ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Power Electronic Systems Laboratory

Energy Storage For Mechatronic Energy Harvesting System

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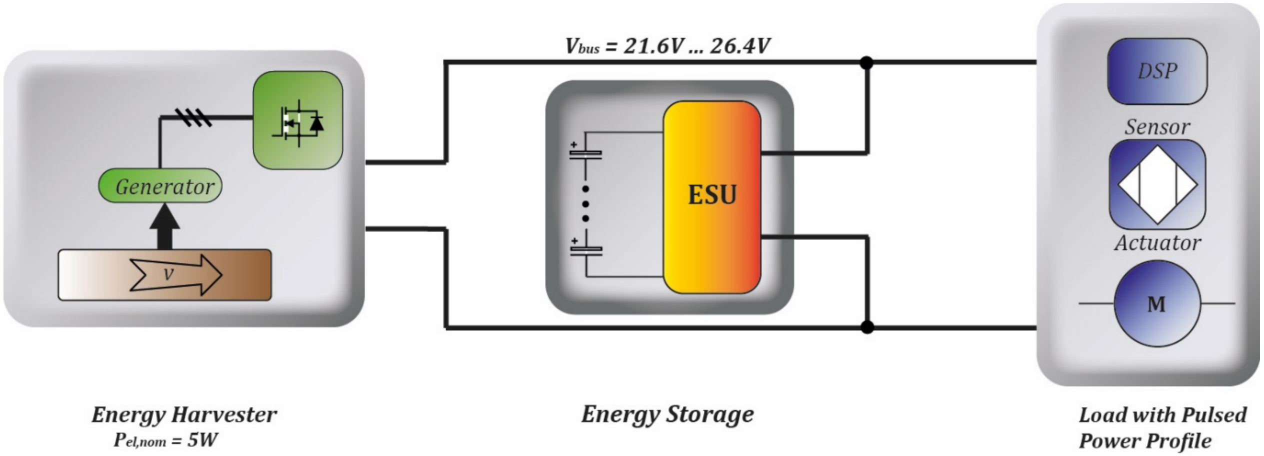
Agenda

1. **Storage Unit Optimization**
2. **Inductor Selection**
3. **Hardware Implementation**
4. **Control Scheme**
5. **Experimental results**
6. **Conclusions and Outlook**

Overview of the System



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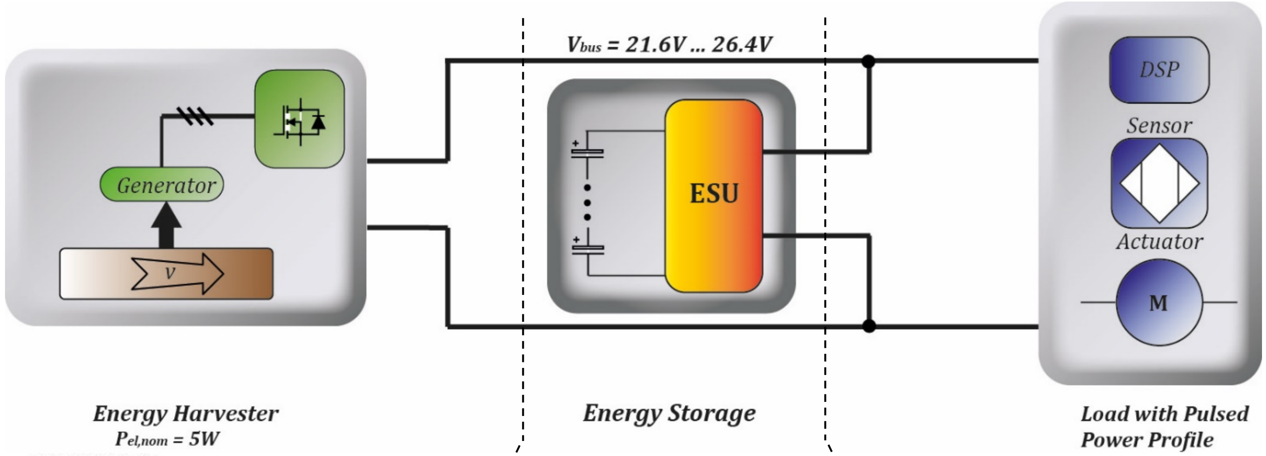

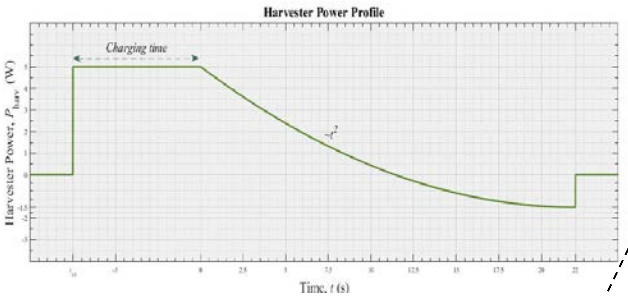

Harvester

$$P_{harv} = \begin{cases} 5\ W, & -t_{charge} \leq t \leq 0 \\ 6.5 \cdot \left(1 - \frac{t}{22}\right)^2 - 1.5, & 0 \leq t \leq 22 \end{cases}$$

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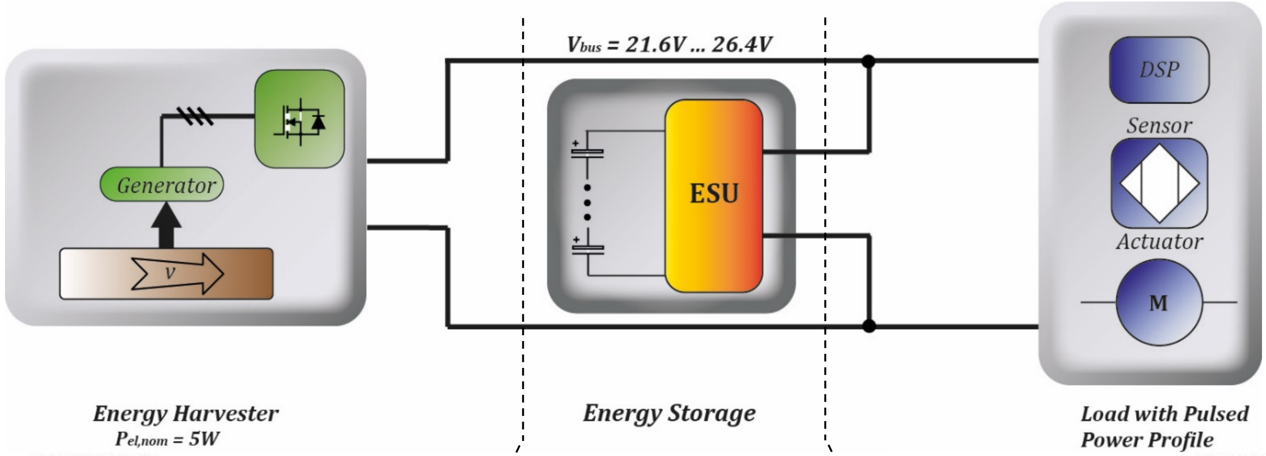

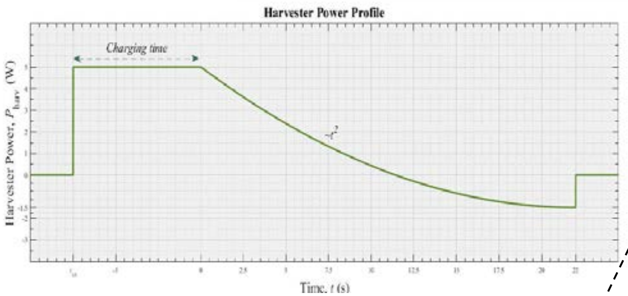

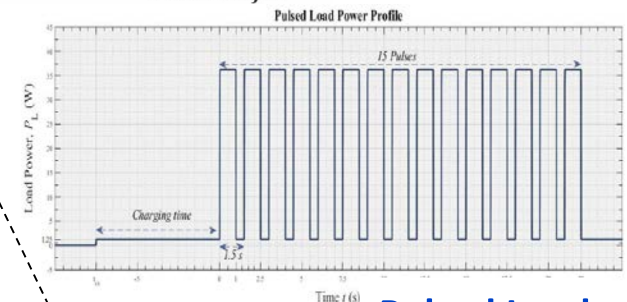

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Pulsed Load

$$P_{\mathrm{L}} = \begin{cases} 1.25\,W, & -t_{ch} \leq t \leq 0 \\ 35 \cdot rect(t) + 1.25, & 0 \leq t \leq 22 \end{cases}$$

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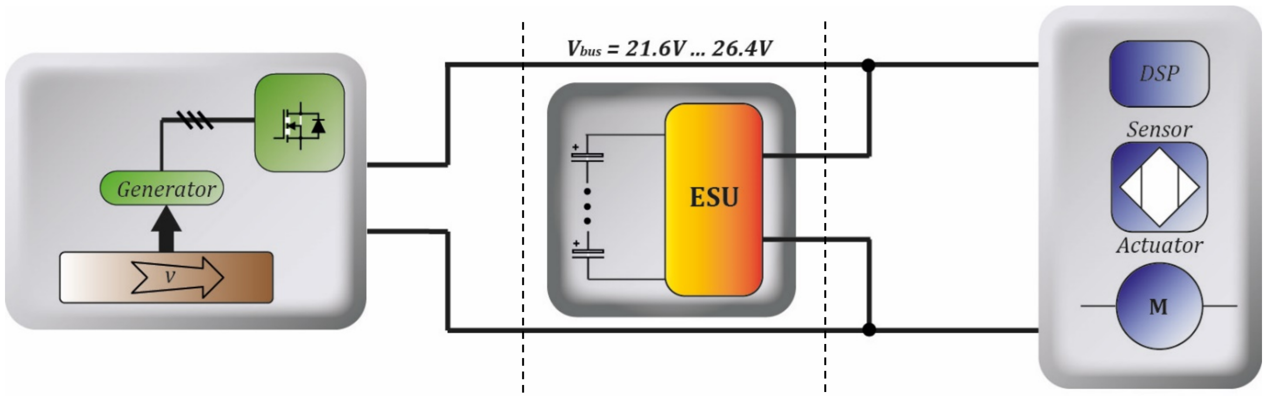
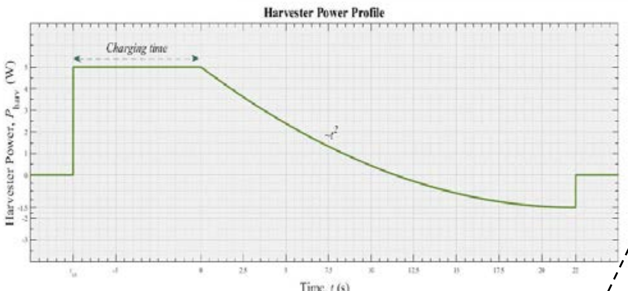


Energy Harvester
$P_{el,nom} = 5W$

Energy Storage

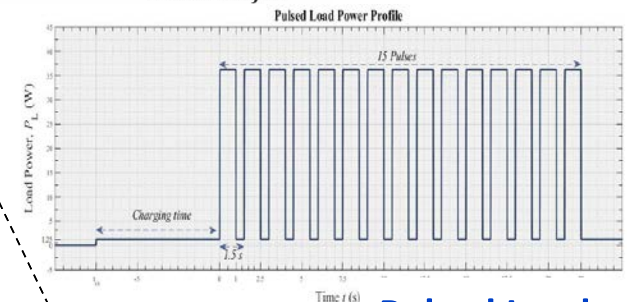
Load with Pulsed Power Profile



Energy Storage Unit

$$P_{store} = P_{load} - P_{harvester} =$$

$$\begin{cases} -3.75\ W, & -t_{ch} \le t \le 0 \\ 35 \cdot rect(t) - 6.5 \cdot \left(1 - \frac{t}{22}\right)^2 + 2.75, & 0 \le t \le 22 \end{cases}$$



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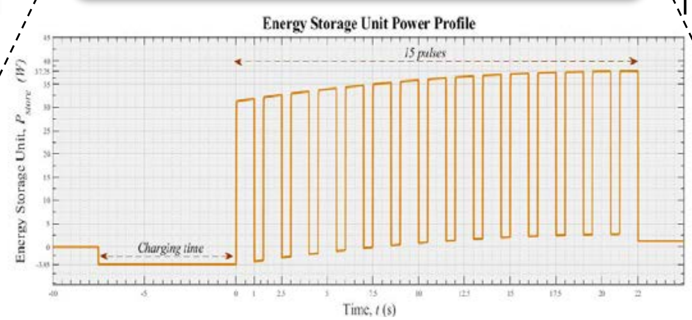
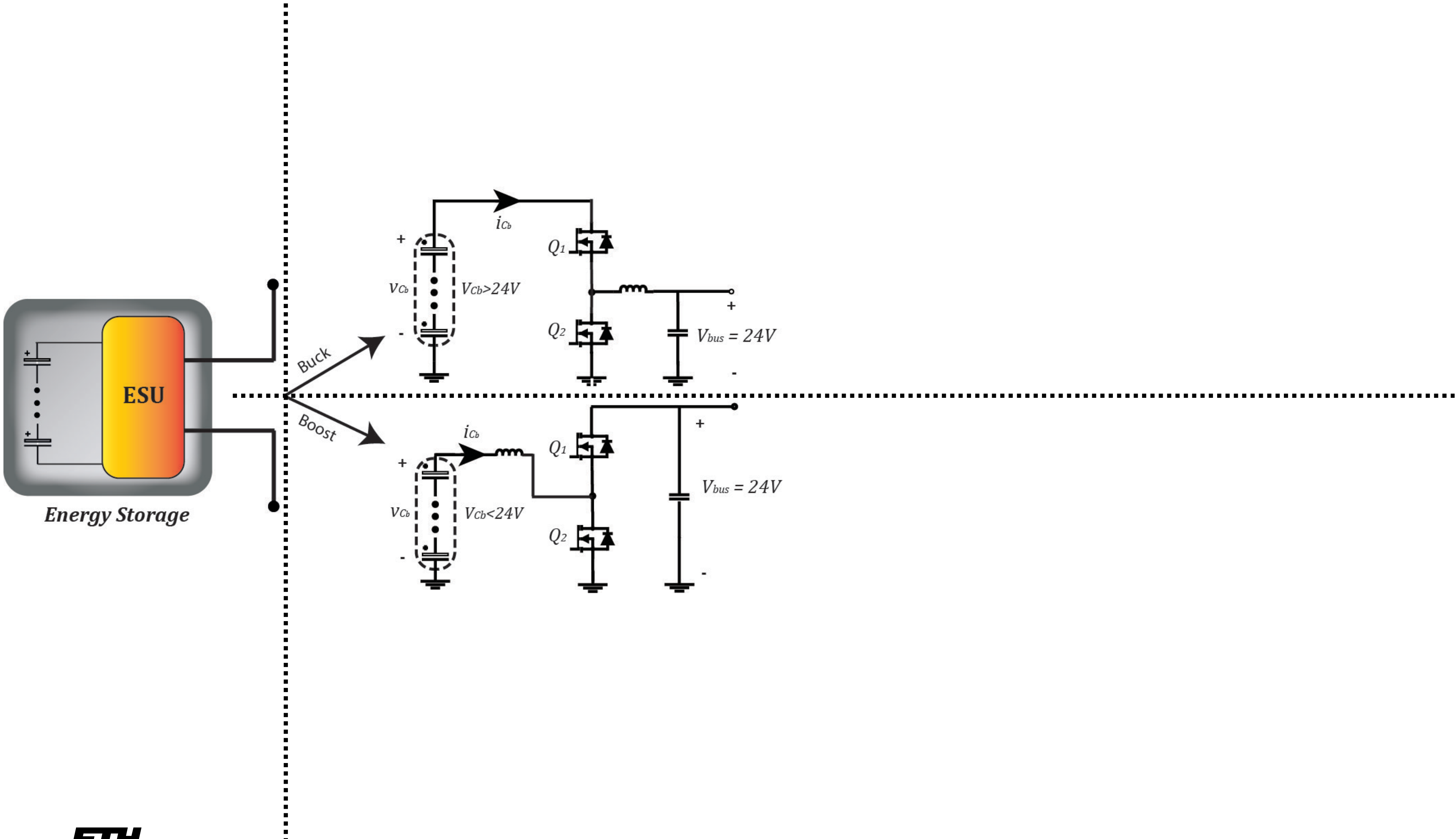


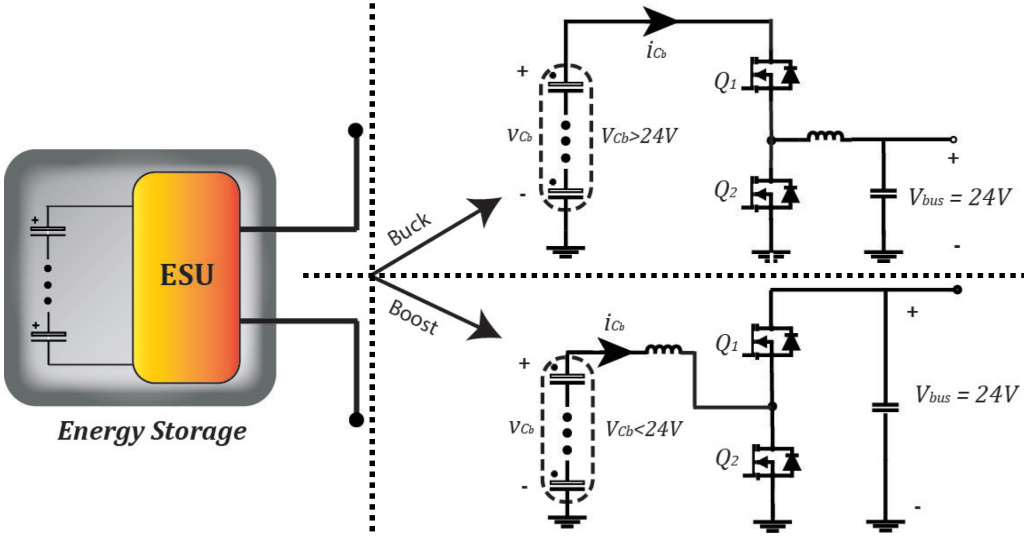
Topology of the Storage System



Topology of the Storage System

Ceralink & ELCO

- Low Energy Density (~0.3kJ/l)
- Large Volume
- Expensive
- ✓ Low $R_{ESR} \rightarrow \eta(\%) \uparrow$



	Price (CHF)	C (F)	V_{nom}(V)	R_{ESR}(mΩ)	Volume (l)
EPCOS (TDK)	16.00	1 µF	500 V	12 mΩ	$3.8 \cdot 10^{-4}$
EPCOS (TDK)	89.00	20µF	500 V	8 mΩ	$8.7 \cdot 10^{-3}$

	Price (CHF)	C (F)	V_{nom}(V)	R_{ESR}(mΩ)	Volume (l)
Nichicon	268	2.2 F	10 V	5 mΩ	2
Vishay	192.5	1 F	25 V	5 mΩ	1.4

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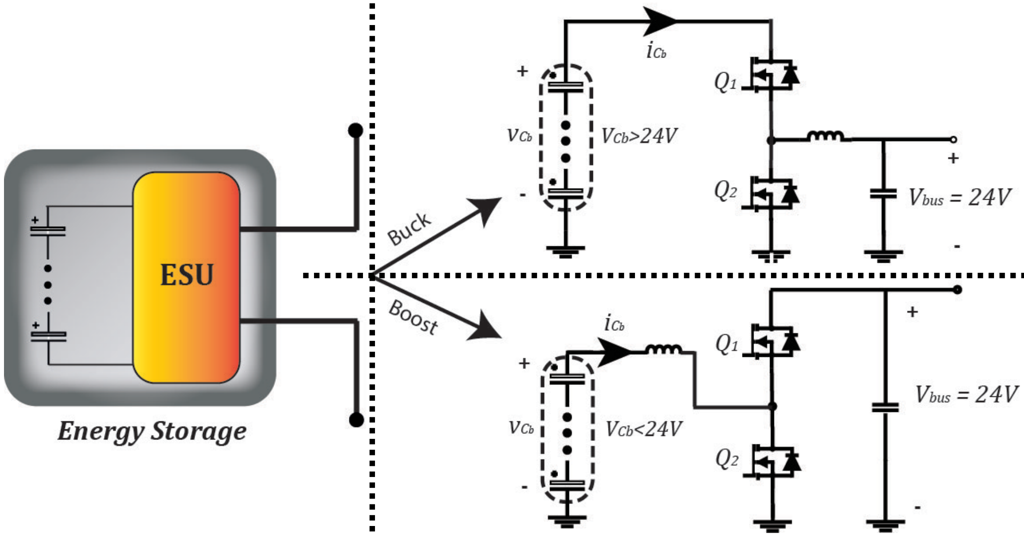

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	Price (CHF)	C (F)	V_{nom}(V)	R_{ESR}(mΩ)	Volume (l)
Eaton Bussmann	6.84	35 F	2.7 V	20 mΩ	$6 \cdot 10^{-3}$
Eaton Bussmann	7.09	60 F	2.7 V	18 mΩ	$10 \cdot 10^{-3}$

Super Capacitors

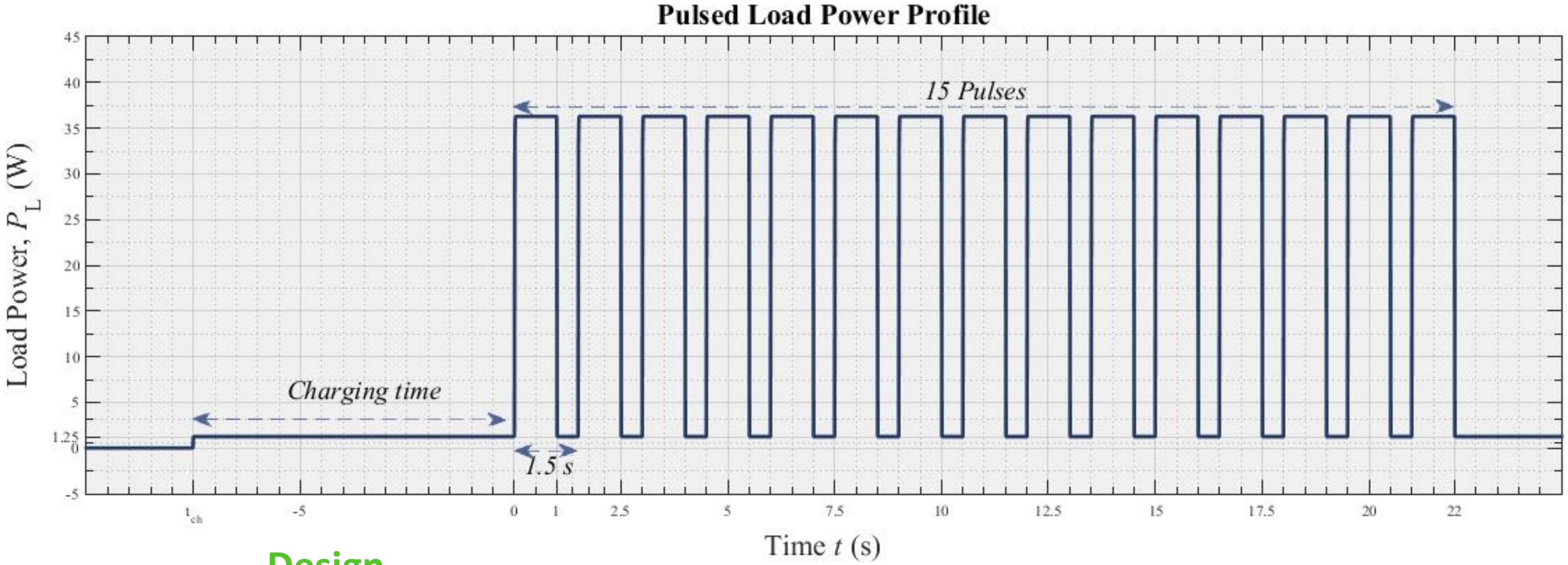
- ✓ Large Energy Density (~15kJ/l)
- ✓ Cheap

Thin Film Batterries

- ✓ Great Volumetric Energy density
- ➢ High $R_{int} \rightarrow \eta(\%) \downarrow$

	Price (CHF)	Capacity (mAh)	V_{nom}(V)	R_{int}(Ω)	Volume (l)
ST Microelectronics	30	0.7 mAh	3.9 V	100 Ω	$5 \cdot 10^{-3}$
Infinite Power Sol.	53.46	2.2 mAh	4.1 V	20 mΩ	$1.25 \cdot 10^{-4}$

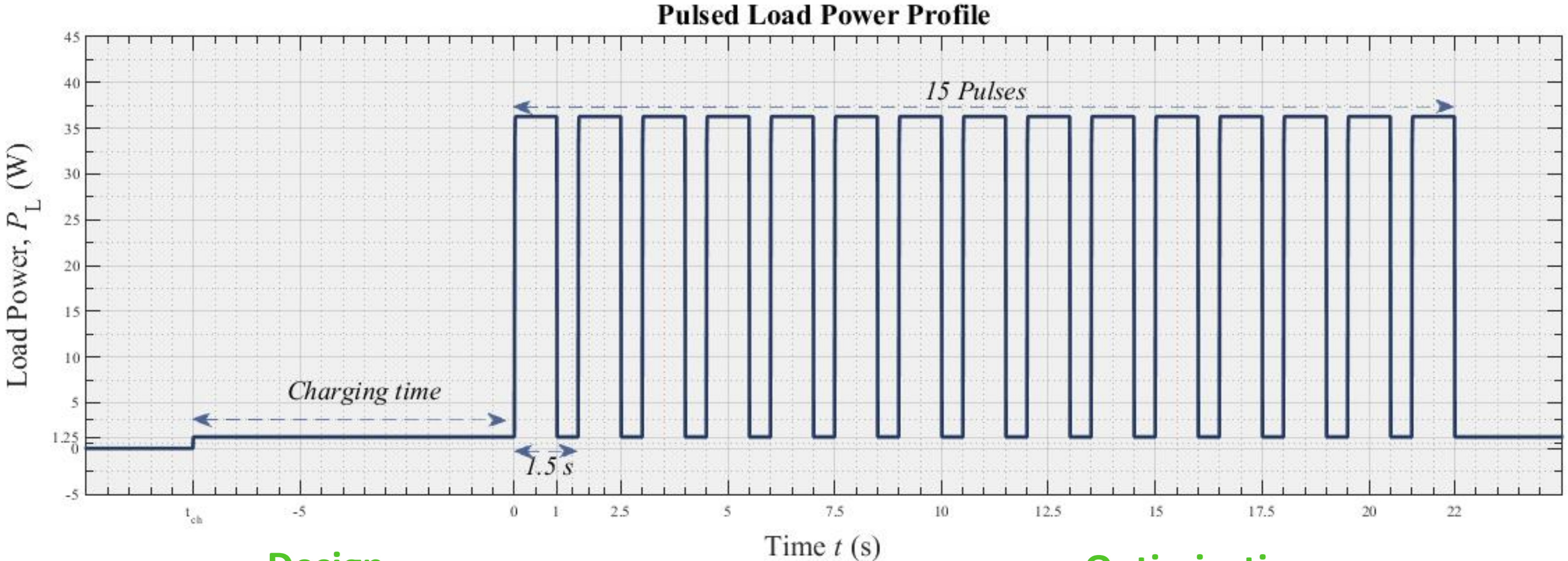
Design of the Storage System



Design

- $E_{Store} = \frac{E_{pulse}+E_{base}}{\eta_{boost}} = 575.5\,J$
- $575.5\,J < E_{ESU} = \int_{\frac{Vbus}{2}}^{Vbus} C \cdot V dV < 2 \cdot 575.5\,\text{J}$
- $3.46\,F \leq C_{C_b}\,(1 \pm 30\%) \leq 7\,F$
- $12\,V \leq V_{C_b} \leq 24\,V$
- $t_{disch} = 22\,s$

Design of the Storage System



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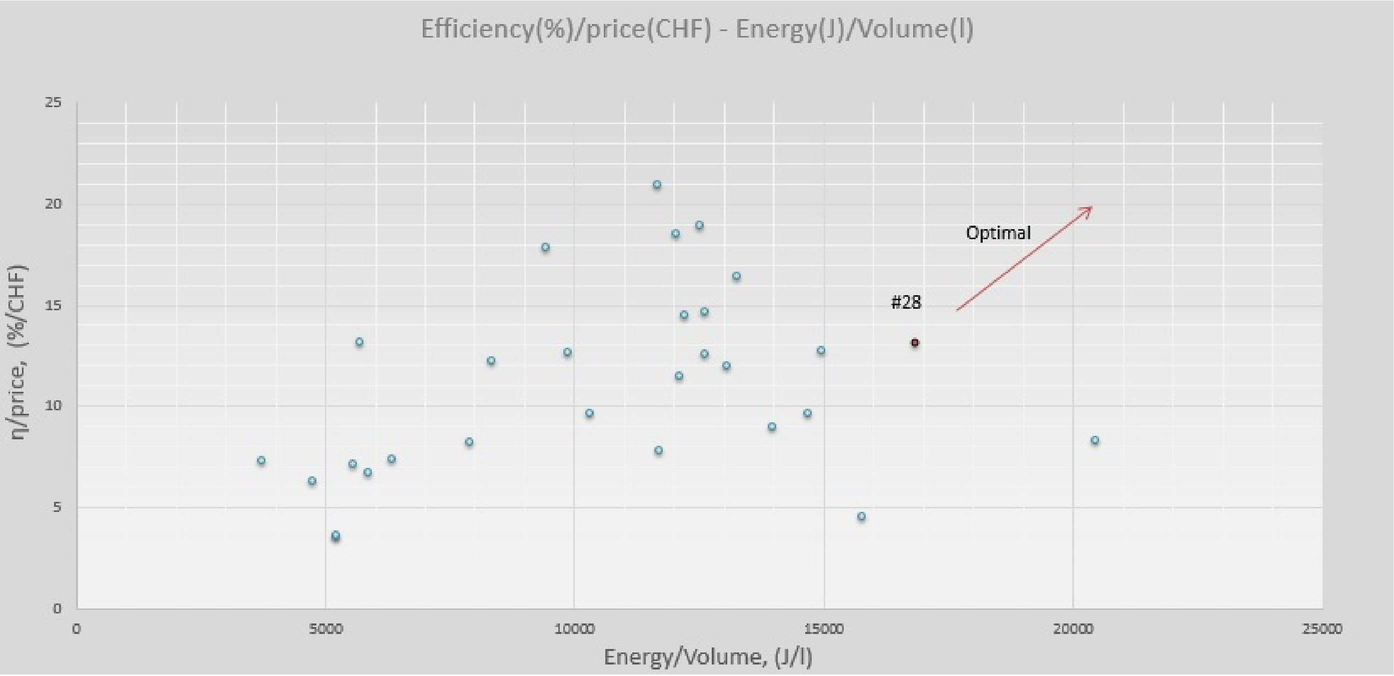
- $t_{disch} = 22\,s$

Optimization

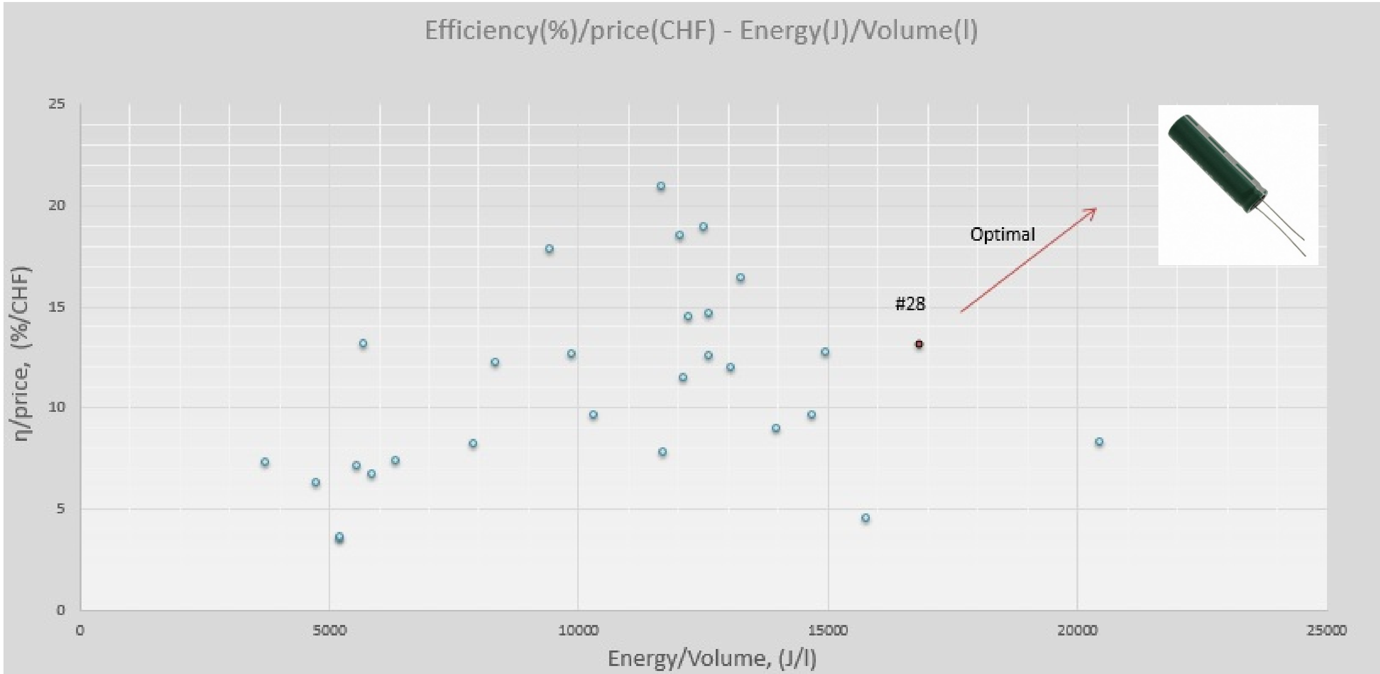
- Cost (CHF)
- Volume (l)
- Efficiency (%)

$$\eta_{C_b} = \eta_{boost} \cdot \frac{E_{store}}{\frac{E_{store}}{\eta_{boost}} + \overline{P_{ESR}} \cdot 15\,s}$$

Super Capacitor Optimization



Super Capacitor Optimization

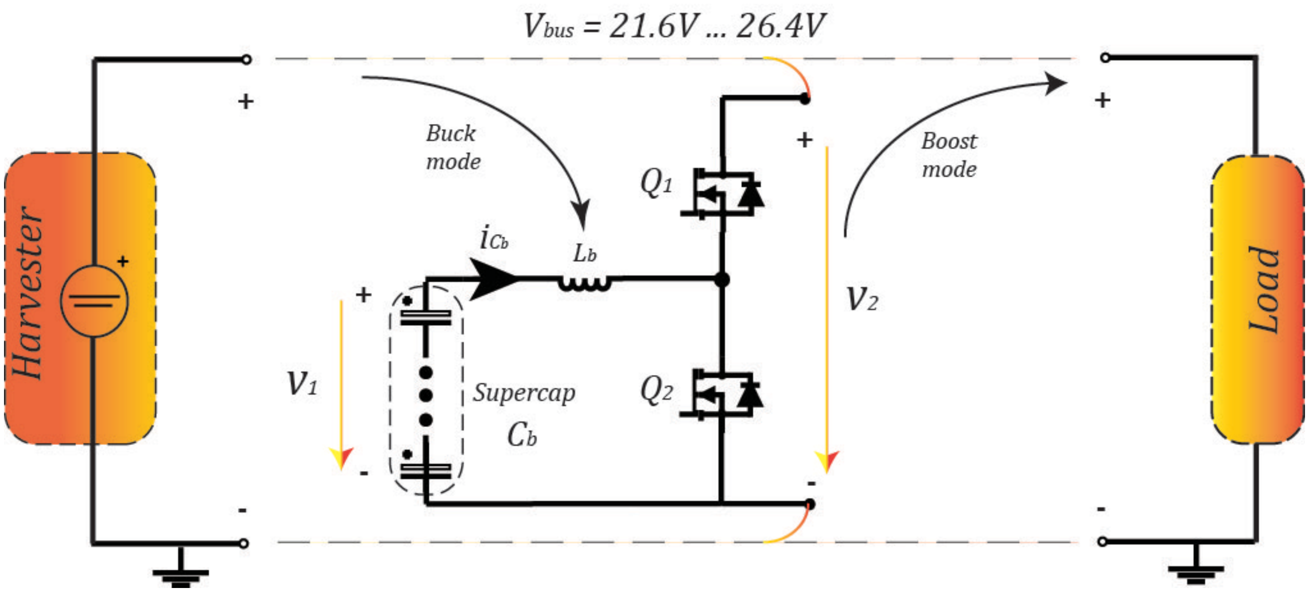


	Eaton Bussmann HV1245-2R7356-R
Price (CHF)	6.84 CHF
C (F)	35 F
Voltage (V)	2.7 V
R_{ESR} mΩ	20 mΩ
Volume (l)	$5.5 \cdot 10^{-5}$

Nominal Case	Worst Case
$C_{tot} = 3.88$ F	$C_{tot} = 2.72$ F
$R_{ESR} = 180$ mΩ	$R_{ESR} = 360$ mΩ
$E_{tot} = 1120.32$ J	$E_{tot} = 783.36$ J
$E_{av} = 840.24$ J	$E_{av} = 587.52$ J
$V_{cb\_after} = 16.25$ V	$V_{cb\_after} = 11.43$ V
$\eta = 89.72\%$	$\eta \approx 80\%$
$t_{ch} = 311$ s	$t_{ch} = 218$ s

Nr	9
Price (CHF)	6.84 · 9 = 61.56 CHF
Voltage (V)	2.7 V· 9 = 24.3 V
Volume (l)	0.05 l

Analysis of the Energy Storage Unit



Requirements

- Operation in CCM
- $\Delta i_{L_b} \leq \pm 20\% \cdot I_{L_b}$
- $V_{bus} = V_2 = \pm 10\% \cdot 24\ V$
- $P_1 = \frac{P_2}{\eta_{boost}}$

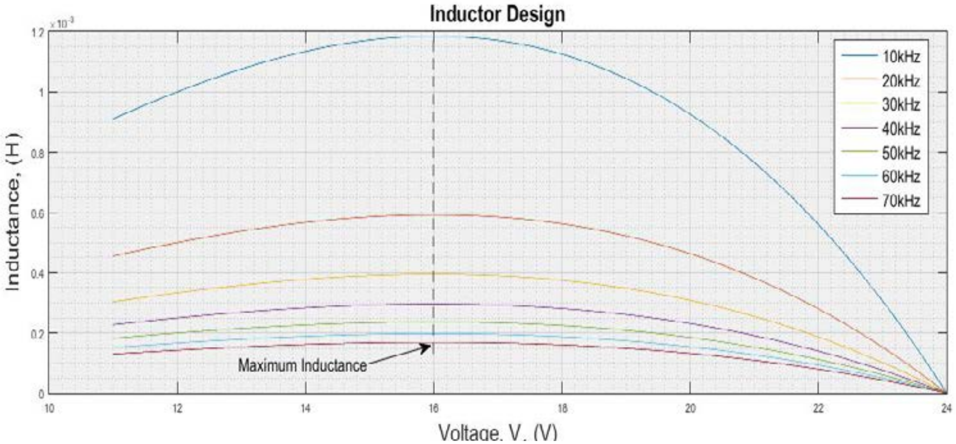
Bus

- $21.6\ V \leq V_2 \leq 26.4\ V$
- $P_2 = \begin{cases} 36.25\ W \\ 1.25\ W \end{cases}$
- $I_2 = \frac{P_2}{V_2} = \begin{cases} 1.5\ A \\ 0.05\ A \end{cases}$

Storage Unit

- $12\ V \leq V_1 \leq 24\ V$
- $0.48 \leq D = \frac{V_1}{V_2} \leq 1$
- $I_1 = I_{L_b} = \frac{I_2}{D} \leq 3.13\ A$
- $\Delta i_{L_b} \leq 0.6\ A$

Inductor Optimization (1)



Inductor Design

$$V_L = L\frac{di}{dt} \approx L\frac{\Delta i_L}{(1-D)\cdot T_s} \Rightarrow$$

$$\boldsymbol{L} = \frac{-\frac{\boldsymbol{V_1^3}}{\mathbf{24\,V}} + \boldsymbol{V_1^2}}{\mathbf{7.2}\cdot \boldsymbol{f_s}}$$

$$\xrightarrow{worst\ case} V_1 = 16V$$

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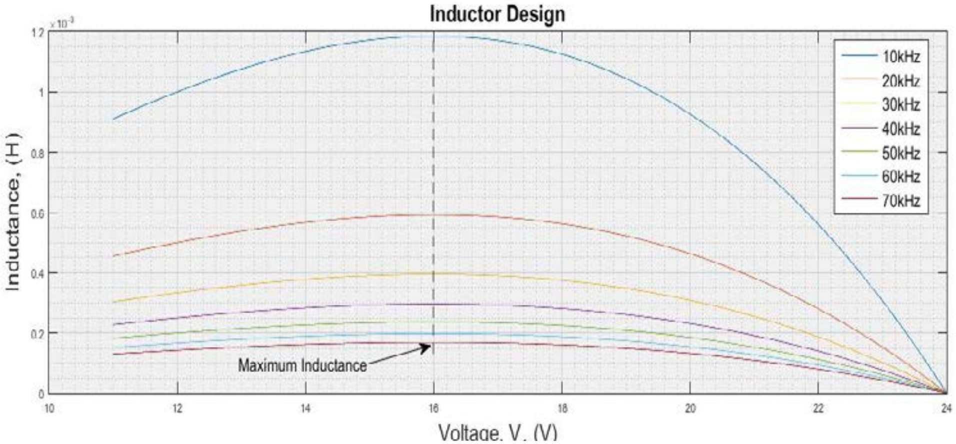

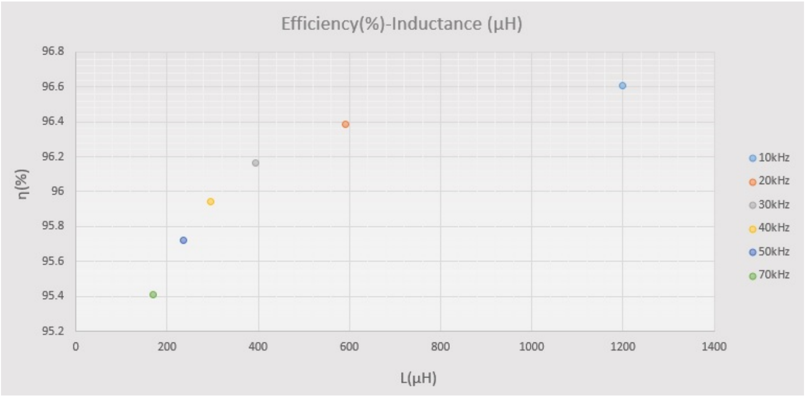

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Efficiency of the ESU

$$\eta_{\mathrm{boost}} = \frac{P_2}{P_2 + P_{loss}}$$

$$\boldsymbol{P_{loss} = P_{Q1} + P_{Q2} + P_{Cb} + P_{Lb}}$$

- $P_Q = P_{Gate,Q} + P_{on,Q} + P_{COSS} + P_{cond,Q}$
- $P_{Cb} = P_{esr,Cb}$
- $P_{Lb} = P_{Core,Lb} + P_{Cu,Lb}$

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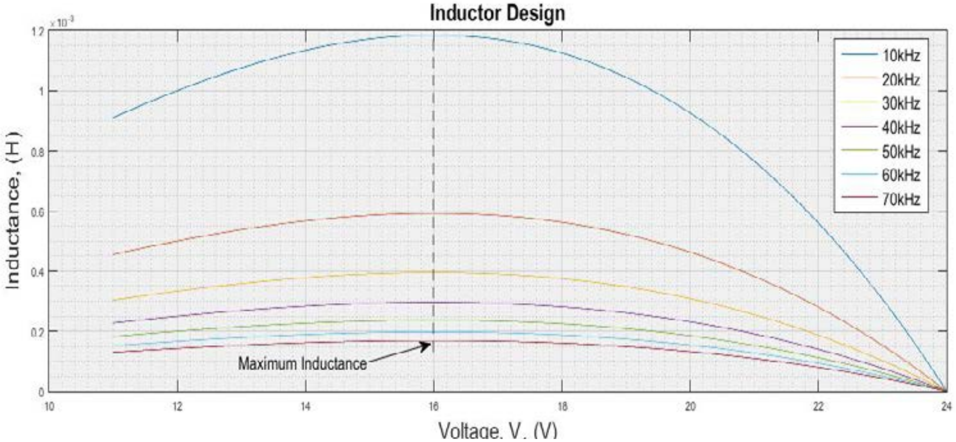

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$$\boldsymbol{L = 237\mu H, f_s = 50kHz}$$

Inductor Optimization (2)

Requirements

- Must achieve correct inductance
- Keep the losses low
- Inductor size as small as possible without saturating the core
- $\eta \sim \frac{1}{DCR\ (m\Omega)}$

- *Commercial Custom cores*
- *GeckoMagnetics simulations*
- *Commercial Fixed value Inductors*

Inductor Optimization (2)

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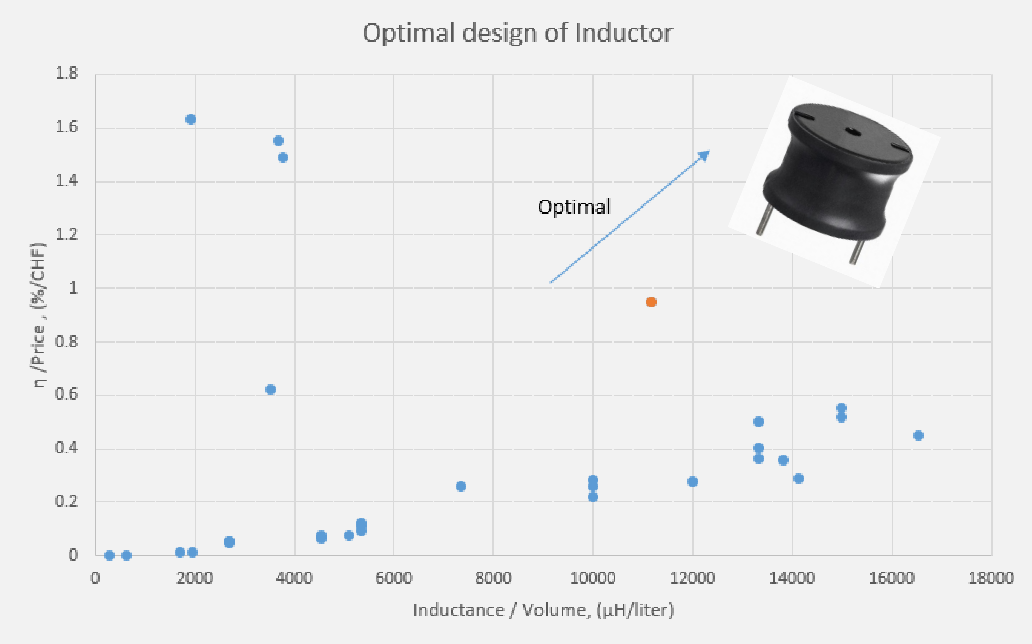
Custom Cores

- $A_c \times A_w \geq \frac{LI_{pk}I_{RMS}}{kB_{pk}J_{RMS}}$
- $N_{min} = \sqrt{\frac{L}{A_L}}$
- $B \leq B_{sat}$
- $A_{cu} \leq \frac{K_u A_w}{N_{min}}$
- *Commercial Cores used: Digikey and Rotima*



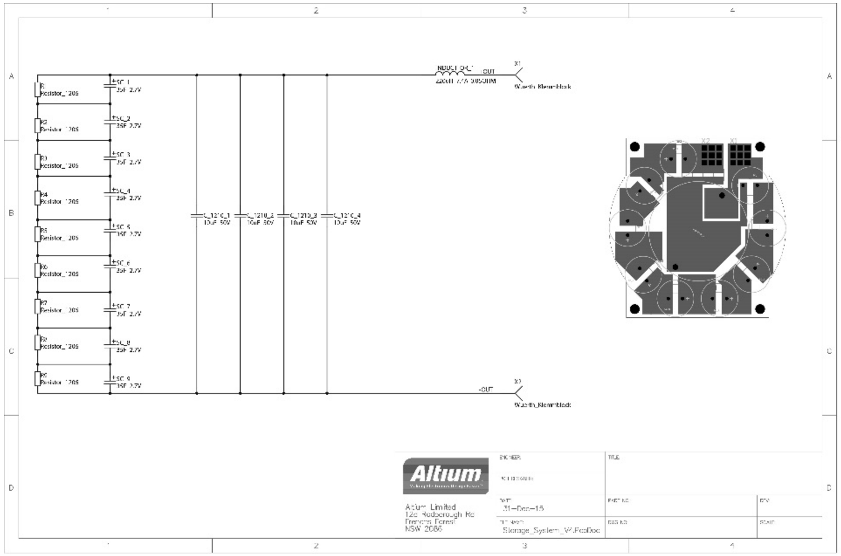
GeckoMagnetics

RM 14 0.15mm	ETD 54/28/19
290 µH	294.59 µH
N87+	N87+
AWG12	AWG12
15 turns	14 turns
9.2 mΩ	9.4 mΩ
0.08 l	0.04 l
7 CHF	11.2 CHF

Selected Inductor

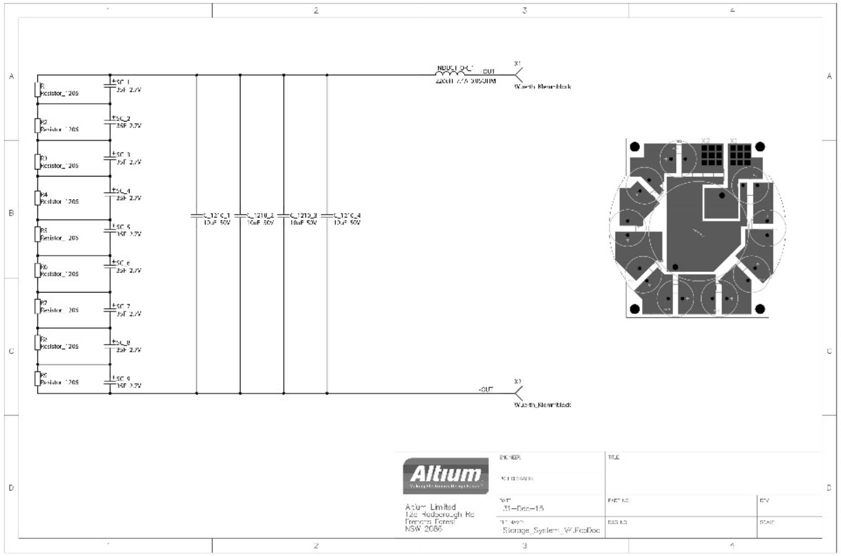
	M8379-ND
Price CHF)	7.65 CHF
Material	Ferrite
L (µH)	220 µH
I_{sat}(A)	7.4 A
R_{ESR}(mΩ)	50 mΩ
Volume (l)	0.03 l

Hardware Implementation



Component	Nr	Volume (l)
Eaton Bussmann (SuperCap)	× 9	0.05
M8379-ND (Inductor)	× 1	0.03
Cap 1210 X7R (Capacitor)	× 4	$4 \cdot 10^{-5}$
Res 1206 (Resistor)	× 9	$6 \cdot 10^{-6}$

Hardware Implementation



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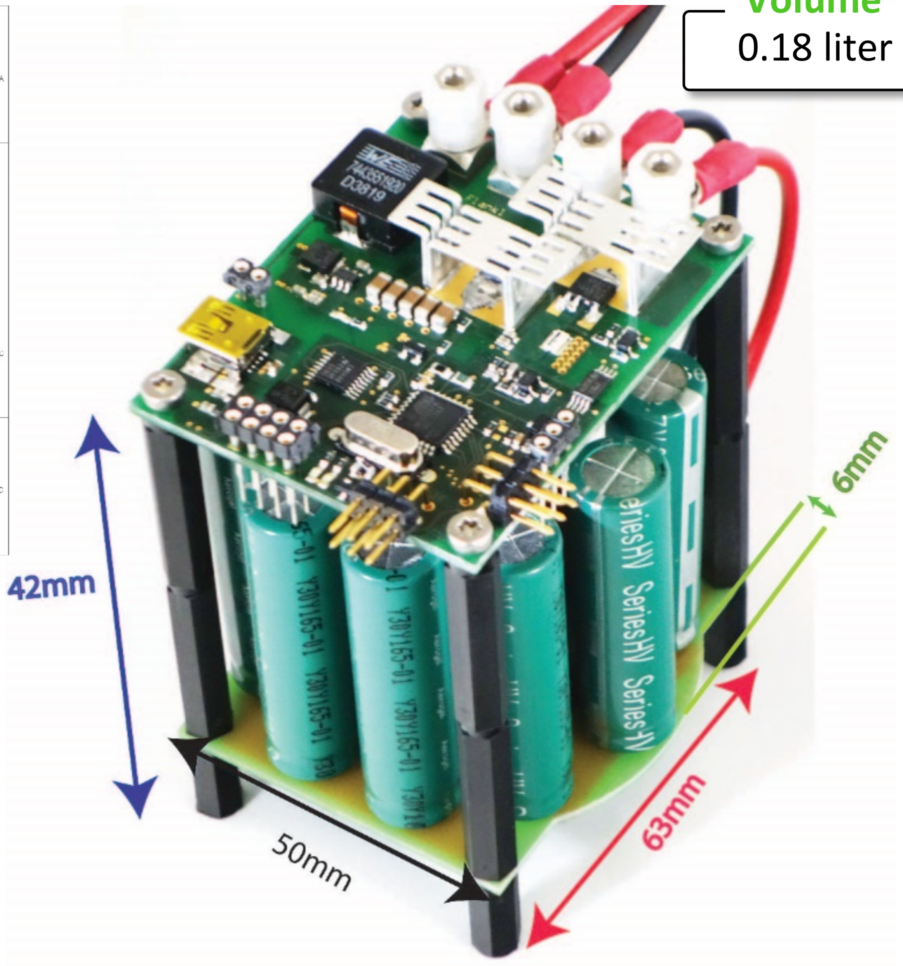
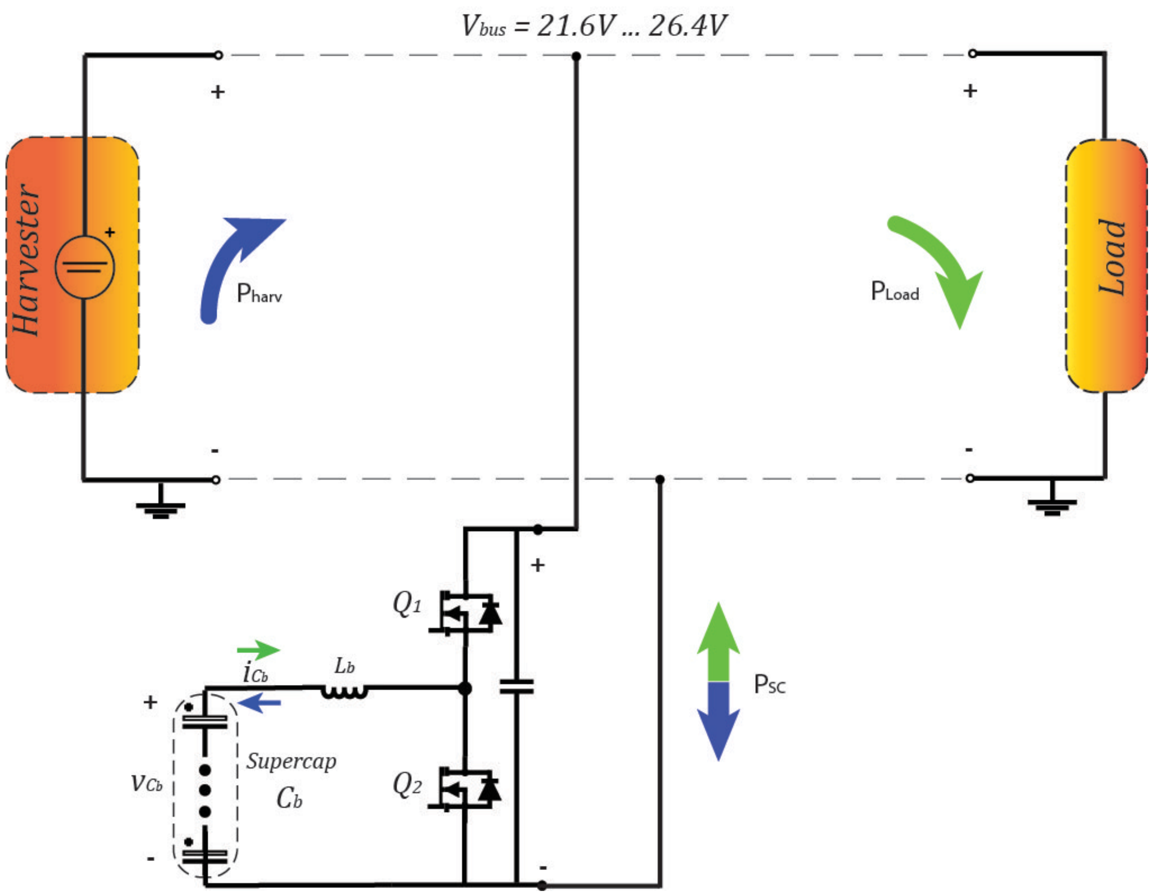
Volume
0.18 liter



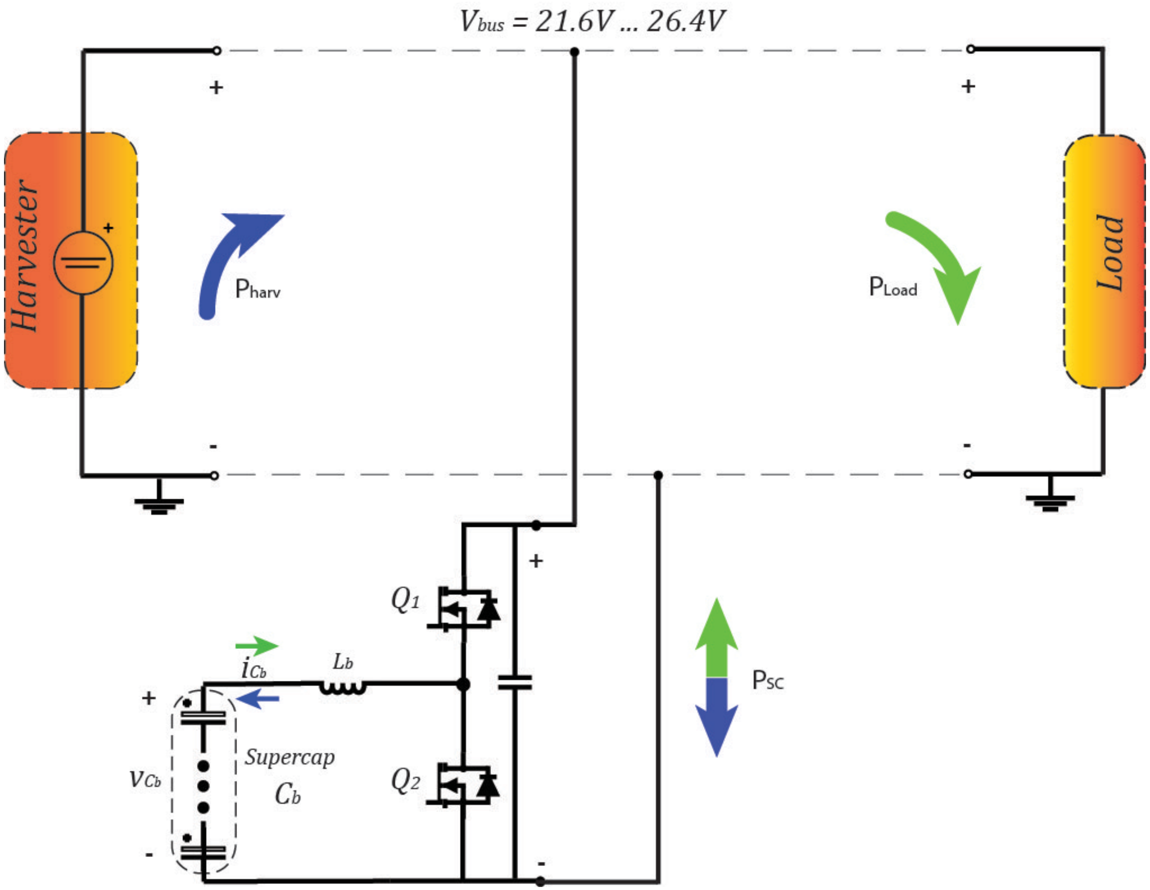
Control Scheme



Requirements

- $V_{bus} = \pm 10\% \cdot 24V$
- Efficient storage of the power provided by the harvester
- Deliver required power to the load

Control Scheme



Requirements

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- Efficient storage of the power provided by the harvester
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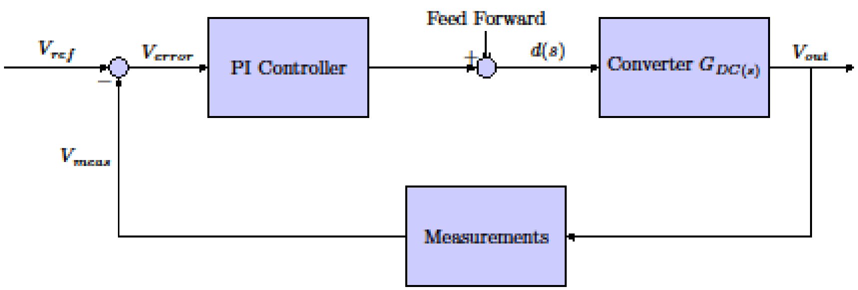
Solution

- Use of a closed-loop control scheme (negative feedback)
- Adjust duty cycle to obtain desired output voltage regardless Load variations and Storage Unit voltage

PI Control



PI Control

- Reduces steady-state error
- Improve the rejection of low frequency disturbances
- Special attention must be given to the stability of the system

Input

$$V_{error} = V_{ref} - V_{meas}$$

PI Controller

$$d(t) = K_p \cdot V_{error} + K_i \cdot \int_0^t V_{error}(\tau) d\tau + Feed\ Forward\ Gain$$

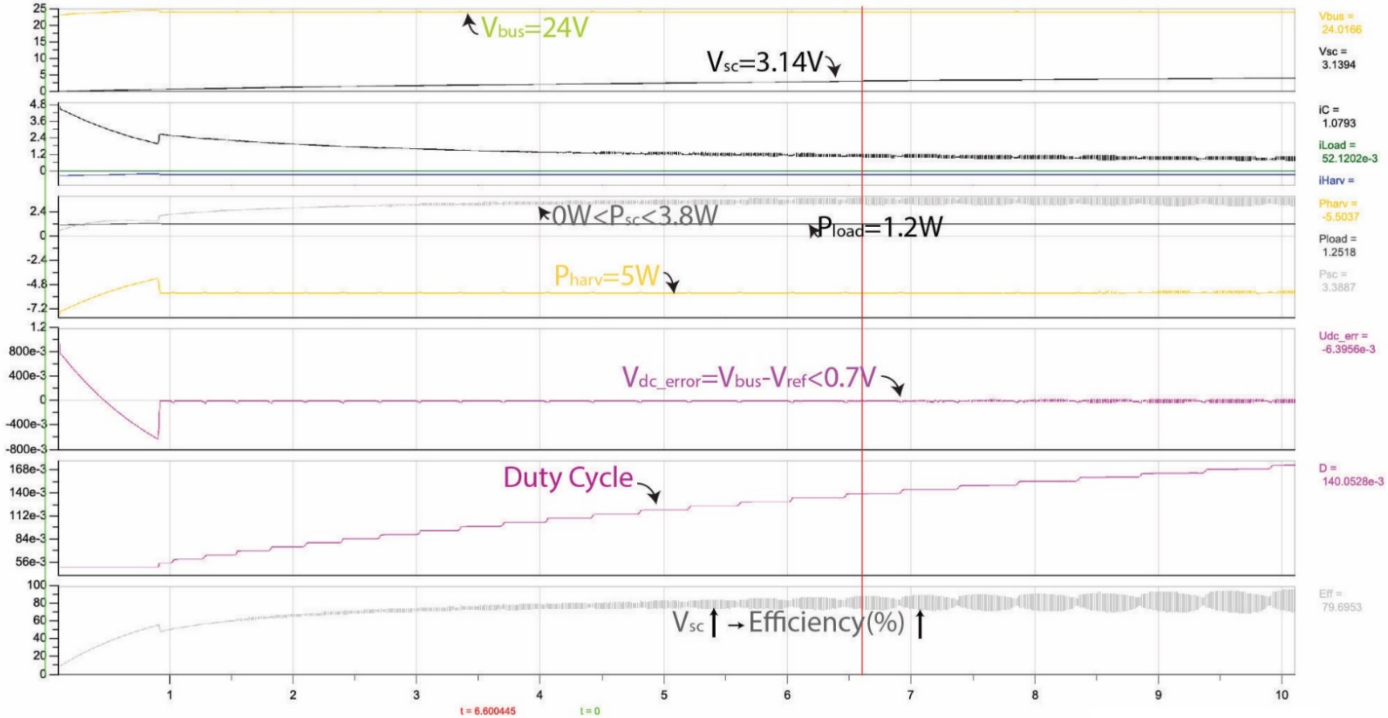
Manual Tuning of PI terms using Ziegler-Nichols technique,

- $K_p = 0.020$
- $K_i = 10$
- $Feed\ Forward\ Gain = \frac{V_1}{24\ V}$

Converter

- $d(t) \rightarrow$ PWM signal to Q1, Q2
- Adjusting input control signal so that bus voltage stable

PI Control Simulations – Charging Stage



Charging $V_{sc} = 0V$

η_{ch} (%)	78%
P_{harv}	5.5 W
P_{ESU}	3 W
P_L	1.25 W
$\lvert V_{bus-error} \rvert$	0.7 V

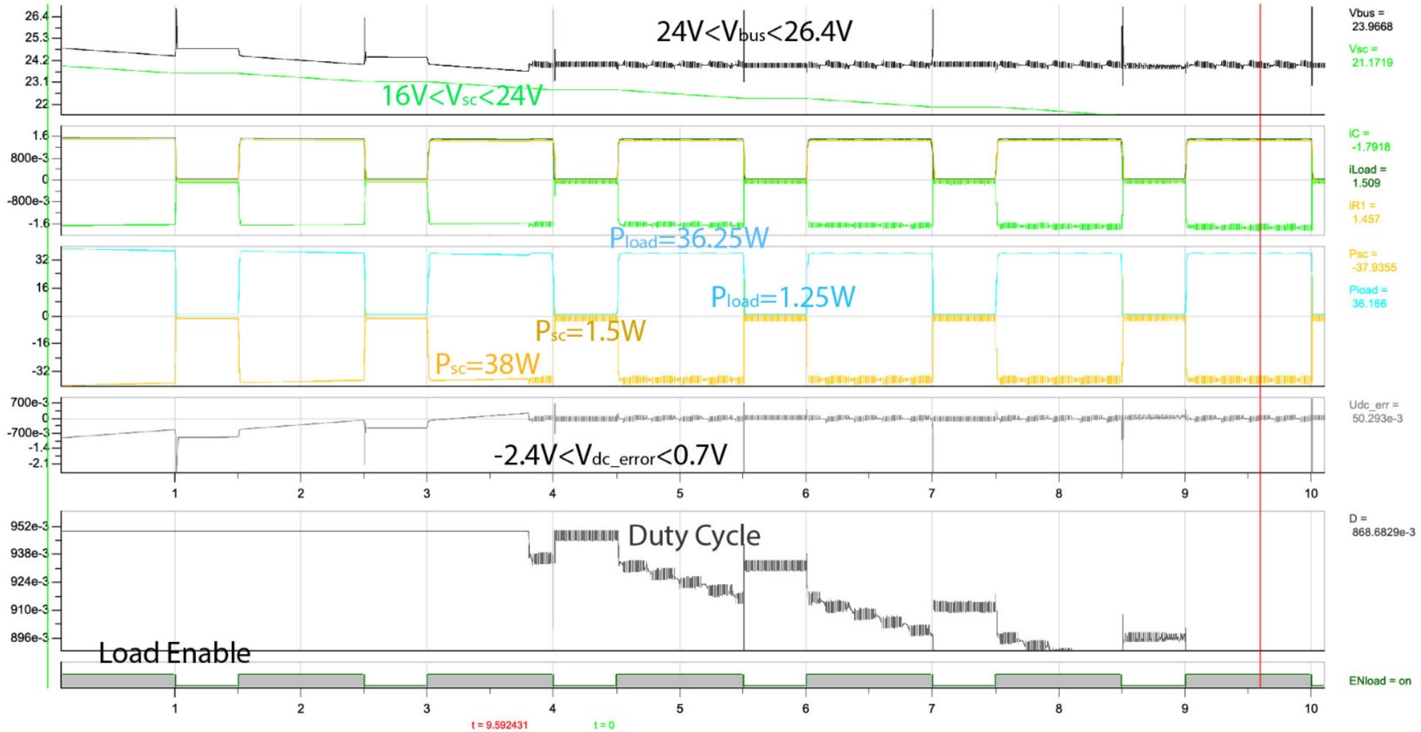
Charging $V_{sc} = 22V$

η_{ch} (%)	85%
P_{harv}	6 W
P_{ESU}	4 W
P_L	1.3 W
$\lvert V_{bus-error} \rvert$	0.4 V

Summary

η_{ch} (%)	≥ 78%
t_{ch}	311 s
P_{harv}	5 W
P_{ESU}	≤ 4 W
P_L	1.3 W
$\lvert V_{bus-error} \rvert$	≤ 1 V

PI Control Simulations – Discharging Stage



Discharging $0 \leq t \leq 10s$

η_{disch} (%)	95 %
P_{ESU}	38 W
P_L	36.2 W
$\lvert V_{bus-error}\rvert$	≤ 2.4 V

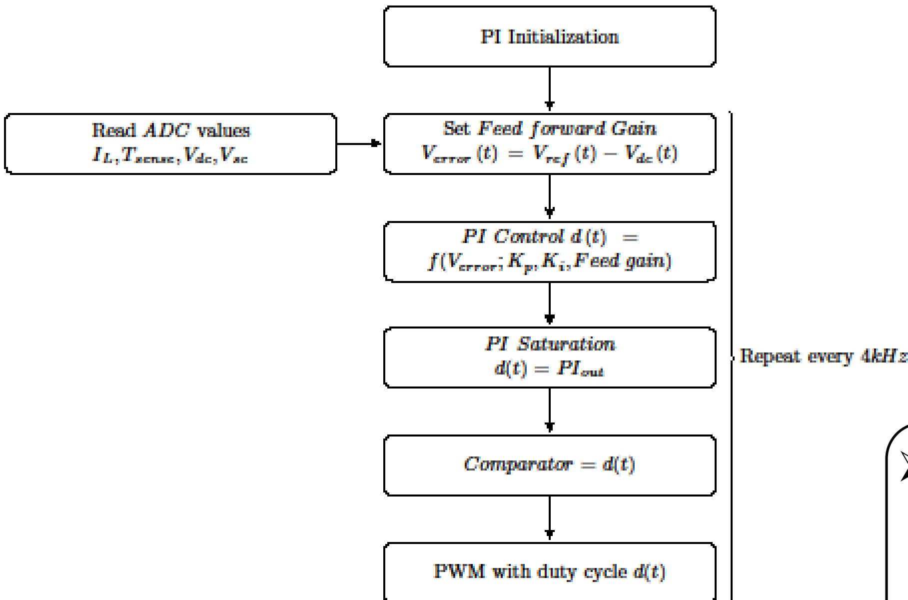
Discharging t=1s

η_{disch} (%)	95%
$V_{bus-max}$	26.4 V
$\lvert V_{bus-error}\rvert$	2.4 V
$V_{bus} - t_{rise}$	300µs
$V_{bus} - t_{oscill}$	2.3 ms

Summary

η_{disch} (%)	95%
t_{disch}	22 s
P_{ESU}	≤ 38 W
P_L	≤ 36.5 W
$\lvert V_{bus-error}\rvert$	≤ 2.4 V

Software Implementation



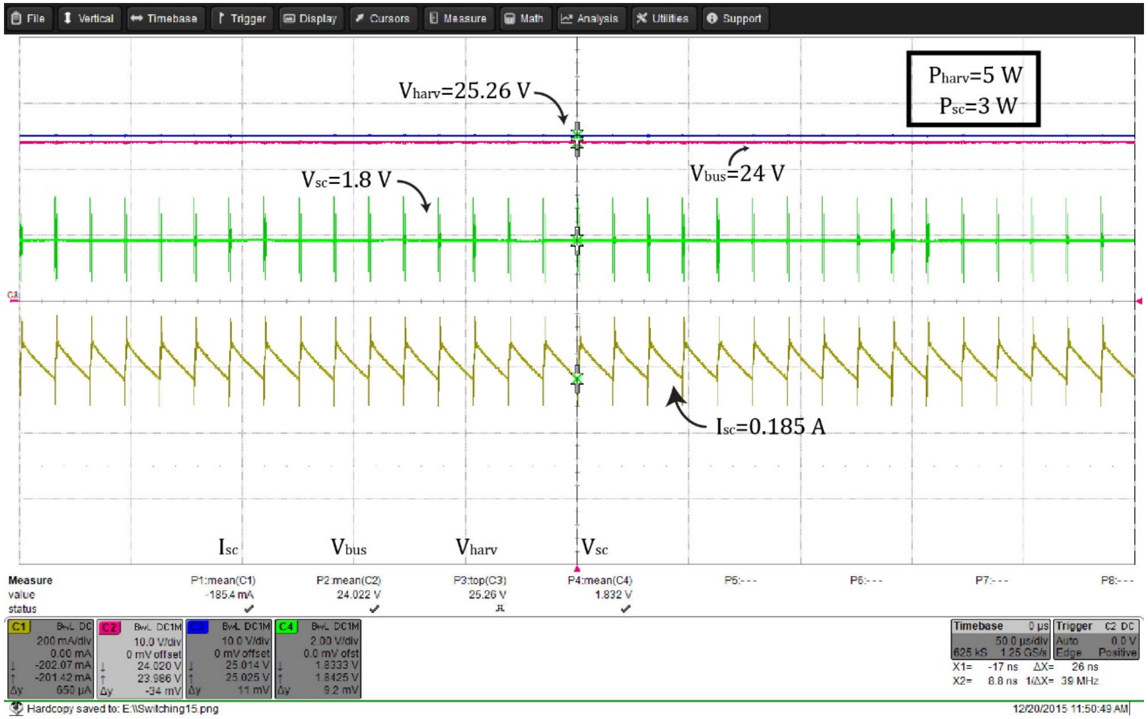
Characteristics

- Used µC: ATMEGA88PA
- Sampling period = 4kHz
- Reading of the ADC values = 128 kHz
- $K_p = 0.020 \frac{digits}{Volt}$
- $K_i = 0.0025 \frac{digits}{Volt}$

Limitations

- Integral windup (K_i term accumulates a significant error)
  ⟹If it reaches a max value → re-initialize
- ADC inputs read large spikes
  ⟹Keep the last values and average them
- Float numbers result in slow running times
  ⟹ Use of integer numbers
- Fast PWM signal of 64 kHz

Experimental Results



- Re-tuning of PI terms
- Keep bus voltage stable $V_{bus} = \pm 10\% \cdot 24V$
- Charging Efficiency, $\eta_{ch} = 75\%$

V_{harv}	25.4 V
I_{harv}	0.2 A
V_{sc}	1.8V · 9 = 16.2 V
I_{sc}	0.185 A
$\lvert V_{bus-error} \rvert$	< 1 V

Experimental

η_{ch-exp}	75%

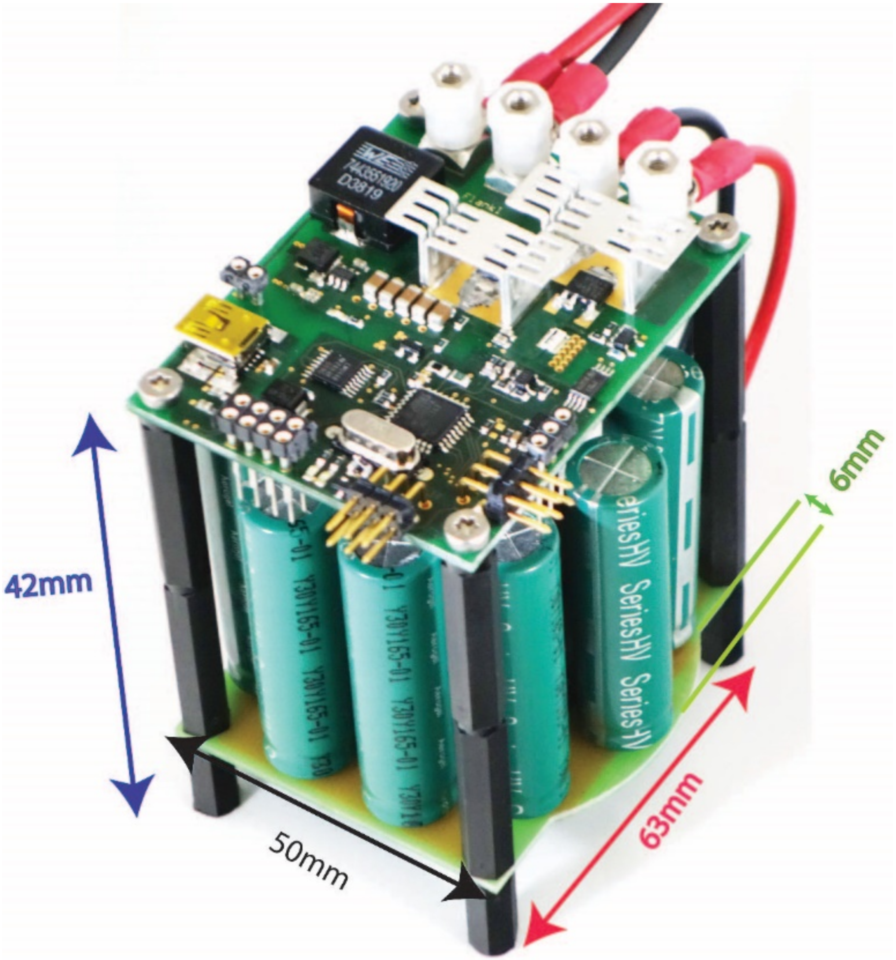
Simulations

η_{ch-sim}	78%

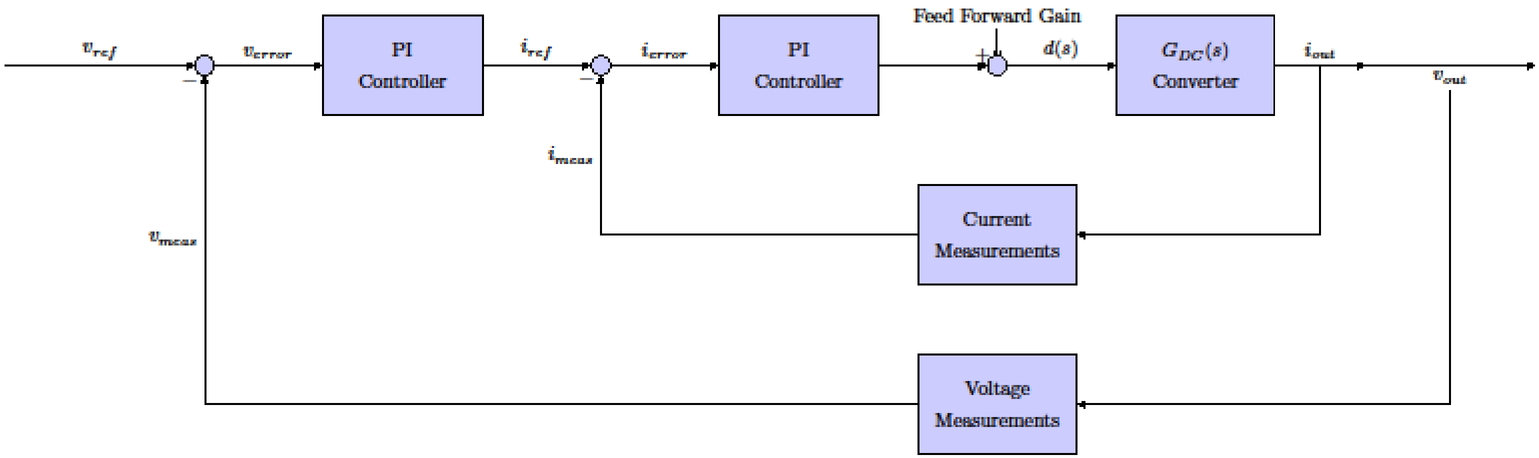
Conclusions

Summary

- Optimum Storage System and inductor design and implementation in terms of cost (CHF), Volume (l) and Efficiency (%) was designed
- PI controller achieved to keep V_{bus} stable regardless load and voltage variations
- Verified by simulations (GeckoCircuits) and experiments



Outlook

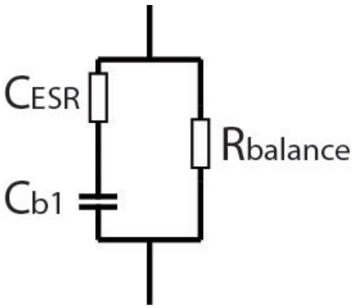


Future work

- Experimental setup for the discharging cycle
- Improved PI control scheme
  - ✓ Cascaded voltage and current loop control
  - ✓ Improved Evaluation of PI terms by using different values for $V_{store} \leq 12V$ and $V_{store} \geq 12V$
  - ✓ Optimization of algorithm for integer numbers

Discussion

Super Capacitors



Balancing SuperCapacitors

$$\tau = C_{b1} \cdot R_{balance}$$

$$P_{losses} = \frac{(24V)^2}{9 \cdot R_{balance}} \leq 0.5\ W$$

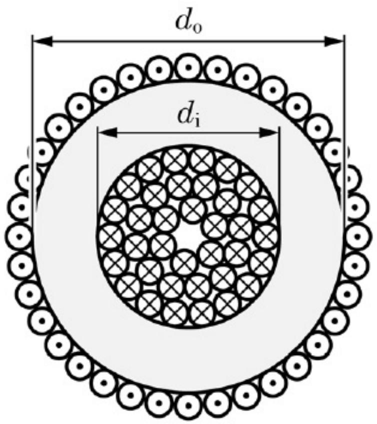
Impact on generator

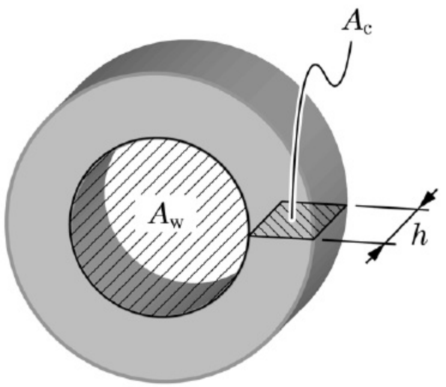
$$P_{store} \approx \frac{1}{\eta_{boost}} \cdot \frac{E_{Cb\_max}}{t_{ch}}$$

Inductor Design

1. Sizing a toroidal Core

$$\left.\begin{aligned} A_c &= h\frac{(d_o-d_i)}{2} \\ A_w &= d_i^2\frac{\pi}{4} \end{aligned}\right\} A_c \times A_w \geq \frac{L I_{pk} I_{RMS}}{k B_{pk} J_{RMS}}$$





2. Check B_{sat}

$$B = \frac{L I_{pk}}{N A_c}$$

$$l_g = \frac{\mu_o L I_{pk,Lb}^2}{B_{max}^2 A_c}$$

In case of exceed of B_{sat}

- Choose larger/different Core/Material
- Operate in lower current
- Increase air gap
- Increase number of turns

3. Number of Turns

$$N = \frac{L I_{pk}}{B_{pk} A_c}$$

$$L = A_L N^2$$

4. Winding type

$$A_{cu} \leq \frac{K_u A_w}{N_{min}}$$

5. Define Power losses

$$P_{Lb} = P_{Core,Lb} + P_{Cu,Lb}$$

$$P_{core} = \begin{cases} P_V \cdot V_e \\ Steinmetz\ equations \end{cases}$$

$$P_{Cu,Lb} = r_{Lb} \cdot I_{Lb,RMS}^2$$

$$r_{Lb} = \rho \cdot \frac{N \cdot MLT}{A}$$

Inductor Results

Ferrite Cores

1. $A_c \cdot A_w \geq 0.5\ cm^4$
2. $B_{sat} \leq 0.3\ T$
3. $N_{min} = \sqrt{\frac{L}{A_L}}$

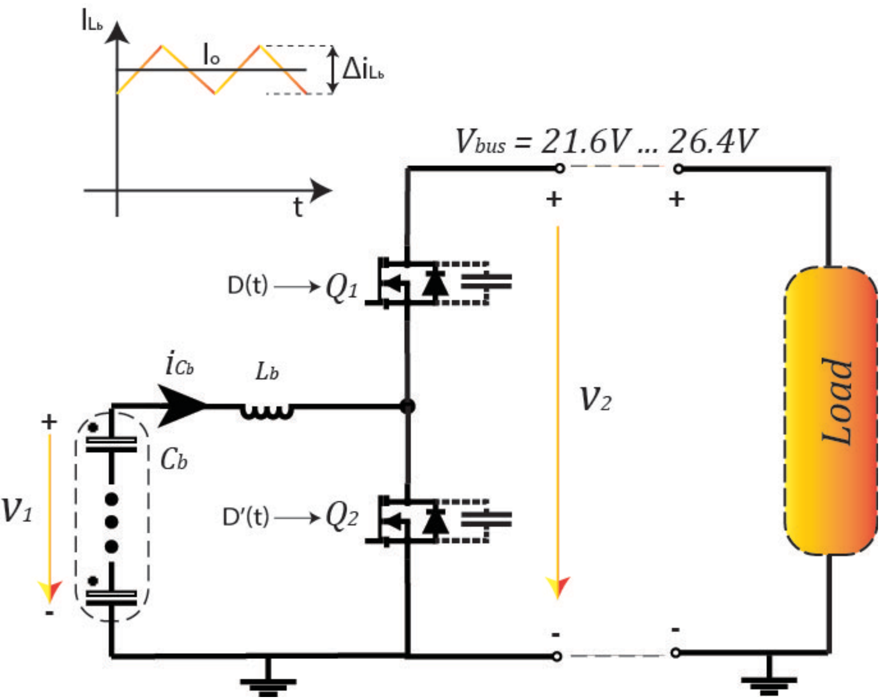
Rotima Cores

1. $A_c \cdot A_w \geq 0.05\ cm^4$
2. $B_{sat} \leq 1.56\ T$
3. $N_{min} = \sqrt{\frac{L}{A_L}}$

Price (CHF)	O.D. (mm)	V (cm^3)	A_c x A_w (cm^4)	N_{min}	B (T)	l_g(mm)
8.61	51.80	45	13.83	8.2	0.65	2.07
15.13	65.30	89	34.69	4.9	0.70	1.33
3.26	31.00	12	2.18	4.8	2.84	5.28
3.37	35.50	13	2.72	7.4	1.71	4.93
3.82	37.50	18	3.98	4.7	2.33	4.24
11.66	60.10	53	19.92	7.5	0.92	2.67
3.47	37.50	18	3.98	6.1	1.80	4.24
10.64	58.30	47	19.92	7.5	0.92	2.67

	O.D. (mm)	V (cm^3)	A_c x A_w (cm^4)	N_{min}	B (T)
MP1603MP	15.79	0.345	0.055	104.7	1.11
MP1710MP	17.47	0.938	0.23	75.6	0.69
MP2010MP	19.93	1.538	0.348	63.9	0.54
MP2310MP	22.96	2.382	0.494	56.1	0.44
MP2510MP	25.55	1.888	0.725	78.8	0.49
MP3310MP	32.43	5.336	1.21	50.1	0.30
MP3510MP	34.92	5.577	1.77	55.5	0.29

Mosfet Losses



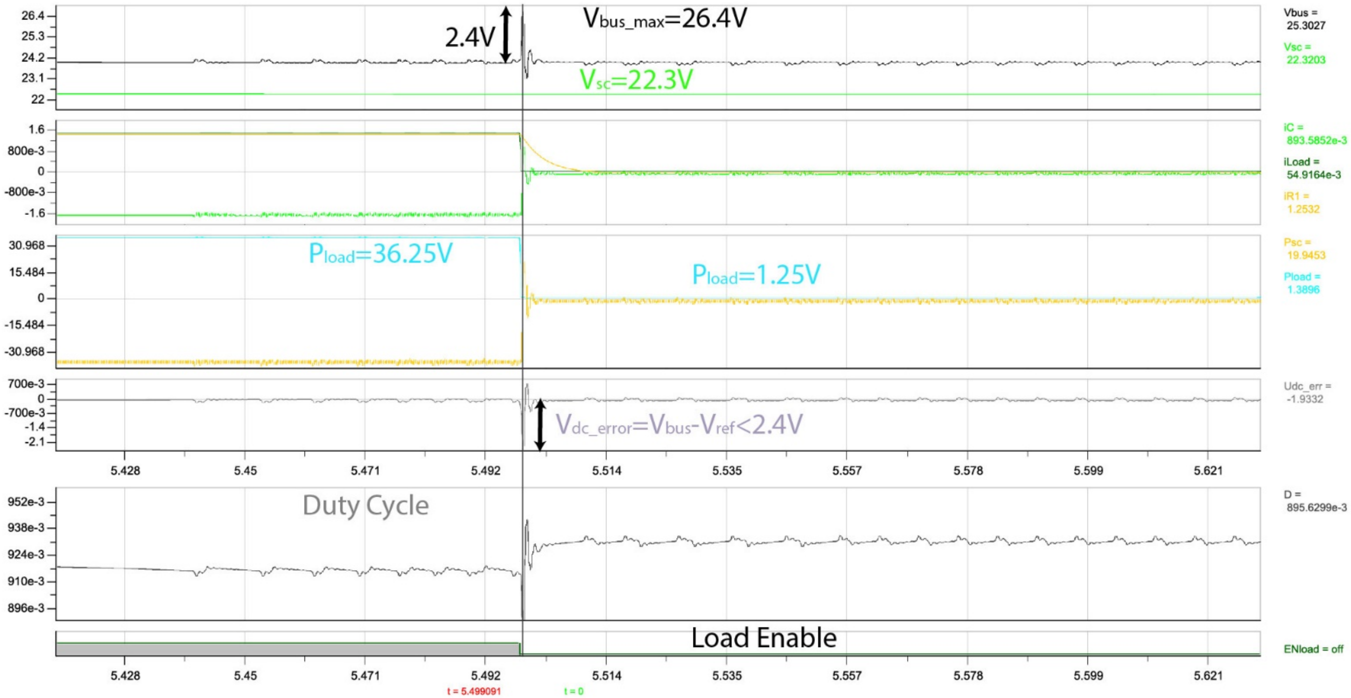
Mosfet losses	
Gate Losses	$P_{Gate,Q1} = Q_G \cdot \Delta V_G \cdot f_s$ $P_{Gate,Q2} = Q_G \cdot \Delta V_G \cdot f_s$
Turn-on Losses	$P_{on,Q1} \approx 0$ $P_{on,Q2} = \frac{V_{Q2} \cdot I_{Q2}}{2} \cdot t_{on} \cdot f_s + Q_{rr} \cdot V_{Q2}$
Turn-off Losses	$P_{off,Q1} \approx 0$ $P_{off,Q2} \approx 0$
C_{oss} Losses	$P_{Coss} = \frac{C_{oss} \cdot V_o^2}{2} \cdot f_s$
Conduction Losses	$P_{Cond,Q1} = I_{RMS,Q1}^2 \cdot r_{DS} = \left(\frac{I_o}{\sqrt{D}}\right)^2 \cdot r_{DS}$ $P_{Cond,Q2} = I_{RMS,Q2}^2 \cdot r_{DS} = \left(\frac{I_o\sqrt{1-D}}{D}\right)^2 \cdot r_{DS}$

$$\eta_{\text{boost}} = \frac{P_2}{P_2 + P_{loss}}$$

$$\boldsymbol{P_{loss}} = \mathbf{P_{Q1} + P_{Q2} + P_{Cb} + P_{Lb}}$$

- $P_Q = P_{Gate,Q} + P_{on,Q} + P_{COSS} + P_{cond,Q}$
- $P_{Cb} = P_{esr,Cb}$
- $P_{Lb} = P_{Core,Lb} + P_{Cu,Lb}$

Discharging Stage at t=1s



Discharging t=1s

$V_{bus-max}$	26.4 V
η (%)	95%
$\|V_{bus-error}\|$	2.4 V
$V_{bus} - t_{rise}$	300μs
$V_{bus} - t_{oscill}$	2.3 ms

ADC Reading Problem