more than you expect

WE Backup Your Application –
Hot Swappable Supercapacitor Backup Solution

APEC 2020 in New Orleans
Capacitor Workshop PSMA

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Introduction of the Presenter

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Background:

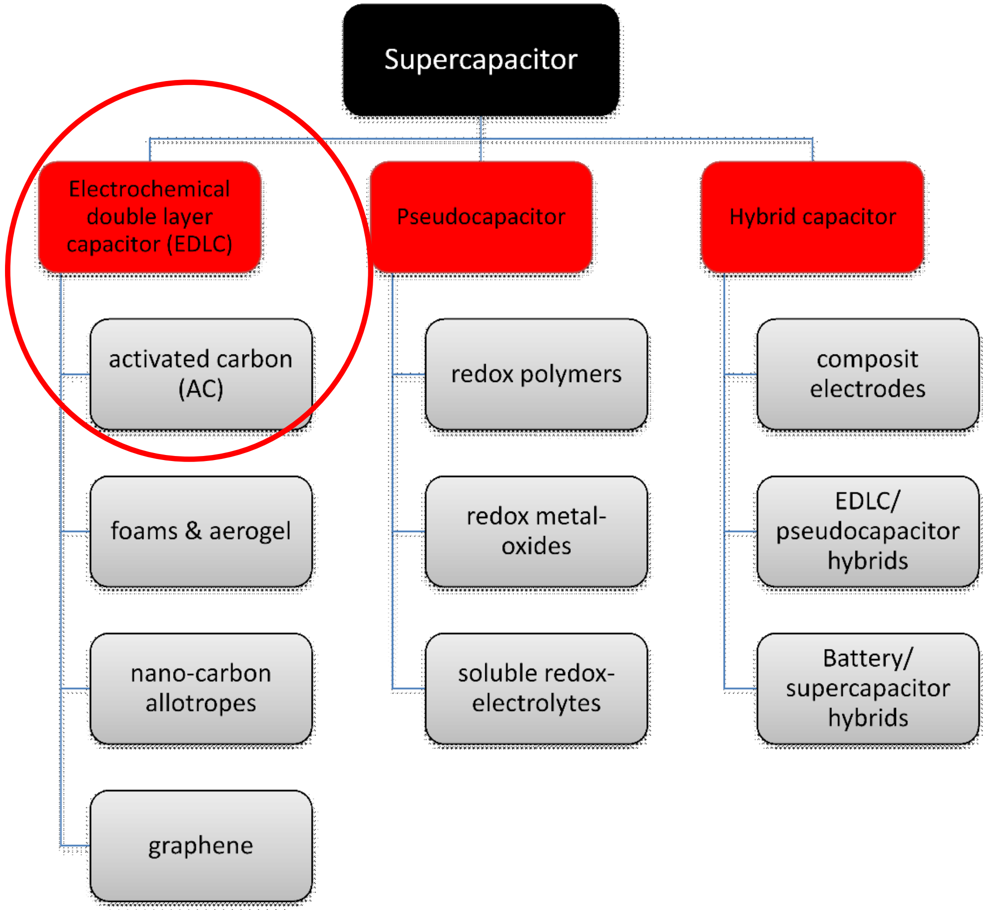
- More than 10 years of work experience in electronics industry
- Background in Electronics, Power Supply Development and formerly worked as Field Application Engineer
- In charge for technical engineering, product services and application support of capacitor division at Würth Elektronik

Agenda

- **Short Roundup about Supercapacitors**
  - Classification of Supercapacitors
  - Model Parameters and Performance
  - Charge-, Discharge and Frequency Behavior

- **WE Backup Your Application**
  - Hot Swappable Supercapacitor Backup Solution
  - Overview and General Information
  - Design-In Process and Lifetime
  - Performance of the Complete Solution

Classification of Capacitors



Types of Supercapacitors based on design of electrodes:

- Double Layer Capacitors
  - Electrodes: carbon or carbon derivatives
- Pseudocapacitors
  - Electrodes: oxides or conducting polymers (high faradaic pseudocapacitance)
- Hybrid capacitors
  - Electrodes: special electrodes with significant double-layer capacitance and pseudocapacitance

Supercapacitors vs. Batteries and Capacitors

Capacitors

- **Very fast charging** and discharging (≪ sec)
- Very high power output
- Very low energy capacity

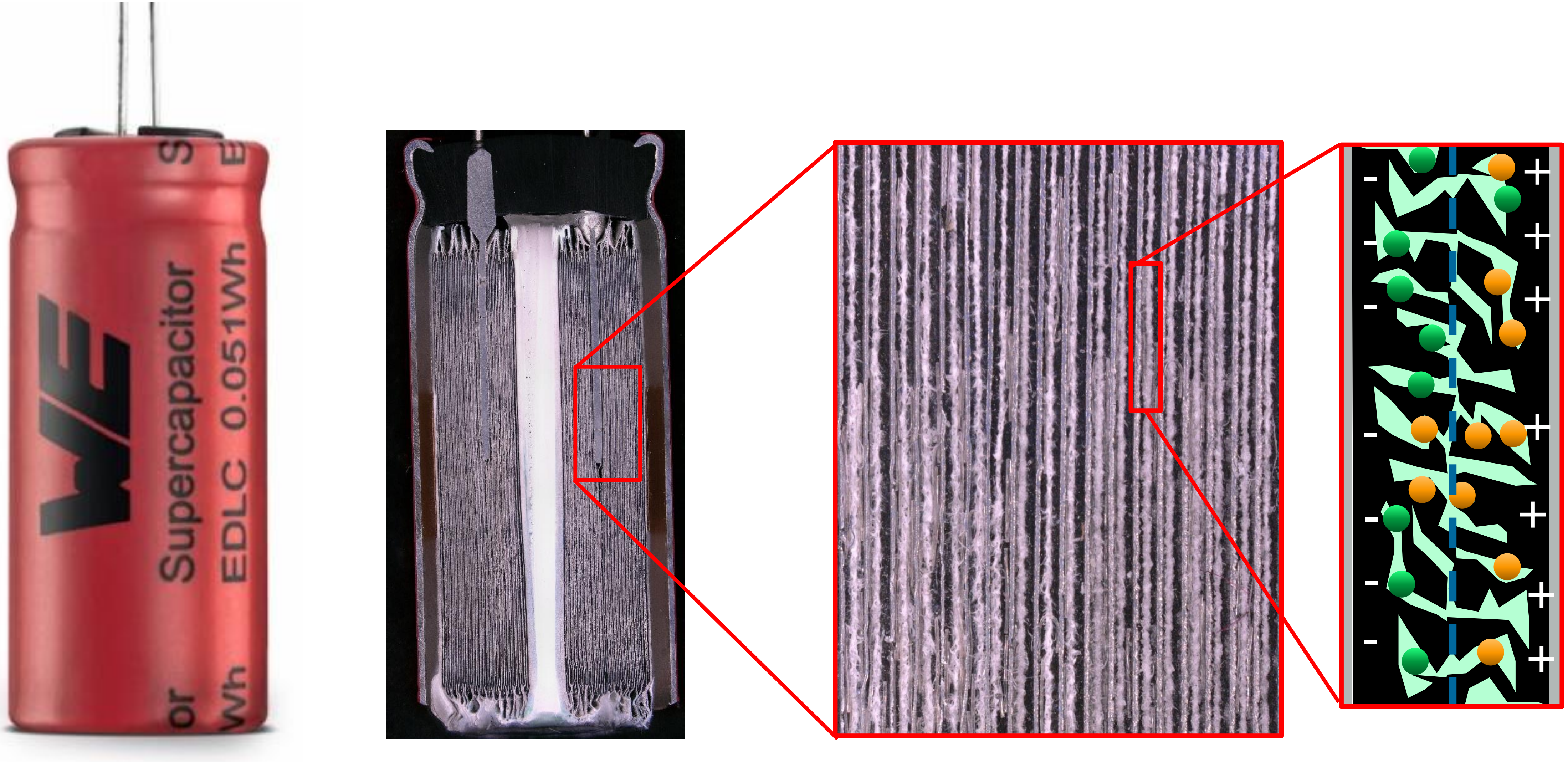
<u>Supercaps</u>

- **Fast charging** and discharging (min – sec)
- High life cycle (≈ 500,000 cycles)
- High power output
  - ≈ 10 times higher than Li-ion battery
- Low energy capacity
  - ≈ 30 times lower than Li-ion battery
- Energy: 0.002 Wh – 0.04 Wh
- Power: 36 W – 90 W

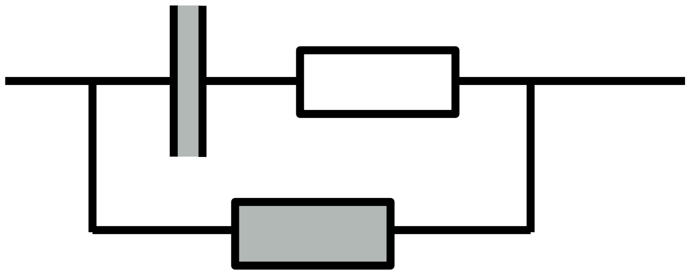
Batteries

- **Long charging** time (hours)
- High energy capacity
- Low power output
- Energy: 1.4 Wh
- Power: 6 W

Structure of the Supercapacitor



Parameter and Performance



Basic Parameters:

- U_r, **Rated Voltage:**
  - is not determined by the equivalent circuit but by electrochemistry (Decomposition Voltage)
    - Non-Aqueous Electrolyte (typ.): $\approx 2\,V$ ... $3V$
    - Aqueous Electrolyte (typ.): $\approx 1.5\,V$
- C **=> Capacitance**
- R_{ESR} **=> ESR**
- R_{Leak} **=> Leakage**
  - Influence on charge storing capabilities ($R_{Leak} \approx 10\text{ k}\Omega \ldots 1\text{ M}\Omega$)

Performance Parameters:

- **Energy storage capacity:**

$$E = \frac{1}{2} \times C \times U_r^2$$

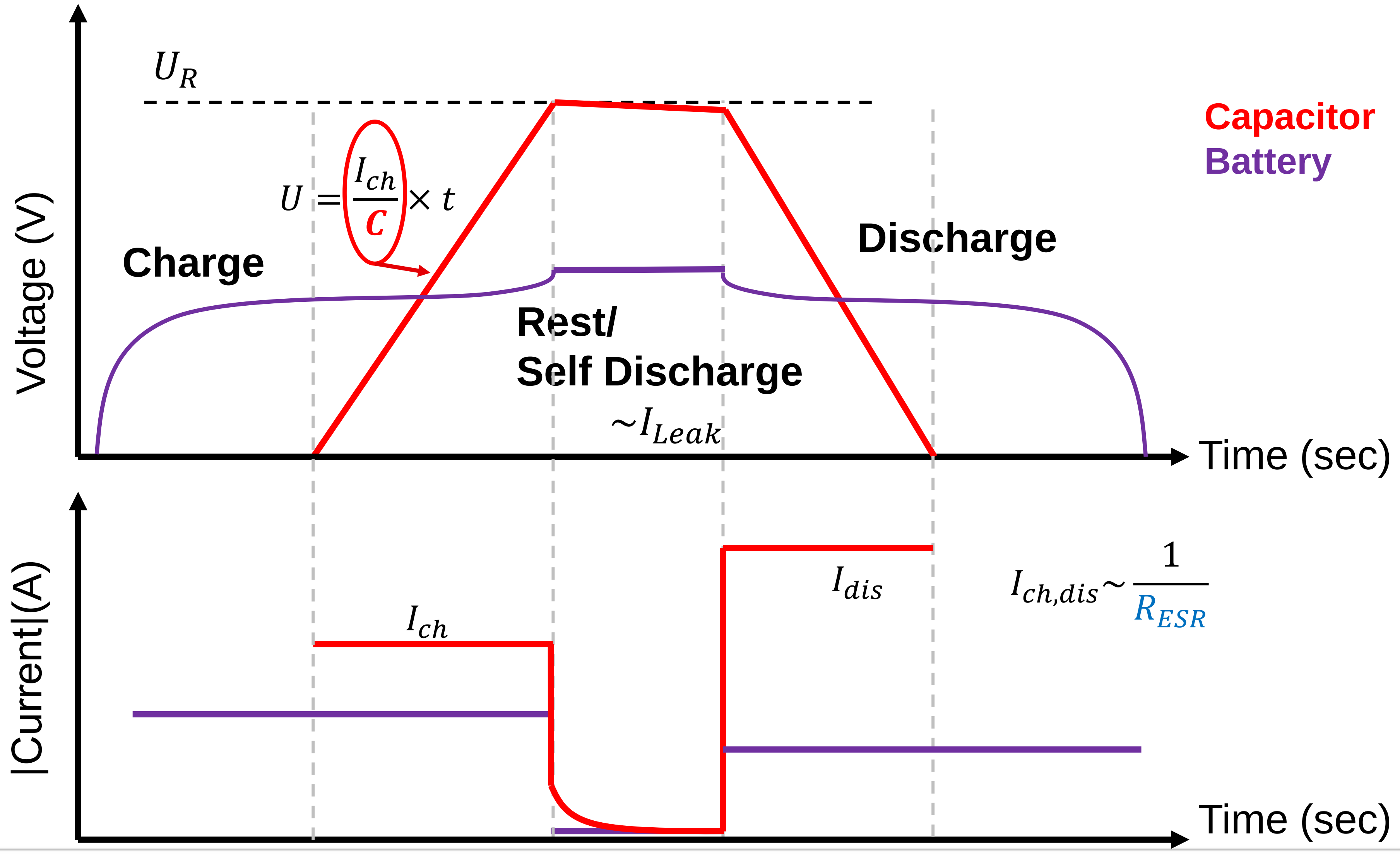
- **Maximum Power output:**

$$P_{max} = \frac{U_r^2}{4\,R_{ESR}}$$

- ***Characteristic R-C Time:***

$$\tau = R_{ESR} \times C$$

Charge and Discharge Behavior



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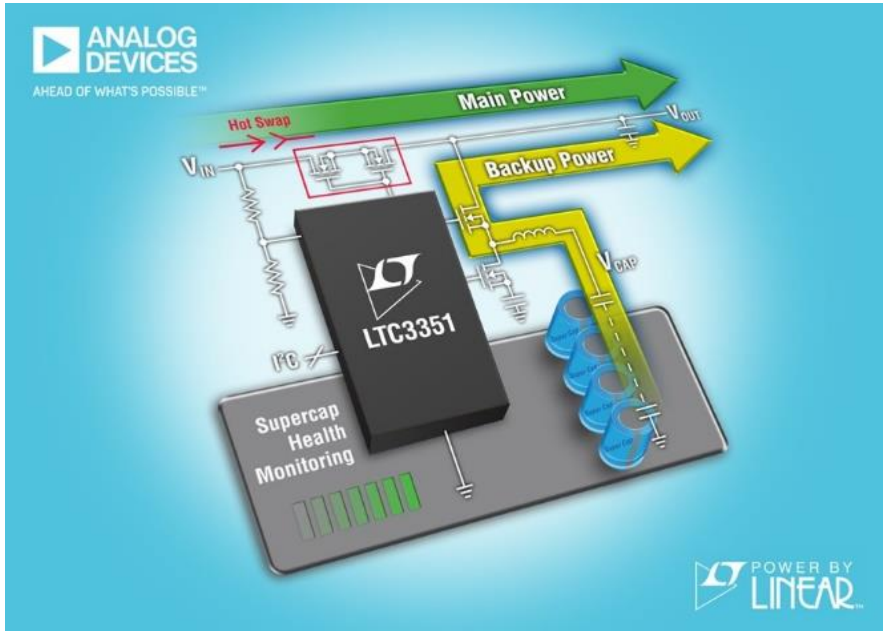
LT3551 – Overview

- **Hot Swappable Supercapacitor Backup Solution**

- **WE want 30W for 15sec. (12V @ 2.5A) at the output**

- **Why we use LT3551?**
  - Integrated hot swap controller with circuit breaker
  - High efficiency synchronous step-down CC/CV charging of one to four series Supercapacitors
  - Step-up mode in backup provides greater utilization of stored energy in Supercapacitors
  - 16-bit ADC for monitoring system voltages/currents, capacitance, and ESR
  - Contains an I2C/SMBus compatible port allows communication with the LTC3351 for configuration and reading back telemetry data



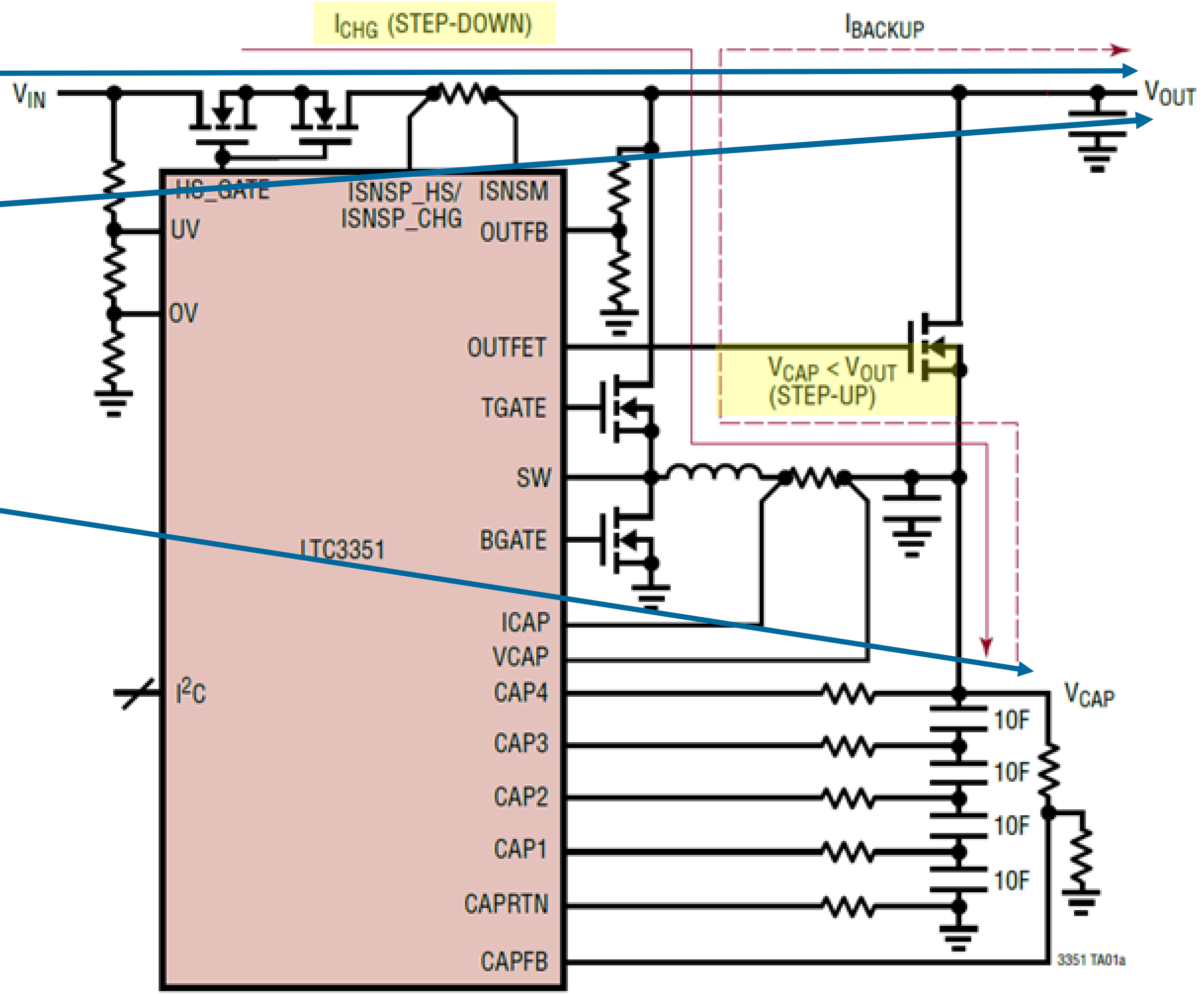
What is Hot Swap / Hot Plug

- **Hot Swapping**
  - Replacing or adding components
  - No shutdown or stopping of the running system
  - No interruption to the system
  - Pre-Charging thru special pins
  - Current limiter or soft start can protect the circuit

- **Hot Plug**
  - Hot plugging describes only the addition of components that would expand the system
  - No significant interruption to the system

Specification of the Application

- **24V input to output rail**
- **Step-Up mode V_{out}**
  - V_{out} = 12 V
- **Step-Down mode V_{CAP}**
  - 4 Supercapacitors
  - V_{CAP} = 10.6 V
- **No direct supply from V_{CAP}**
  - $V_{CAP} < V_{out}$
- **f_{sw}**
  - 450 kHz
- **Input current limit**
  - I_{max_charge} = 2,5 A
- **Constant Power Discharge**
- **Supply the load and charge the Supercapacitor**



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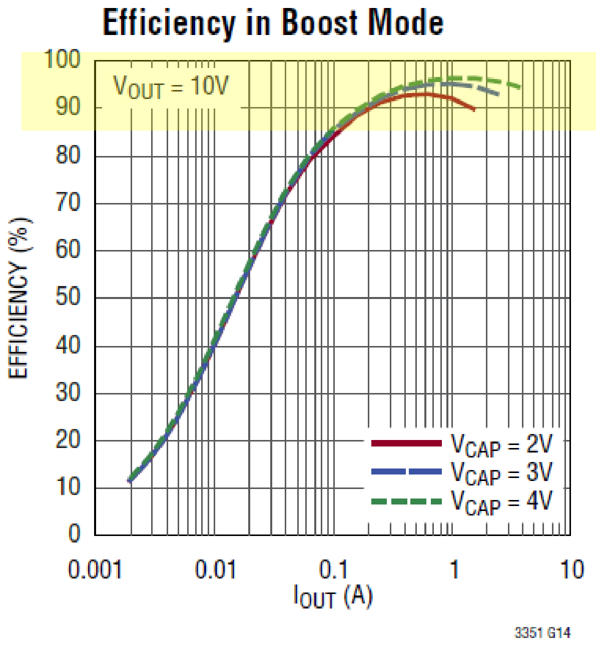
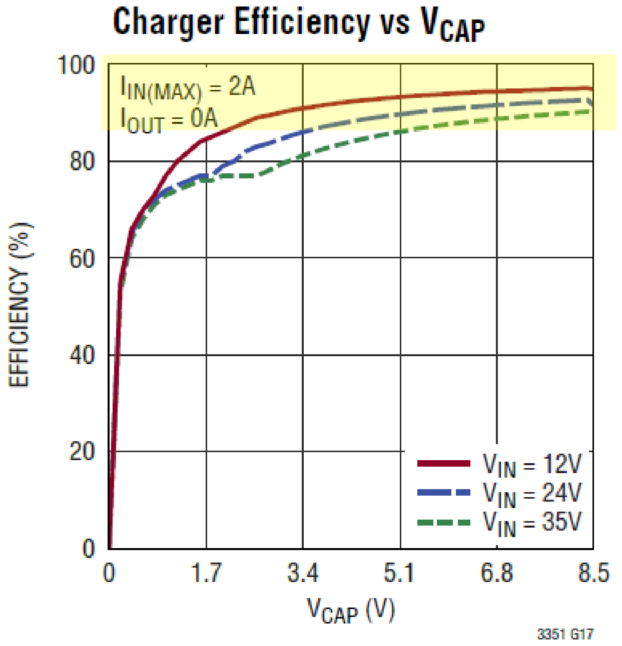
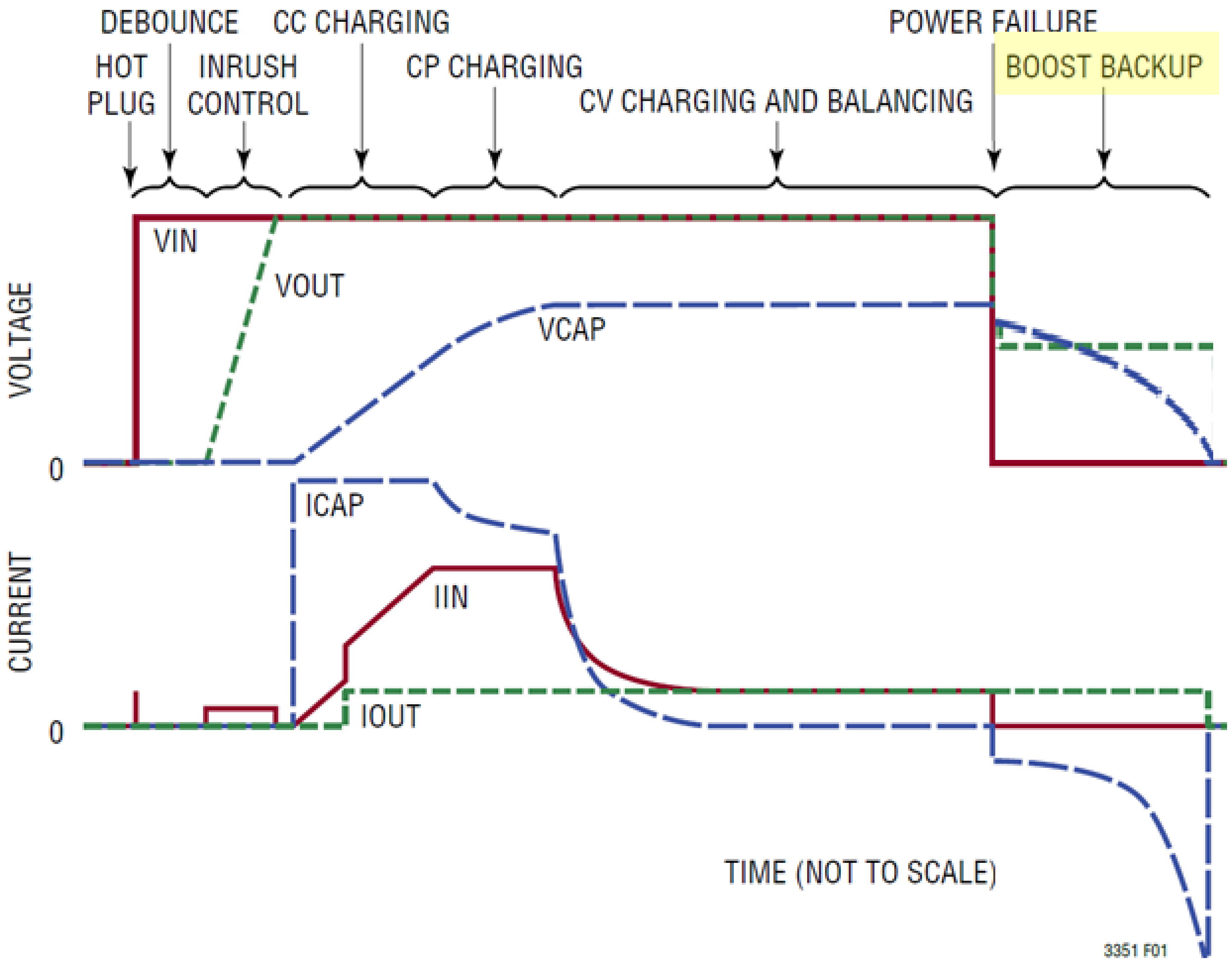




LT3351 Hot Swap / Hot Plug



How to Choose the Supercapacitor

SN009a EN

- **Backup is defined due to the application**

- **The four steps of design-in**
  - Choose the mode of discharge
    - Constant Power

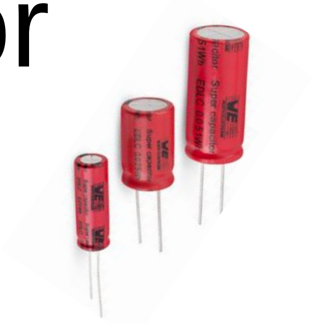
  - Calculate the capacitance (operating time, output power, output current)
    - 30 W => 12 V @ 2.5 A for 15 sec.
    - E = P * t = 30 W * 15 s = 450 J
    - $C = 2 \cdot \frac{E}{V_1^2 - V_2^2} = 2 \cdot \frac{450\ J}{10.6\ V^2 - 2 V^2} = 4.2\ F$

  - Identify the suitable charging process
    - Constant Current, Constant Power and Constant Voltage

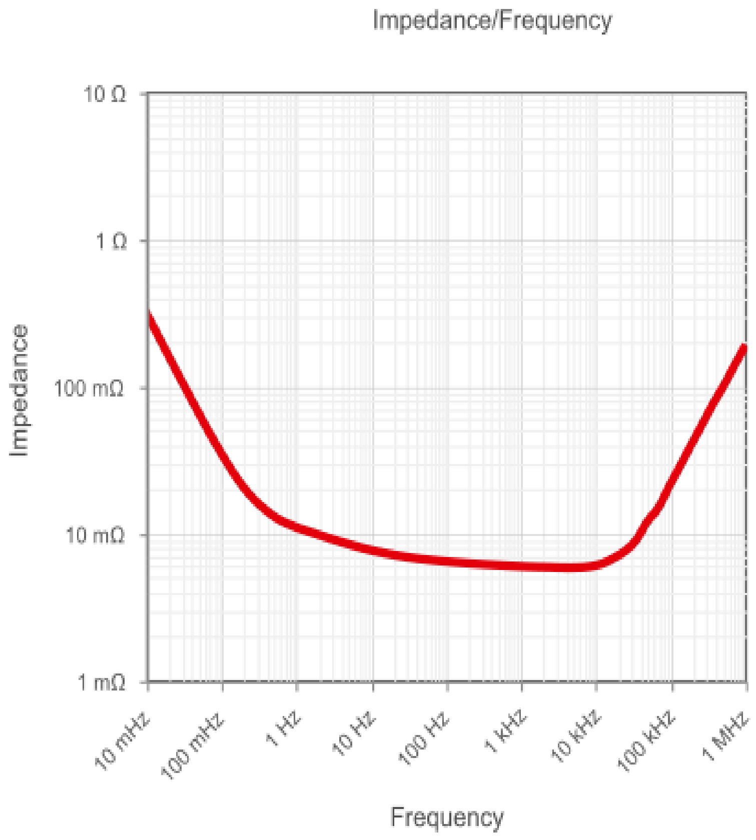
  - Calculate charging current
    - Highest possible current for the LTC3351 => 6,4A

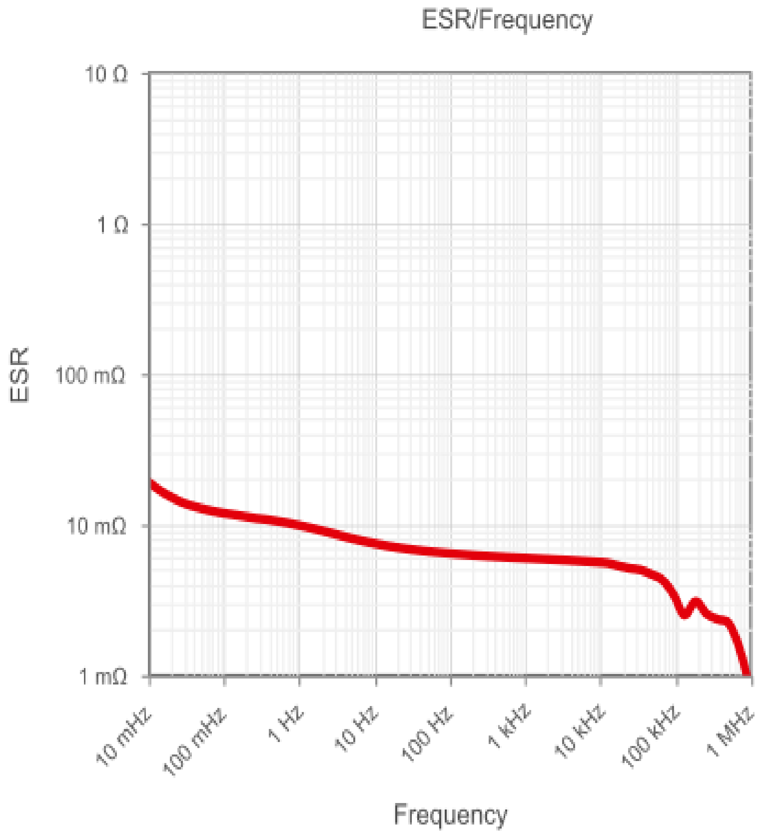
SN009a EN => https://weshare.we-group.com/departments/productmanagement/eiCap/AppNotes/SN009a%20EN.pdf

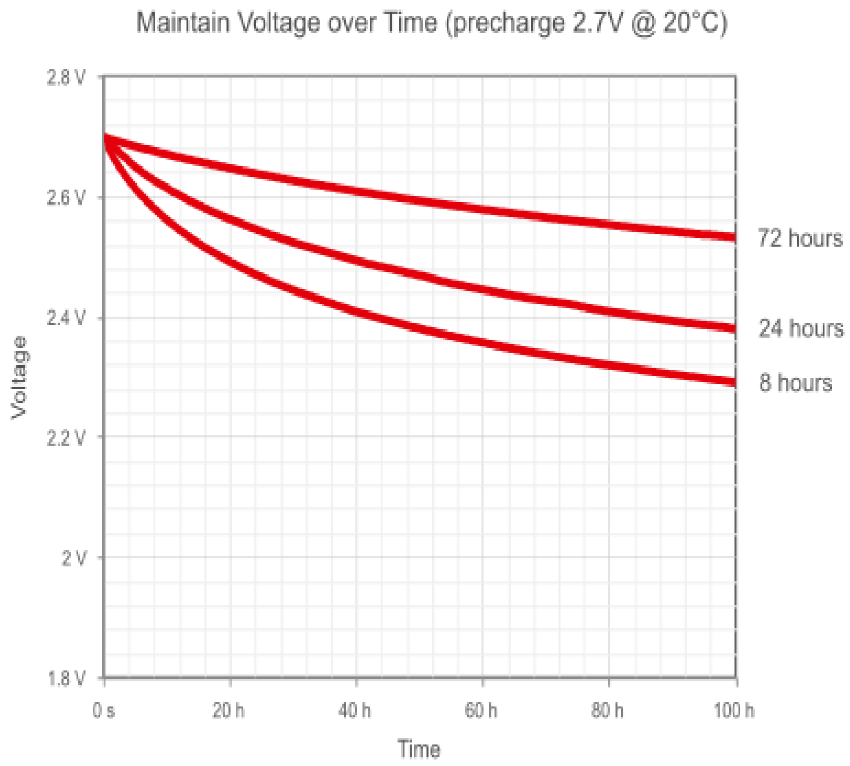
Choosing the right Supercapacitor



- **WE** **use 50F / 2.7V Supercapacitor radial type 850617022002**







Supercapacitor Bank

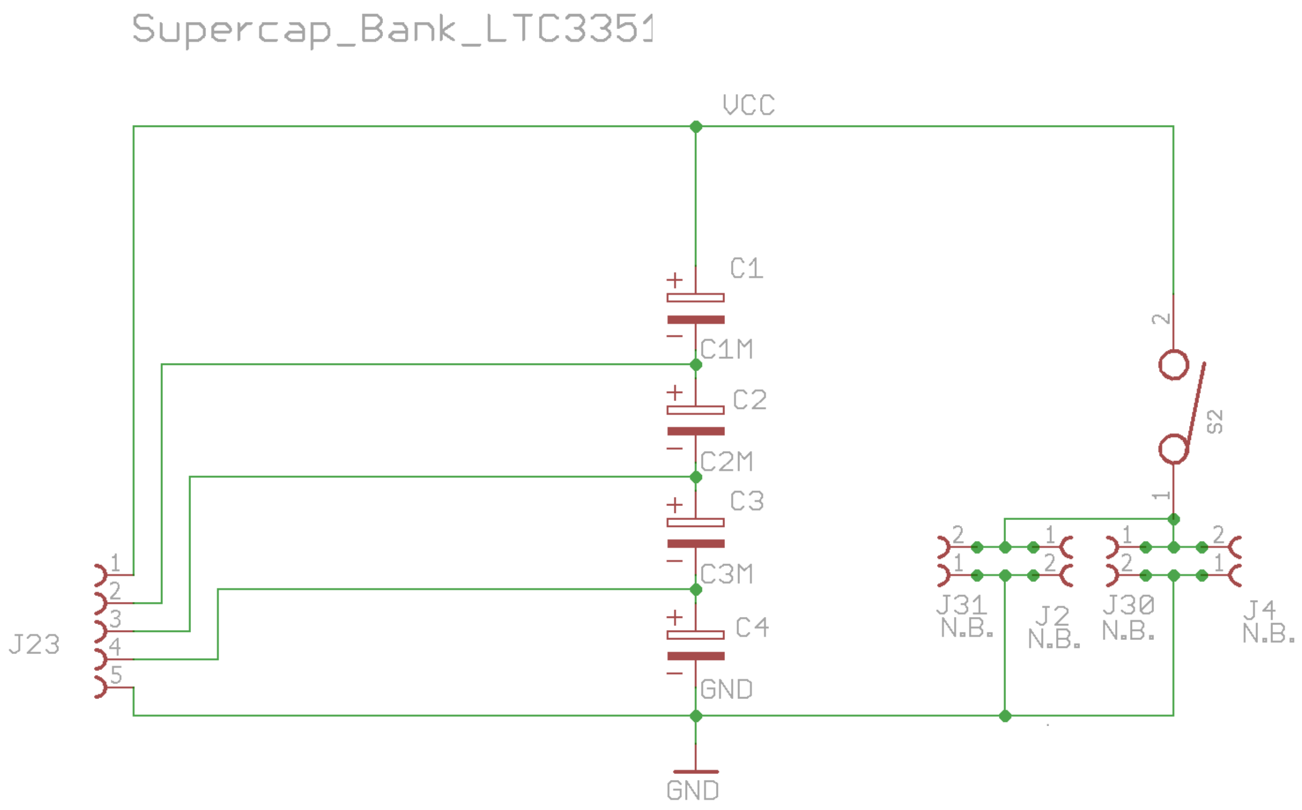
- **4 Supercapacitors in series connection**

- **$E_{total} = ½ * C_{total} * U_{VCAP}^2$**
  - C_{total} = 12,5 F
  - U_{VCAP} = 10.6 V
  - ⇒ E_{total} = 702.25 J

- **Max. Power = U_r^2 / 4 * (4 * ESR)**
  - **V_{CAP} = 10.6 V**
  - **ESR for one Supercapacitor = 2.23 mR**
  - **Max. Power = 3053 W**

- **No balancing on board required**
  - LTC3351 integrated active stack balancer

- **Additional circuitry is for discharging the bank**



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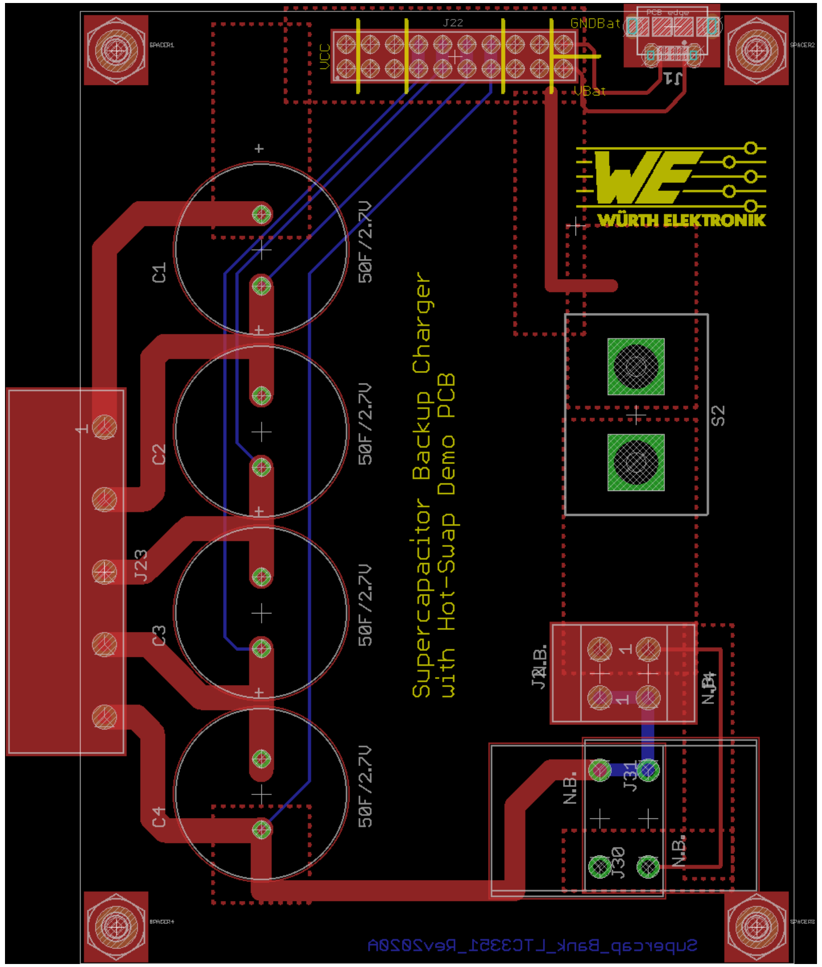
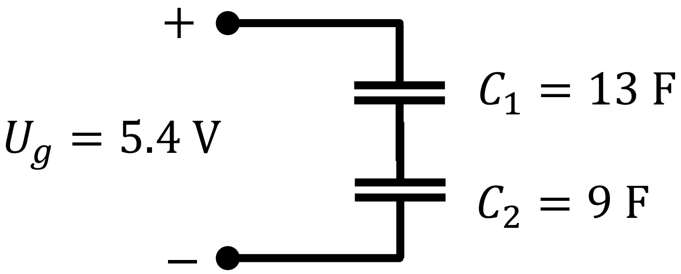


Balancing of Supercapacitor

- **Worst Case Example:**
  - Two in series connected capacitors with a rated capacitance of 10 F (tol.: -10%, +30%)
  - Rated voltage of 2.7 V are charged at 5.4 V

- **Following equations are need for the calculations:**
  - $\mathrm{U_g} = U_1 + U_2$
  - $U_2 = \frac{q}{C_2}$ and $U_1 = \frac{q}{C_1}$
  - $\rightarrow U_1 = \frac{5.4\ \mathrm{V}}{(1.44+1)} = \mathbf{2.21V}$
  - $\rightarrow U_2 = \frac{5.4\ \mathrm{V}}{\left(\frac{1}{1.44}+1\right)} = \mathbf{3.19V}$ (Caution, Overvoltage!)



Balancing of Supercapacitor

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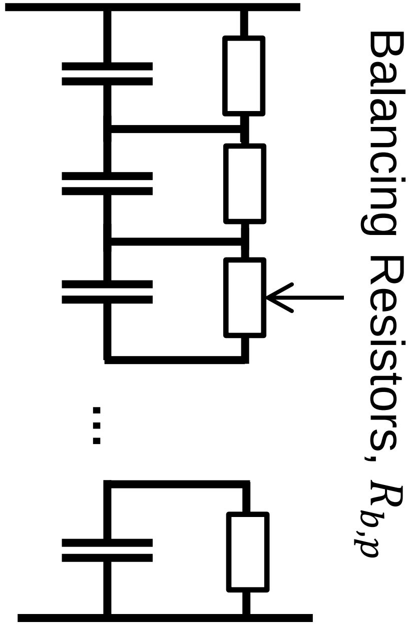
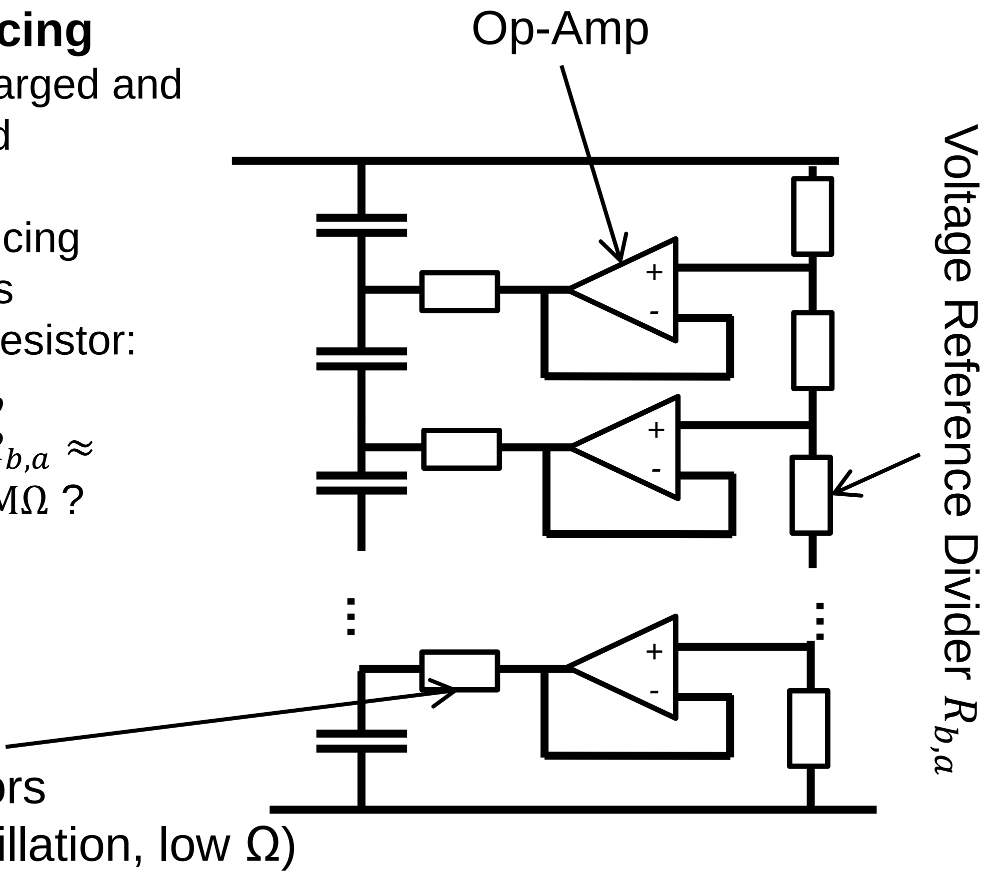
- **Passive Balancing**
  - If operated primarily under DC conditions
  - Low cost
  - Slow balancing
  - High losses
  - Balance Resistor:
    $R_{b,p} \approx \frac{1}{10} \times \frac{U_r}{I_{Leak}}$
  - Typically $R_{b,a} \approx$ 1kΩ … 100kΩ



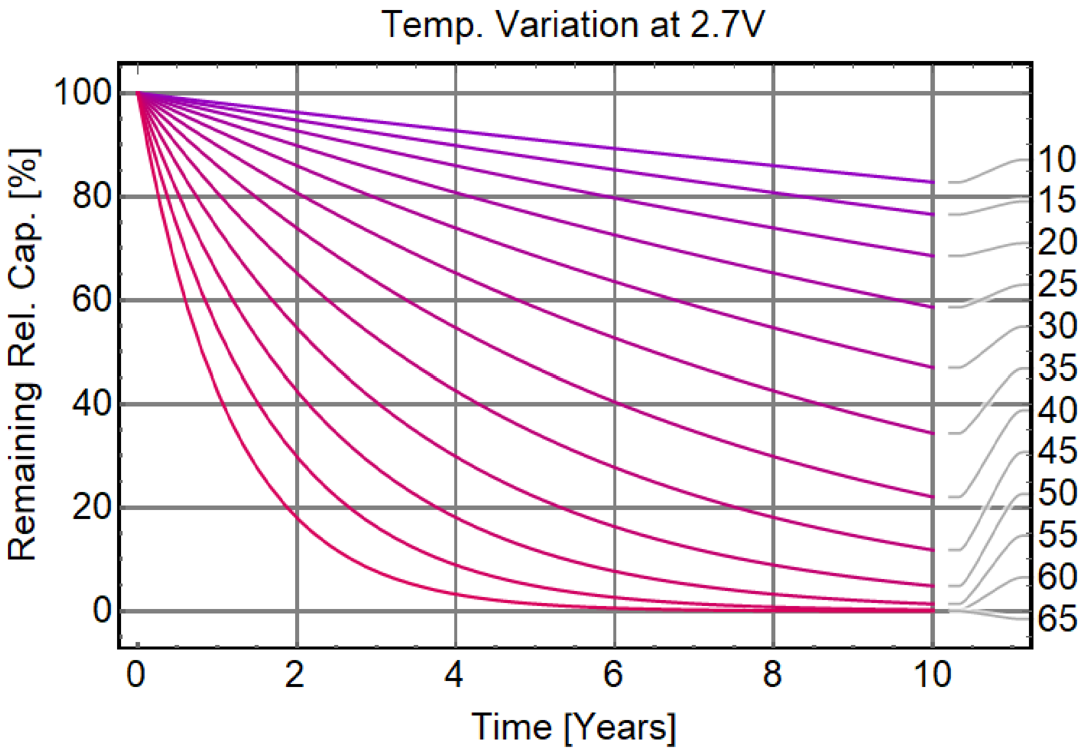
- **Active Balancing**
  - If often charged and discharged
  - High cost
  - Fast balancing
  - Low losses
  - Balance Resistor:
    $R_{b,a} > R_{b,p}$
  - Typically $R_{b,a} \approx$ $1M\Omega$ … 10MΩ ?

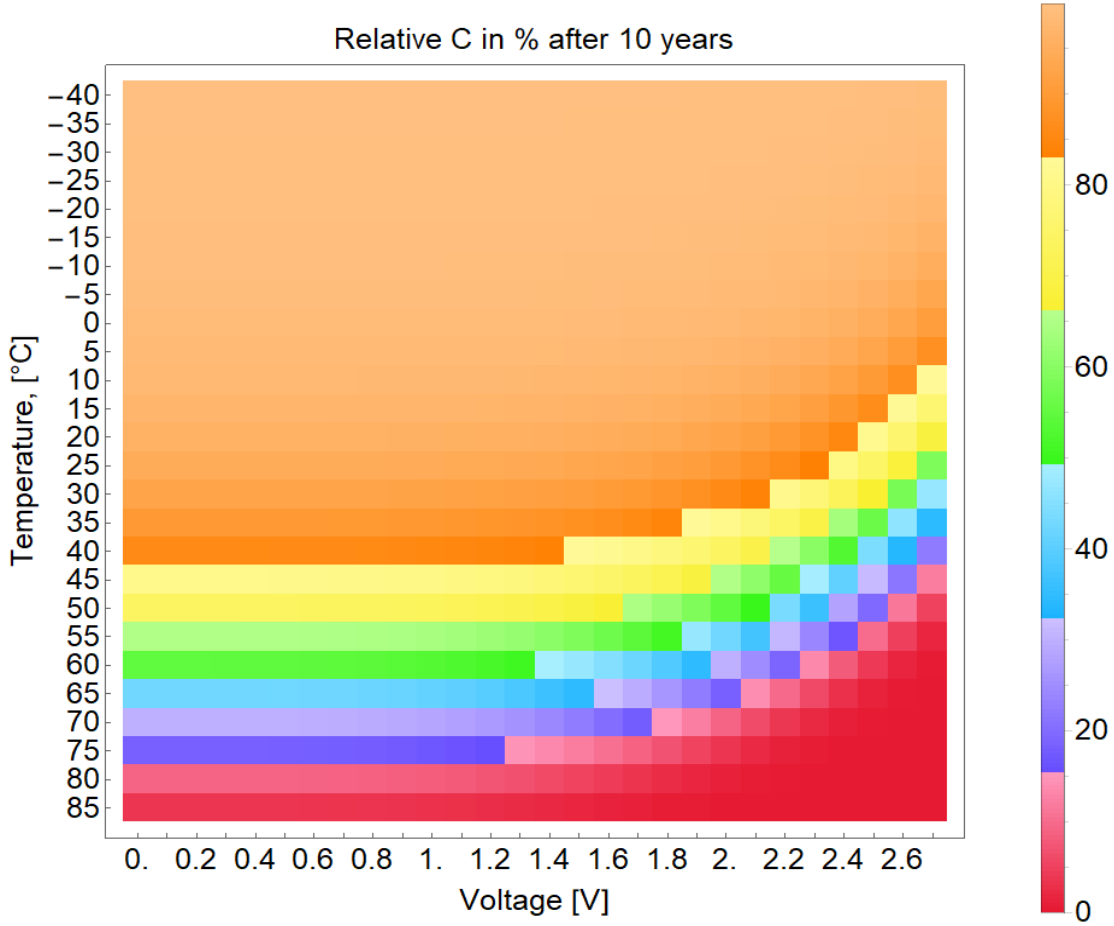


$R_{b,p}$	↓	↑
Balancing Speed	↑	↓
Losses	↑	↓

Lifetime of Supercapacitor

- Supercapacitors lose capacitance as they age
- ESR will rise over the lifetime





Lifetime of Supercapacitor

- **Lifetime for 4 Supercapacitors in series**

- **V_{CAP} = 10.6 V**
  - Voltage on a single cell => 2,65 V

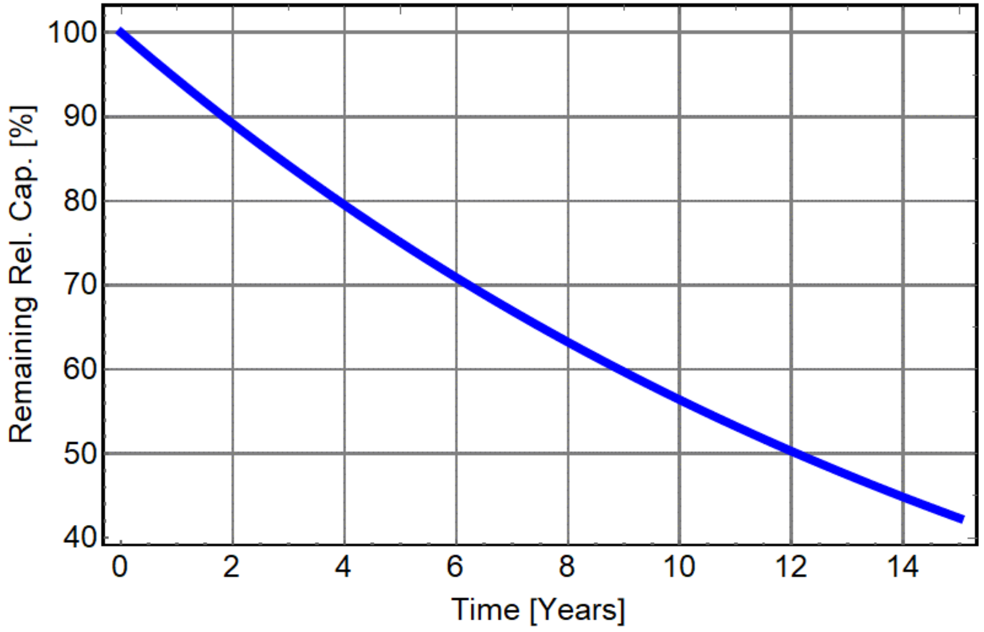
- **Defined Mission Profile**
  - Max. Temp = 40 °C
  - Max. Voltage = 2.65 V

- **We use 4 * 50 F Supercapacitors in series**
  - C_{total} = 12,5 F
  - With a tolerance of -10% => C_{total} = 11.25 F

- **After 12 years => C_{total} = 5.6 F**
  - Calculated capacitance 4.2 F
  - Lifetime definition -30% capacitance and 2x ESR

- **Lifetime depends on voltage and temperature**
- **Current increases self heating**

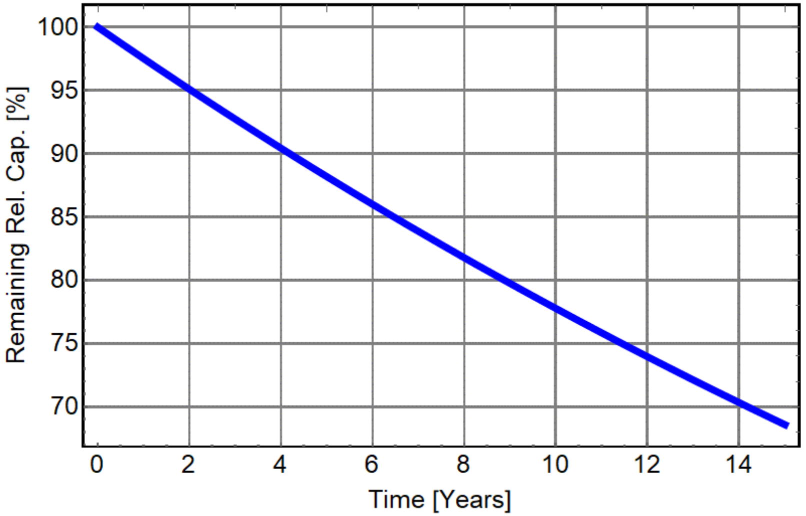
Mission Profile			
Time [h]	Temp. [°C]	Voltage [V]	Model
10	40	2.65	DC Voltage Model
2	40	1.	DC Voltage Model
6	25	0	DC Voltage Model
6	25	0	DC Voltage Model



Lifetime of Supercapacitor

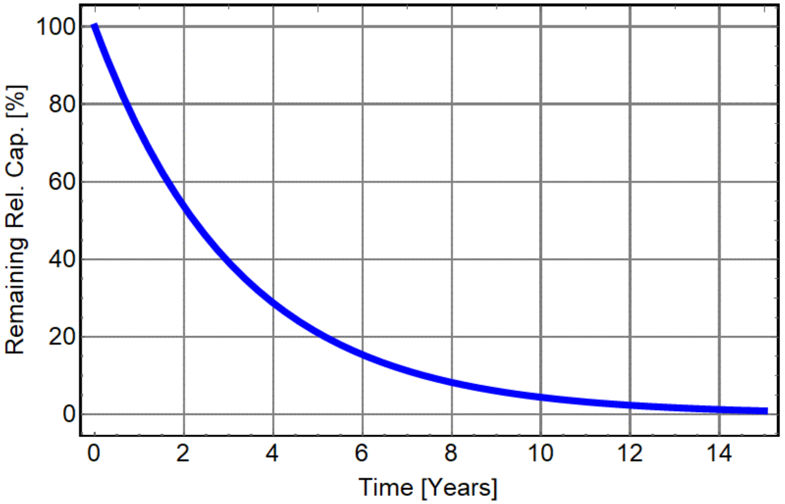
- **Same Mission Profile**
- **Different cell voltage with 2.3 V**

Mission Profile			
Time [h]	Temp. [°C]	Voltage [V]	Model
10	40	2.3	DC Voltage Model
2	40	1.	DC Voltage Model
6	25	0	DC Voltage Model
6	25	0	DC Voltage Model

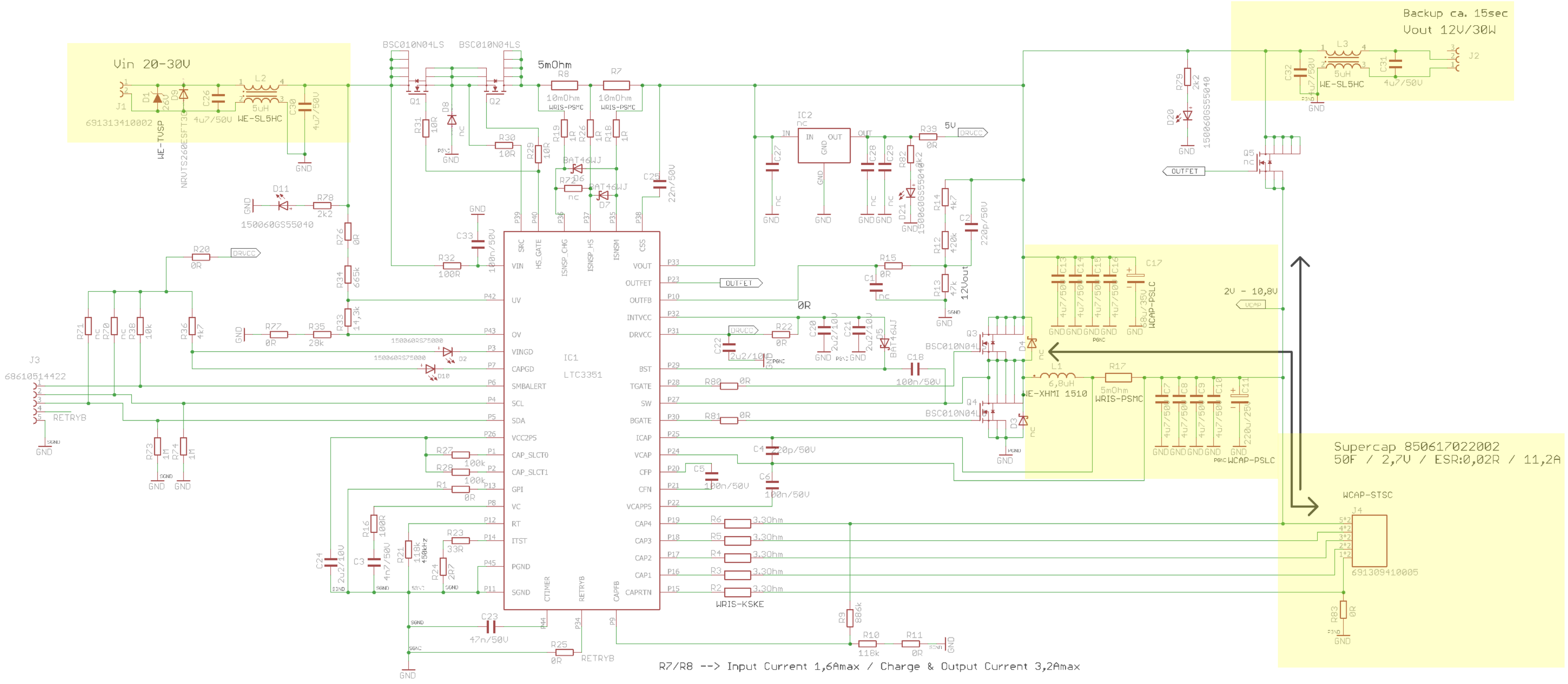


- **Same Mission Profile**
- **Different temperature at the Supercapacitor with 65 °C**

Mission Profile			
Time [h]	Temp. [°C]	Voltage [V]	Model
10	65	2.65	DC Voltage Model
2	65	1.	DC Voltage Model
6	25	0	DC Voltage Model
6	25	0	DC Voltage Model



Backup Solution



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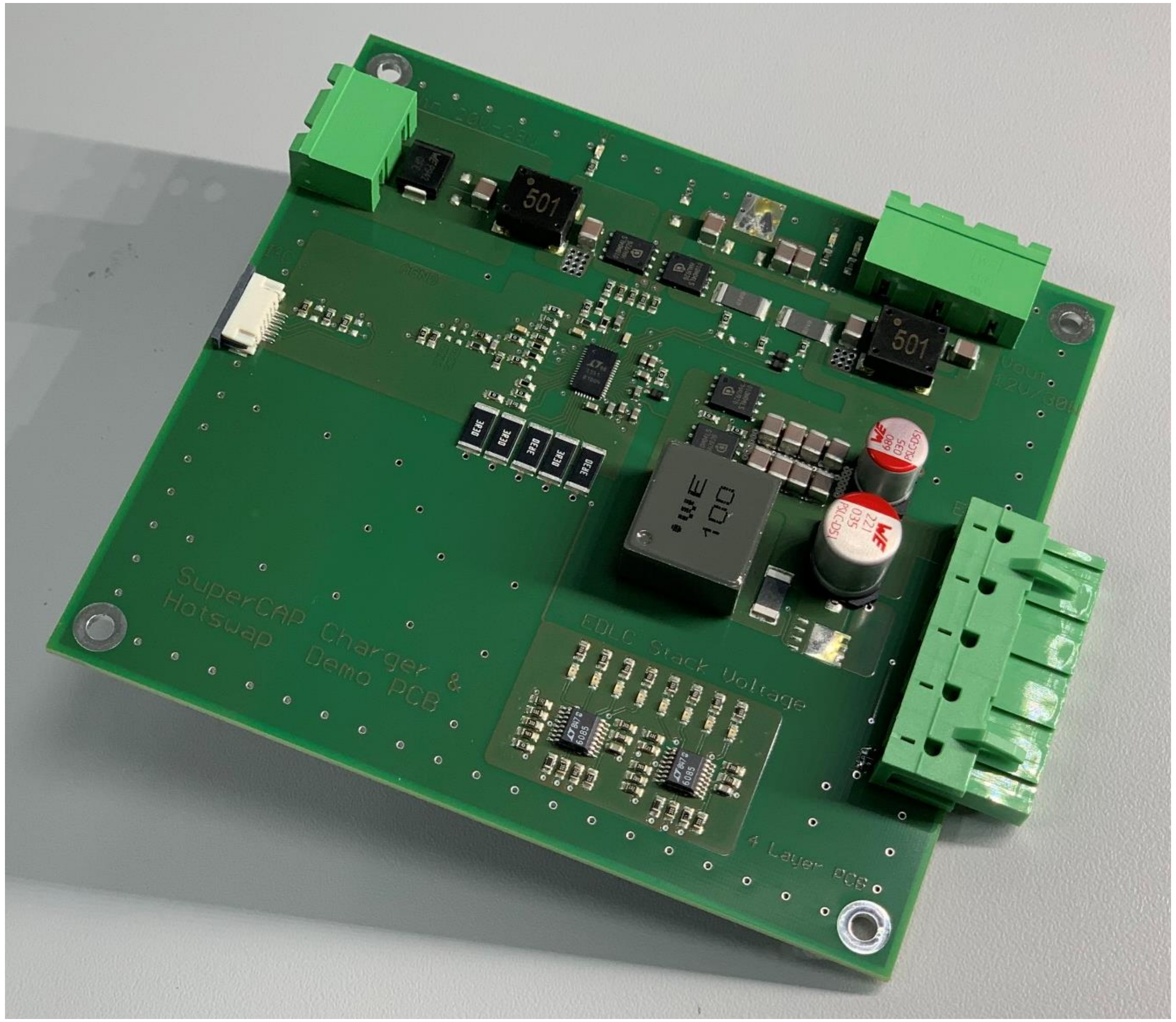
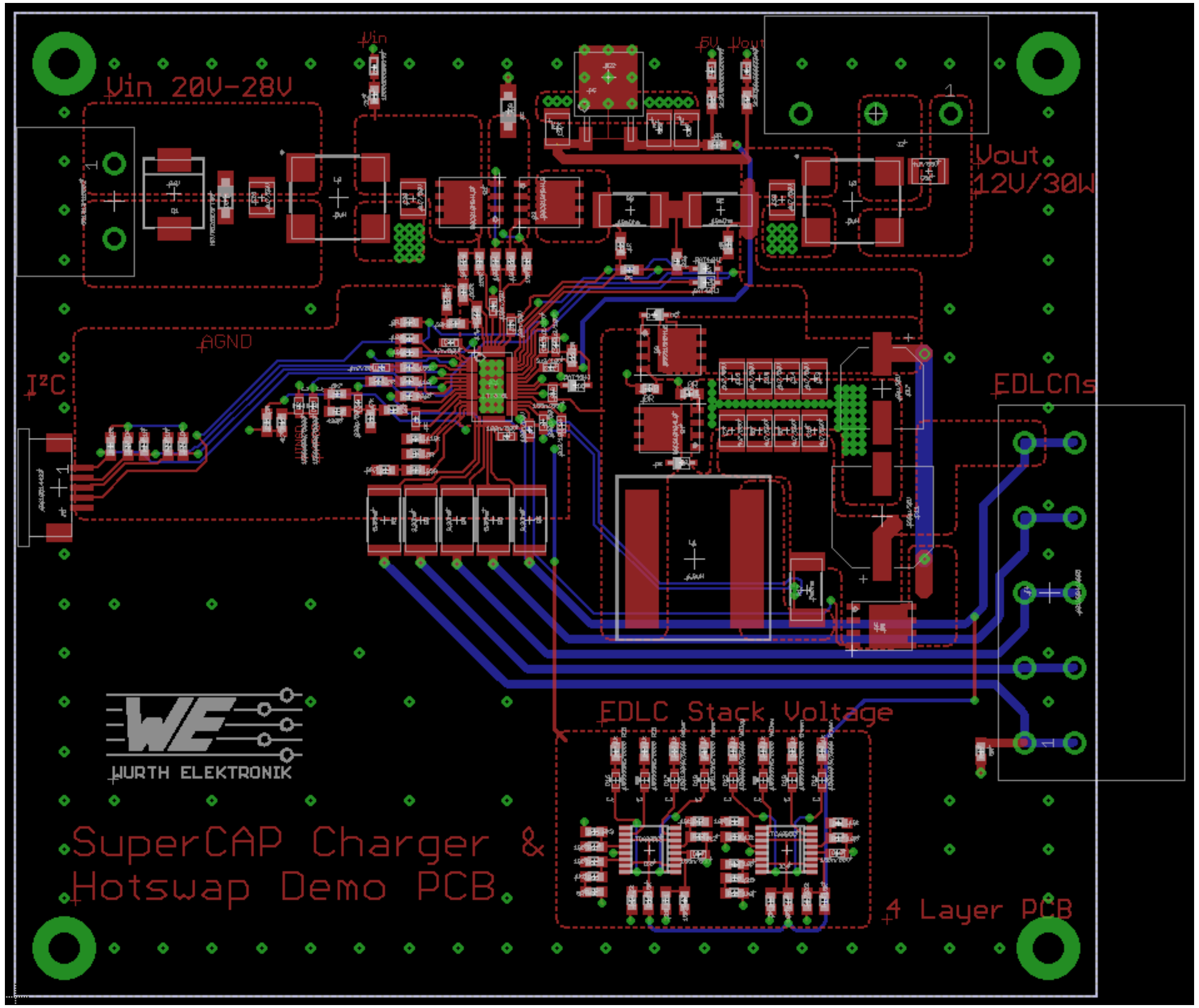
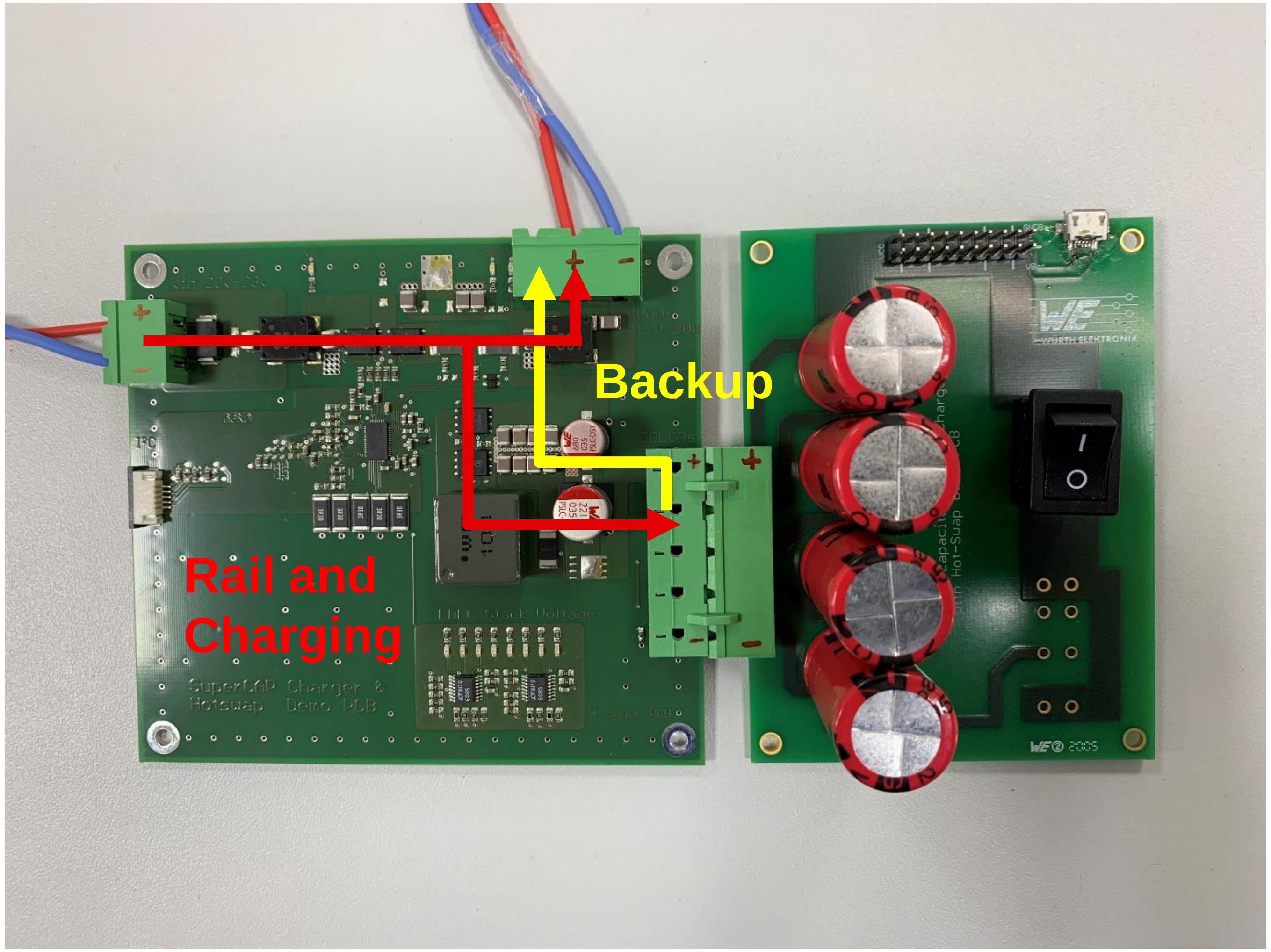
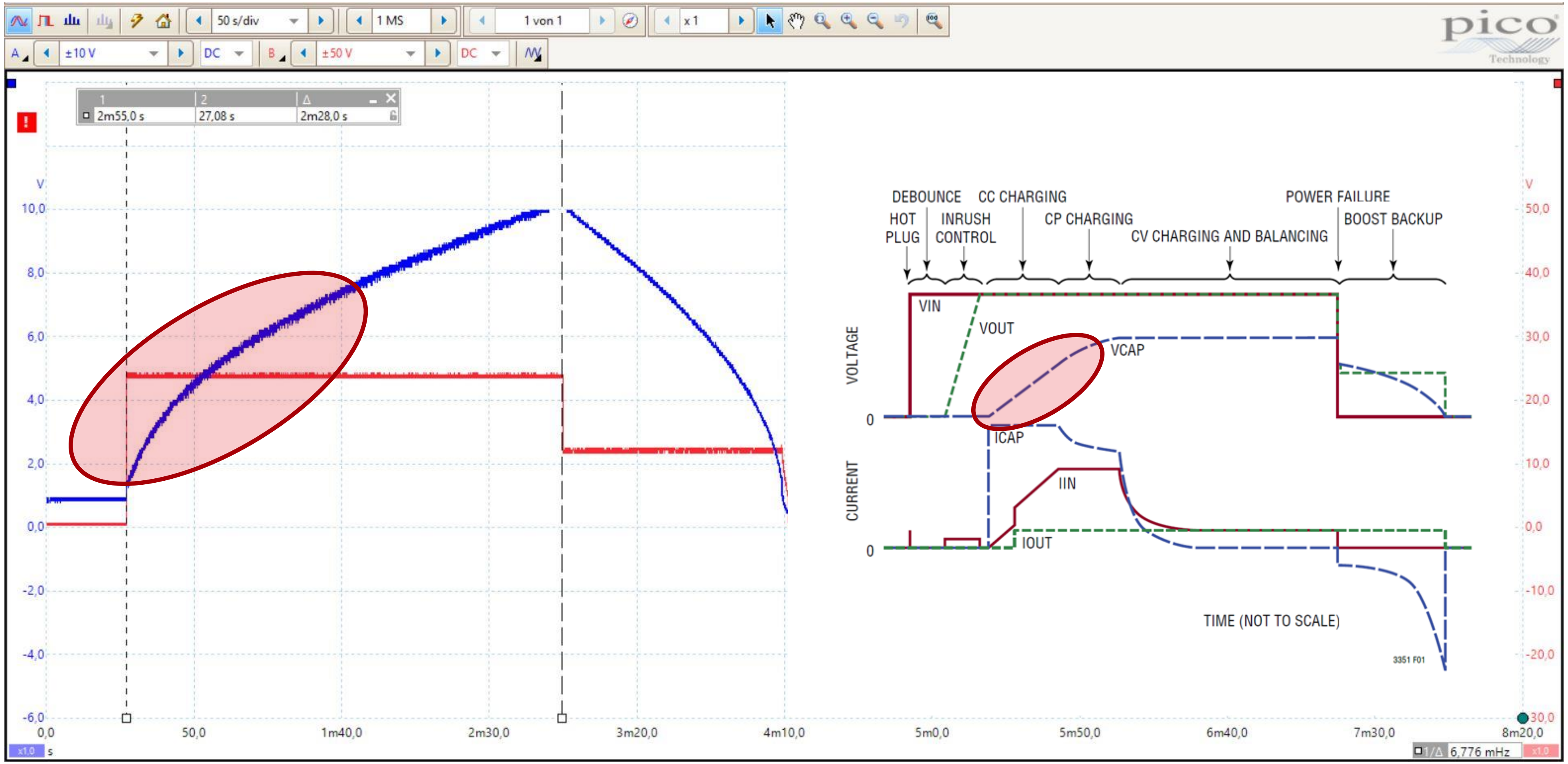




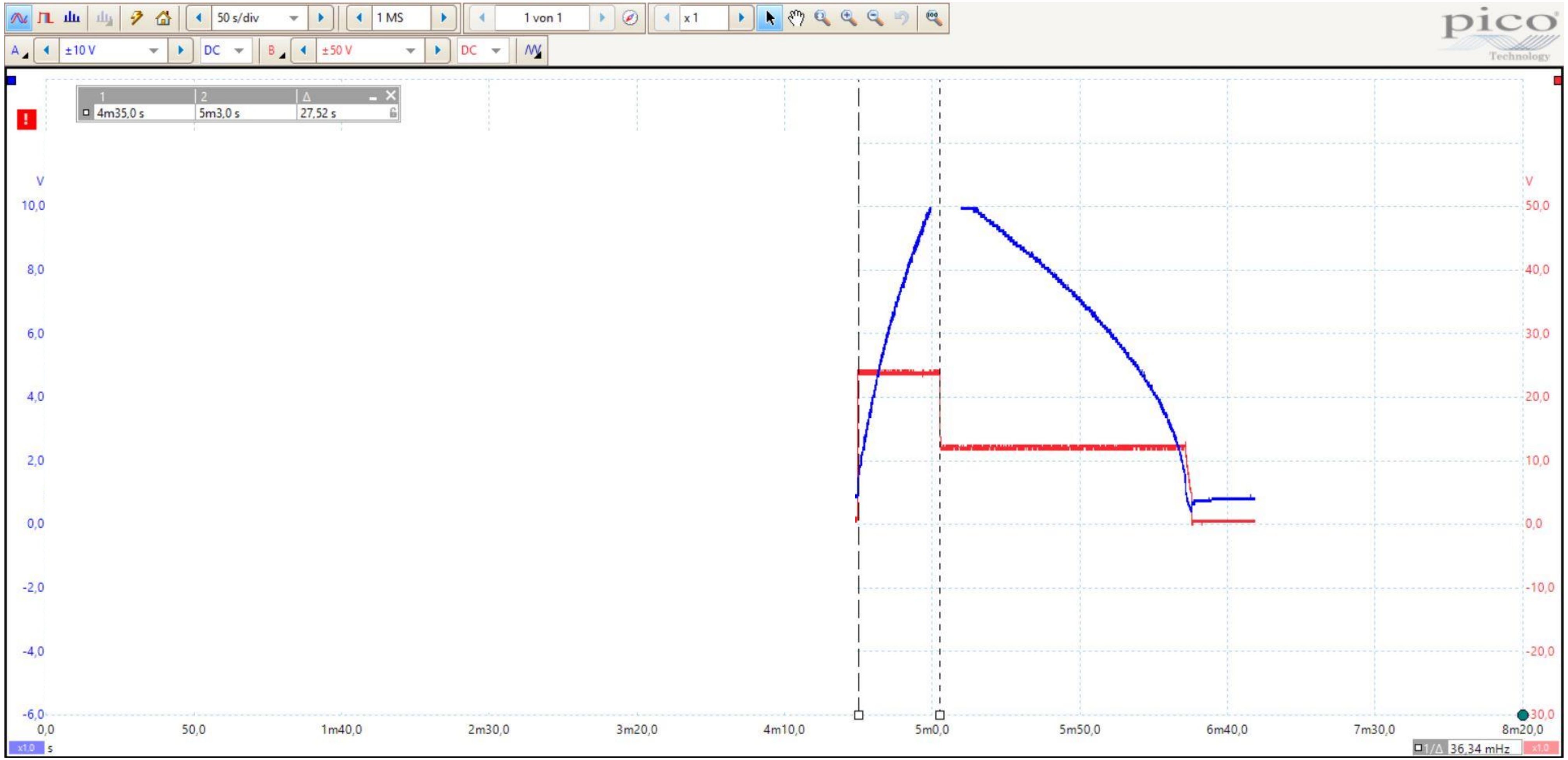
Backup Solution Real World



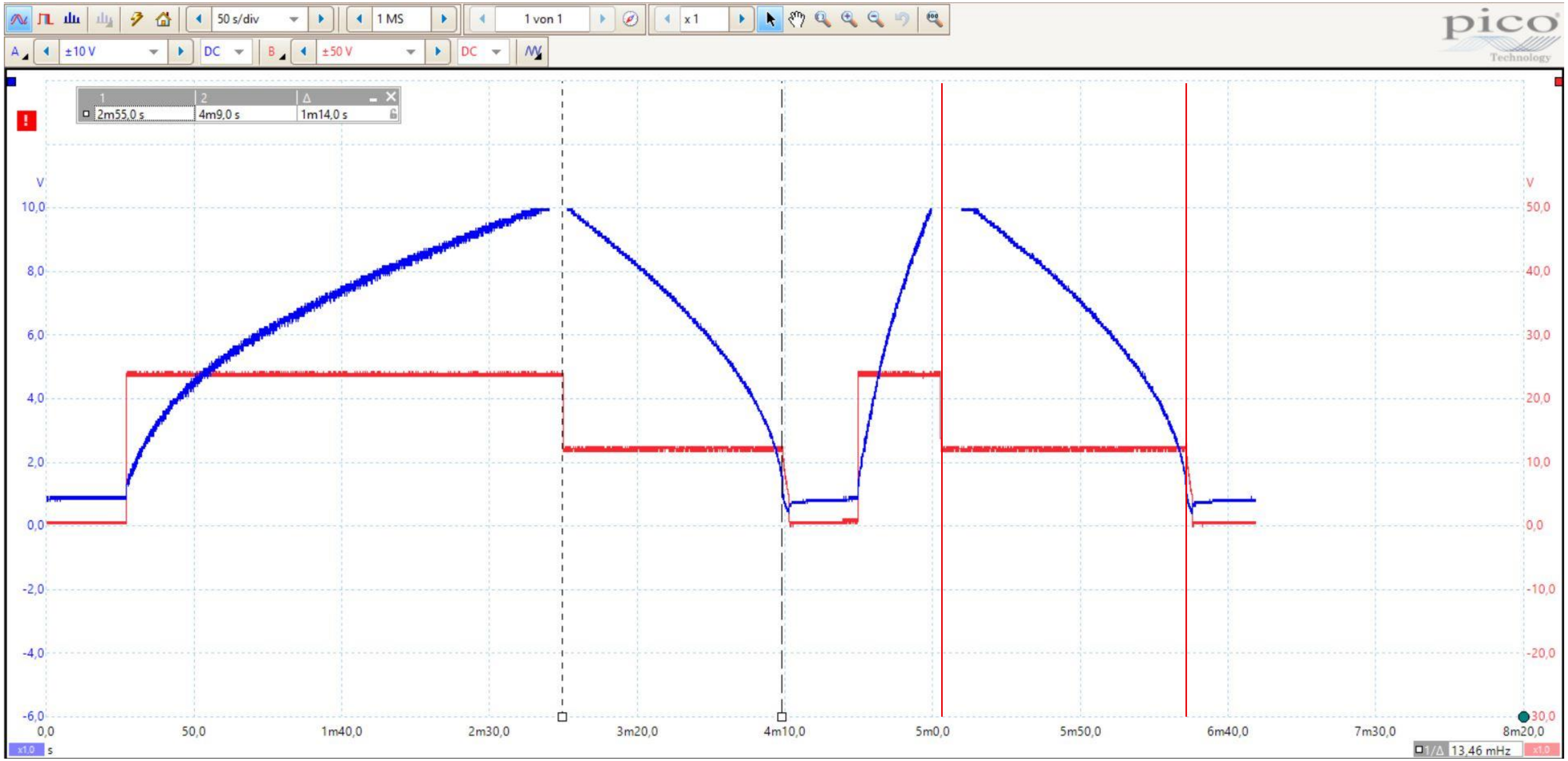
Performance Charging with Load



Performance Charging without Load



Performance Charging / Discharging



Design and Application Review

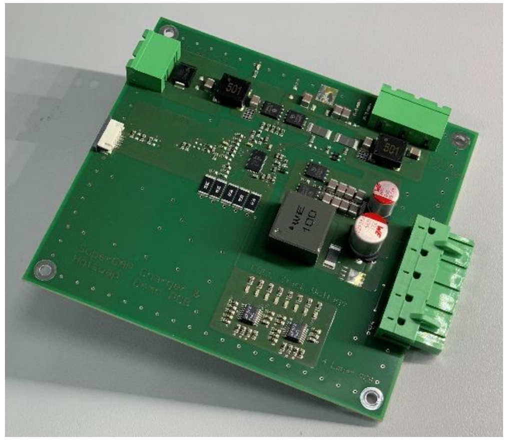
- **Backup Solution with a size of 10 cm x 18.5 cm**
  - 3.94 inch x 7.3 inch

- **Vin 24V and Backup voltage 12 V**
- **Output Power 30 W => 12 V @ 2.5 A**

- **Eval-Board and Software for LTC3351 available**

- **Support Note for Design-In Process**
- **Application Note for the whole Process**
- **Currently working on a Supercapacitor Bank Calculation Tool**

- **WE support you in your Design**



Questions?

Thanks for your attention!