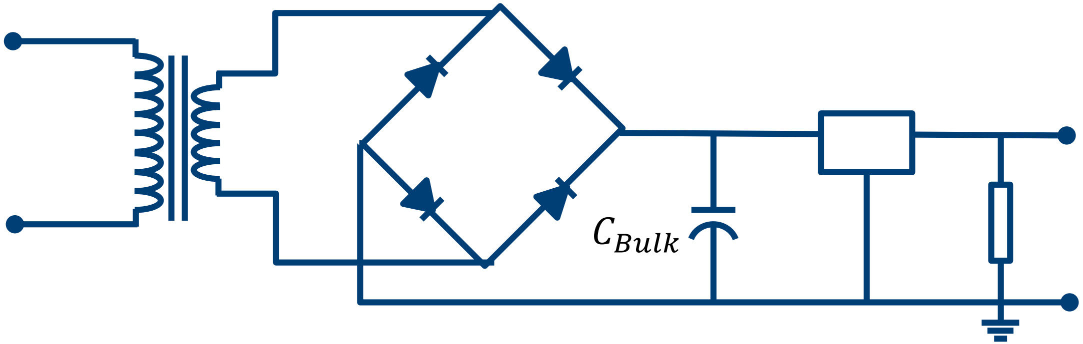
AGING EFFECTS OF AL-ELECTROLYTIC CAPACITOR

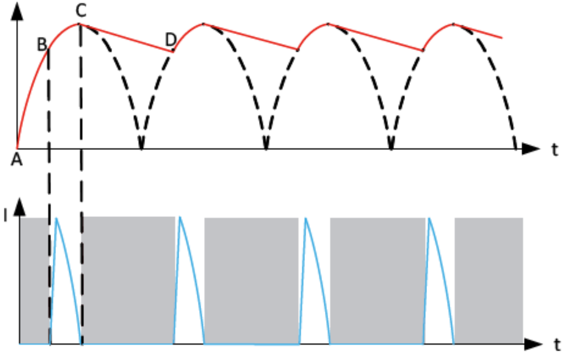
- ► Impacts On Aging Of Aluminum Electrolytic Capacitors Are:
  - **Temperature**
    - Loss Of Electrolytic
    - Leakage Current >> Oxide Degradation
  - **Ripple Current**
    - Local Heating >> Loss Of Electrolytic
  - **Voltage**
    - Leakage Current

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

LINEAR POWER SUPPLY CIRCUIT

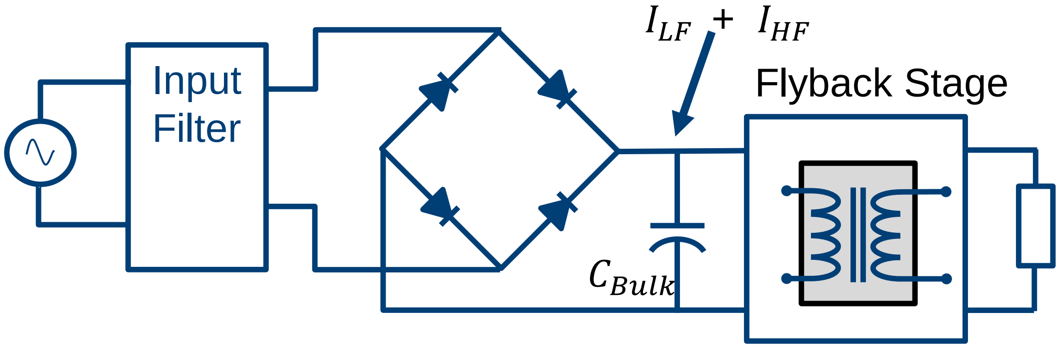
- They Still Need A Storage Element To Smooth The Rectified Pulsating Voltage (Low frequency) After The Bridge Rectifier
- Use Of The Large Bulk Capacitor Based On Aluminum Electrolytic Technology Is The Preferred Choice





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

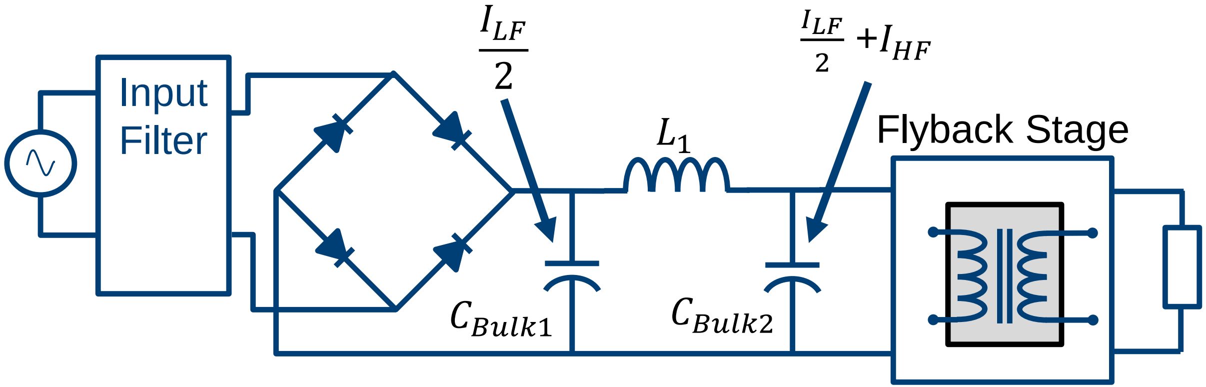


$$I_{eff} = \sqrt{\frac{I_{LF}^2}{K_{LF}^2} + \frac{I_{HF}^2}{K_{HF}^2}}$$

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

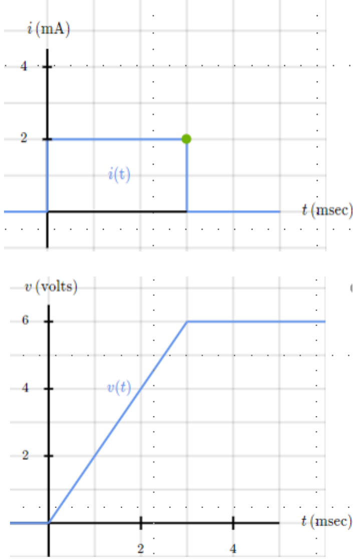
$$Q = \int_{t1}^{t2} i(t)dt\ [As]$$

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

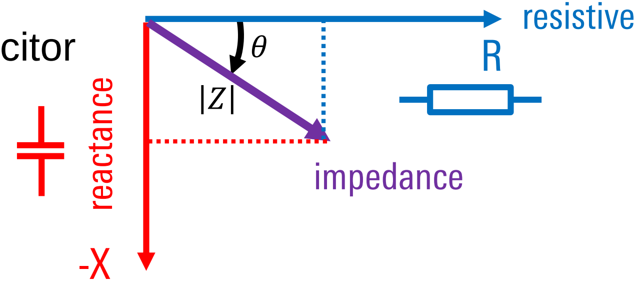
$$C = \frac{\Delta Q}{\Delta U}$$



ESR CALCULATION AT SWITCHING FREQUENCY

- Impedance Of Electrolytic Capacitor

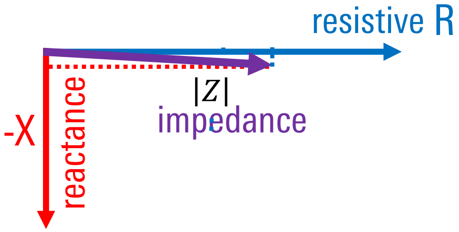
$$Z = \sqrt{ESR^2 + X_C^2}$$



- Capacitive Reactive Can Be Neglected At Switching Frequency

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

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

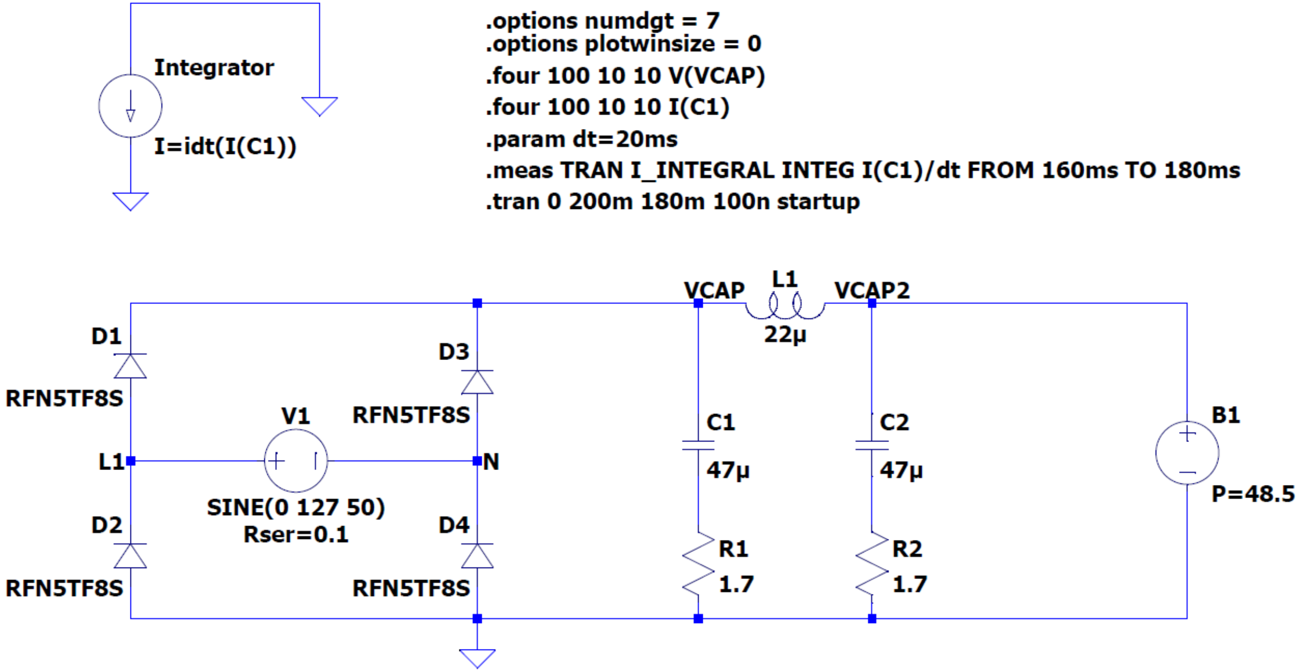


- ESR Can Be Calculated From Voltage And Current Switching Peak To Peak

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

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

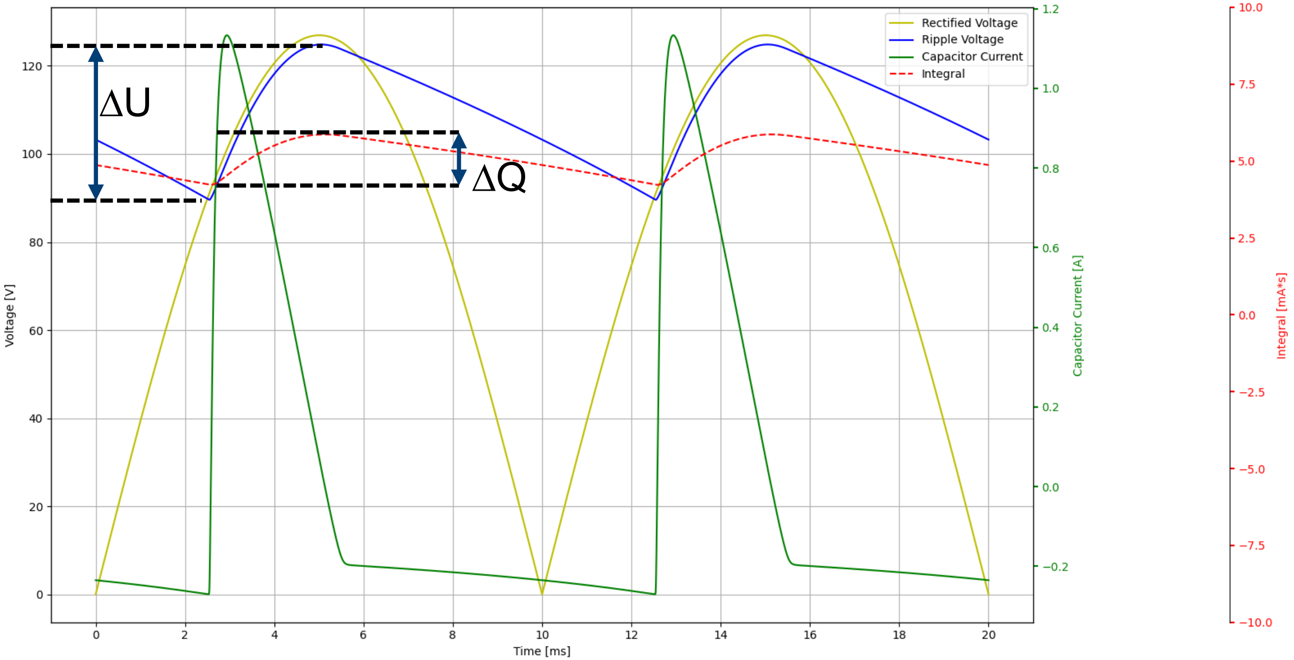
BASIC CIRCUIT SIMULATION – LF RIPPLE



```
.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

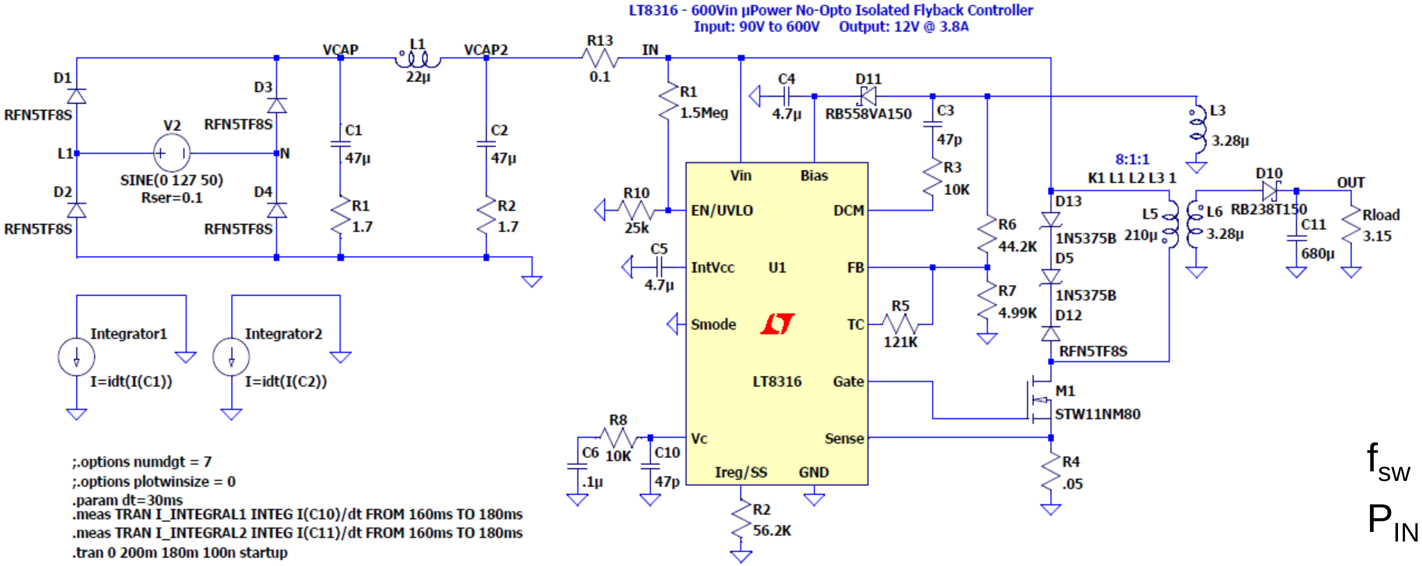


$$C = \frac{\Delta Q}{\Delta U} = 46{,}5\mu\text{F}$$

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

EXTENDED SIMULATION CIRCUIT

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



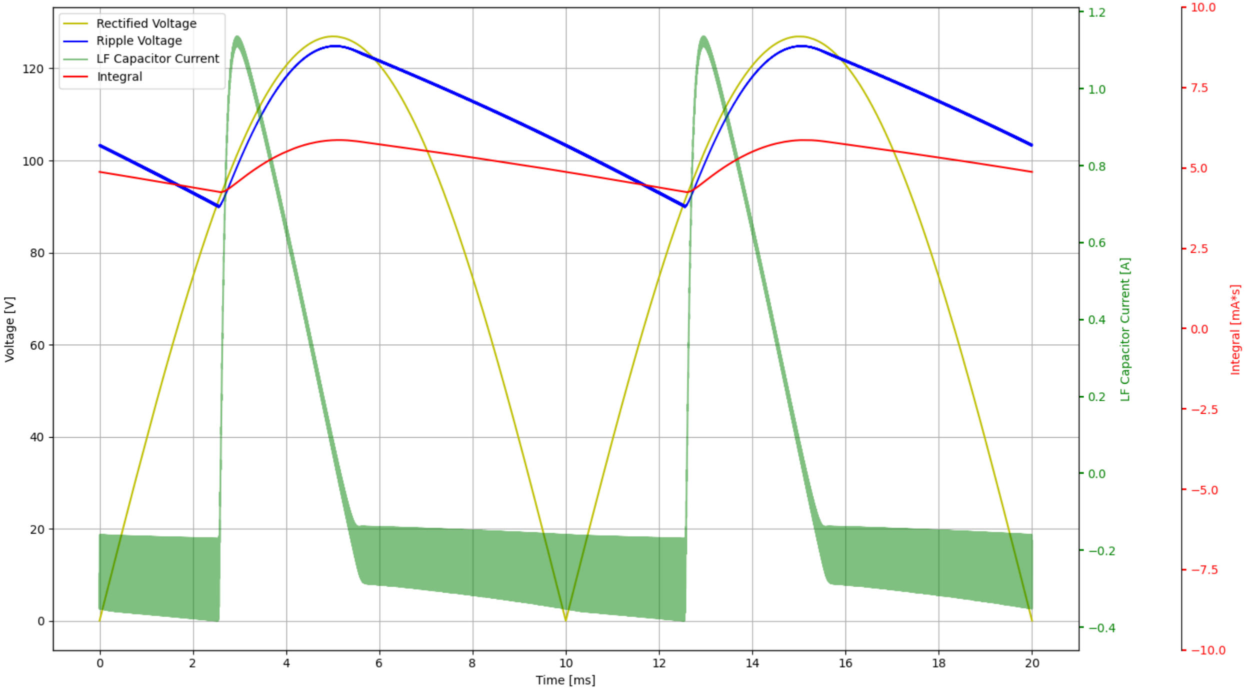
```
;.options numdgt = 7
;.options plotwinsize = 0
.param dt=30ms
.meas TRAN I_INTEGRAL1 INTEG I(C10)/dt FROM 160ms TO 180ms
.meas TRAN I_INTEGRAL2 INTEG I(C11)/dt FROM 160ms TO 180ms
.tran 0 200m 180m 100n startup
```

f_{SW} = 100kHz .. 110kHz

P_{IN} = 47,6W

SIMULATION RESULTS @ LF CAPACITOR

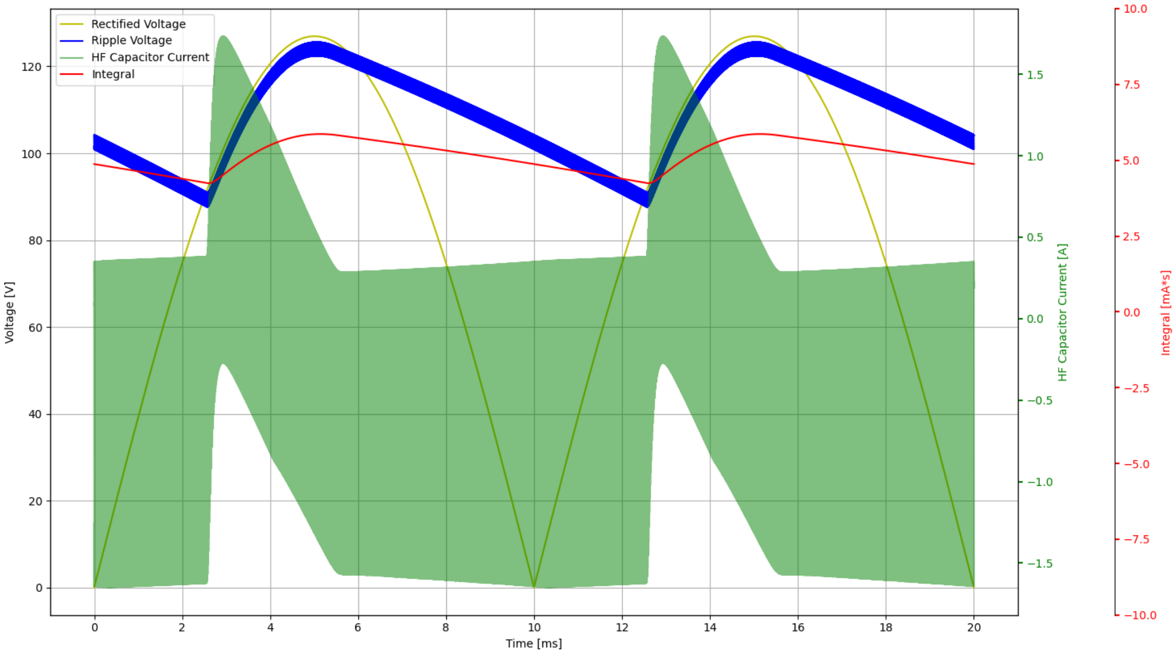
- LF Ripple Simulation To Derive RMS Current And Capacitance



$C_{LF} = 46{,}3\mu F$

$I_{C\_RMS} = 415mA$

SIMULATION RESULTS @ HF CAPACITOR



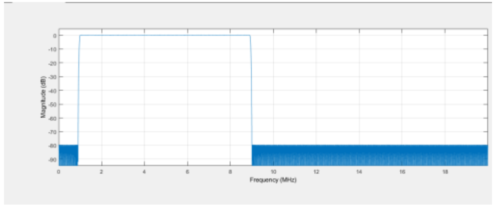
C_{HF} = 46,4µF

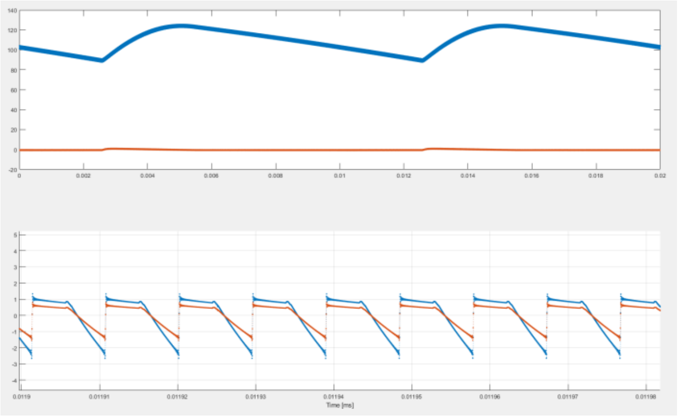
$I_{RMS\_Effective}$ = 741mA

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)

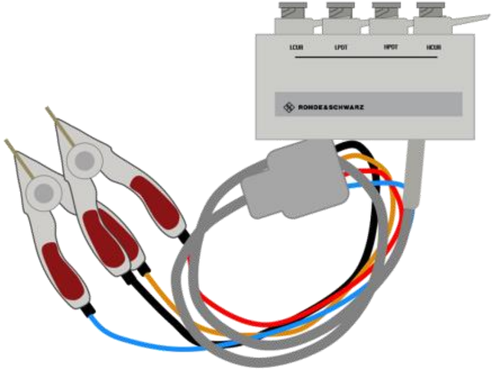
OSCILLOSCOPE

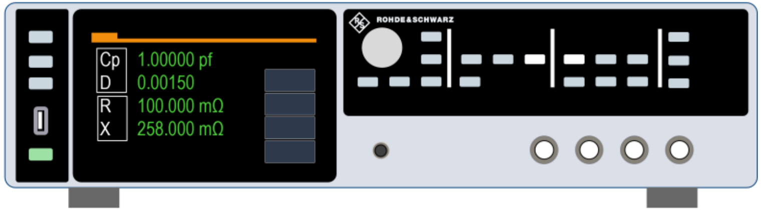
- An Device With The Following Characteristic Is Essential:
  - Bandwidth Of At Least 1GHz Is Required
  - Use Of Customized Digital Filter
  - Integral Math Function Should Be Used To Calculate Q Charge
  - Measurement Function Like RMS, Peak to Peak, etc.
  - Powerful Curser Setting Supports The User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

The RTO6 Is The Perfect Choice To Perform The Challenging Task

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





CAPACITANCE EVALUATION PART I

- Capacitance Measurement At Line Frequency

	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Meas Group 1 C1								
Peak to peak	13.264 V	13.267 V	13.217 V	13.239 V	13.239 V	19.814 mV	10	10
Meas Group 2 M2								
Peak to peak	603.8 µA*s	603.83 µA*s	601.72 µA*s	602.67 µA*s	602.67 µA*s	789.71 nA*s	10	10
Meas Group 3 C2								
Peak to peak	1.392 A	1.4118 A	1.3895 A	1.4003 A	1.4003 A	8.1229 mA	10	10
Rise time	314.12 µs	341.48 µs	314.12 µs	329.49 µs	329.66 µs	11.162 µs	10	10

C1: 2 V/ DC, 322 V, 1 MΩ, 10 kHz, RT-ZHD07

C2: 250 mA/ DC, 650 mA, 1 MΩ, 10 kHz, RT-ZC20B

M2: 100 µA*s/, integral(C2Wfm1), 200 µA*s

Cursor Result 1: Y1 -93.06 µA*s, Y2 510.74 µA*s, ΔY 603.8 µA*s

Cursor Result 2: Y1 313.917 V, Y2 327.1976 V, ΔY 13.2806 V

ProbeMeter 1: Differential 320.42 V, Common mode 0 V

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

Trigger: C1 Edge 320 V Auto Stop
Horizontal: 400 µs/ 0 s
Acquisition: 50 MSa/s HD-Mode RT 200 kpts 16 bit Hist 10
2022-03-02 14:33:28

	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Meas Group 1 C1								
Peak to peak	13.432 V	13.446 V	13.322 V	13.391 V	13.391 V	38.805 mV	10	10
Meas Group 2 M2								
Peak to peak	626.5 µA*s	627.09 µA*s	621.66 µA*s	624.65 µA*s	624.65 µA*s	1.7765 µA*s	10	10
Meas Group 3 C2								
Peak to peak	1.5376 A	1.5392 A	1.5055 A	1.5234 A	1.5235 A	13.416 mA	10	10
Rise time	368.64 µs	368.64 µs	325.99 µs	352.42 µs	352.67 µs	14.028 µs	10	10

Statistics: Reset

C1: 2 V/ DC 321 V 1 MΩ 10 kHz RT-ZHD07
C2: 400 mA/ DC 500 mA 1 MΩ 10 kHz RT-ZC20B
M2: 100 µA*s/ integral(C2Wfm1) 100 µA*s

Cursor Result 1: Y1 -111.18 µA*s, Y2 515.32 µA*s, ΔY 626.5 µA*s
Cursor Result 2: Y1 314.498 V, Y2 327.9368 V, ΔY 13.4388 V

HD Mode With BW Limit 10kHz (16Bit)
(Switching Frequency Rejection)

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

DUT
230VAC @ Iout = 20V/2A

RIPPLE CURRENT MEASUREMENT PART1

- ► Ripple Current Measurement At Line Frequency

	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Meas Group 1 C1								
Peak to peak	13.533 V	13.66 V	13.533 V	13.605 V	13.605 V	40.998 mV	10	10
Frequency	99.82 Hz	99.868 Hz	99.676 Hz	99.799 Hz	99.799 Hz	80.138 mHz	10	10
Meas Group 3 C2								
Peak to peak	1.623 A	1.6429 A	1.617 A	1.6288 A	1.6289 A	7.8987 mA	10	10
RMS	255.18 mA	255.8 mA	254.07 mA	255.08 mA	255.08 mA	531.69 µA	10	10
Frequency	99.897 Hz	99.899 Hz	99.7 Hz	99.819 Hz	99.819 Hz	99.383 mHz	10	10

C1: 2 V/ DC, 320 V, 1 MΩ, 50 MHz, RT-ZHD07

C2: 200 mA/ DC, 600 mA, 1 MΩ, 50 MHz, RT-ZC20B

Cursor Result 2
Y1 314.17 V
Y2 327.7273 V
ΔY 13.5573 V

ProbeMeter 1
Differential 320.83 V
Common mode -10 mV

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

Trigger: C1 Edge 319 V Auto Stop

Horizontal: 2 ms/ 6.01 ms

Acquisition: 50 MSa/s HD-Mode RT 1 Mpts 16 bit Hist 10

	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Meas Group 1 C1								
Peak to peak	14.292 V	14.292 V	14.168 V	14.222 V	14.222 V	44.782 mV	10	10
Frequency	101.24 Hz	101.24 Hz	100.63 Hz	100.93 Hz	100.93 Hz	238.41 mHz	10	10
Meas Group 2 M1								
Peak to peak	2.2475 A	2.2574 A	2.2447 A	2.2498 A	2.2498 A	3.6701 mA	10	10
RMS	470.23 mA	470.23 mA	470.14 mA	470.18 mA	470.18 mA	23.082 µA	10	10
Frequency	284.36 kHz	284.63 kHz	283.56 kHz	284.15 kHz	284.15 kHz	330.95 Hz	10	10
Meas Group 3 C2								
Peak to peak	3.7648 A	3.7898 A	3.7643 A	3.7759 A	3.7759 A	9.9394 mA	10	10
RMS	540.02 mA	540.13 mA	539.35 mA	539.8 mA	539.8 mA	252.69 µA	10	10

Statistics: Reset

C1: 2 V/ DC 321 V 1 MΩ 50 MHz RT-ZHD07

C2: 400 mA/ DC 450 mA 1 MΩ 50 MHz RT-ZC20B

M1: 400 mA/ FIR(userdef,C2,"C:\Use... 0 A

Cursor Result 2: Y1 314.0237 V, Y2 328.2925 V, ΔY 14.2688 V

ProbeMeter 1: Differential 321.1 V, Common mode -20 mV

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

	Current	Max	Min	Mean	RMS	σ (S-dev)	Event count	Wave count
Meas Group 1 M1								
Peak to peak	995.66 mV	1.0624 V	995.66 mV	1.021 V	1.0211 V	16.109 mV	26	26
Frequency	285.12 kHz	286.94 kHz	284.18 kHz	285.52 kHz	285.52 kHz	723.25 Hz	26	26
Meas Group 2 M2								
Peak to peak	1.861 A	1.8781 A	1.81 A	1.8504 A	1.8504 A	17.297 mA	26	26
Frequency	285.2 kHz	286.5 kHz	284.46 kHz	285.42 kHz	285.42 kHz	533.48 Hz	26	26

C1	C2	M1	M2
2 V/ DC	400 mA/ DC	200 mV/	400 mA/
321 V 1 MΩ	488 mA 1 MΩ	FIR(userdef,C1,"C:\Use...	FIR(userdef,C2,"C:\Use...
50 MHz RT-ZHD07	50 MHz RT-ZC20B	0 V	100 µA

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

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

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

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

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

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

$$T_0 = 105°C$$

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

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

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

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

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

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

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 addition, 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

THANK YOU

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			
Used Capacitor (2000h)	I_{RMS_Total}	*232*	*299*	*47,4*	*49,8*	*25,6*
	I_{RMS_HF}	*X*	*217*			
	I_{RMS_LF}	*232*	*207*			

ESR IN-CIRCUIT MEASUREMENT ACCURACY

- < 5% failure must be accepted

$$ESR * 1.05 > \sqrt{ESR^2 + X_C^2}$$

$$ESR^2 + \left(\frac{1}{2\pi f C}\right)^2 < 1.1025 * ESR^2$$

$$\frac{1}{f * C} < 2.0116 * ESR$$

$$f > \frac{1}{2.0116 * ESR * C} \qquad f > \frac{1}{2.0116 * 1.7 * 47\mu F} = 6.22kHz$$