VHDL-AMS modeling of adaptive electrostatic harvester of vibration energy with dual-output DC-DC converter

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Outline

- **Introduction**
  - Vibration energy harvester
  - Basic architecture of conditioning circuit
  - Goals of this work
- **Auto-calibration of the system**
  - Algorithm
  - Modeling results
- **Power management of the harvested energy**
  - Improved architecture of the conditioning circuit
  - Modeling results
- **Conclusions**

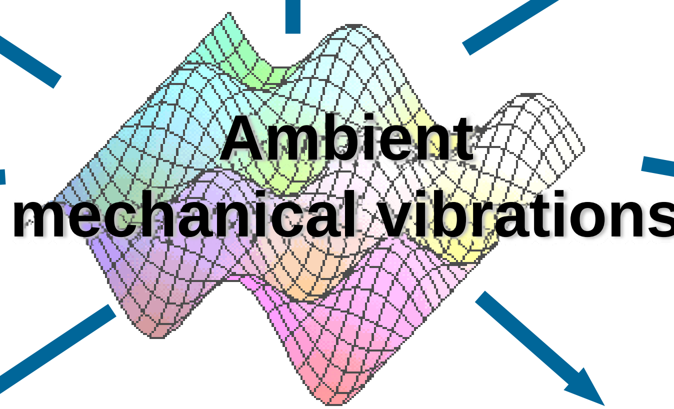
Application of research

Cars

Trains

Aircrafts

Industrial tools



Human
body

Vibrating structures

Environment surveillance

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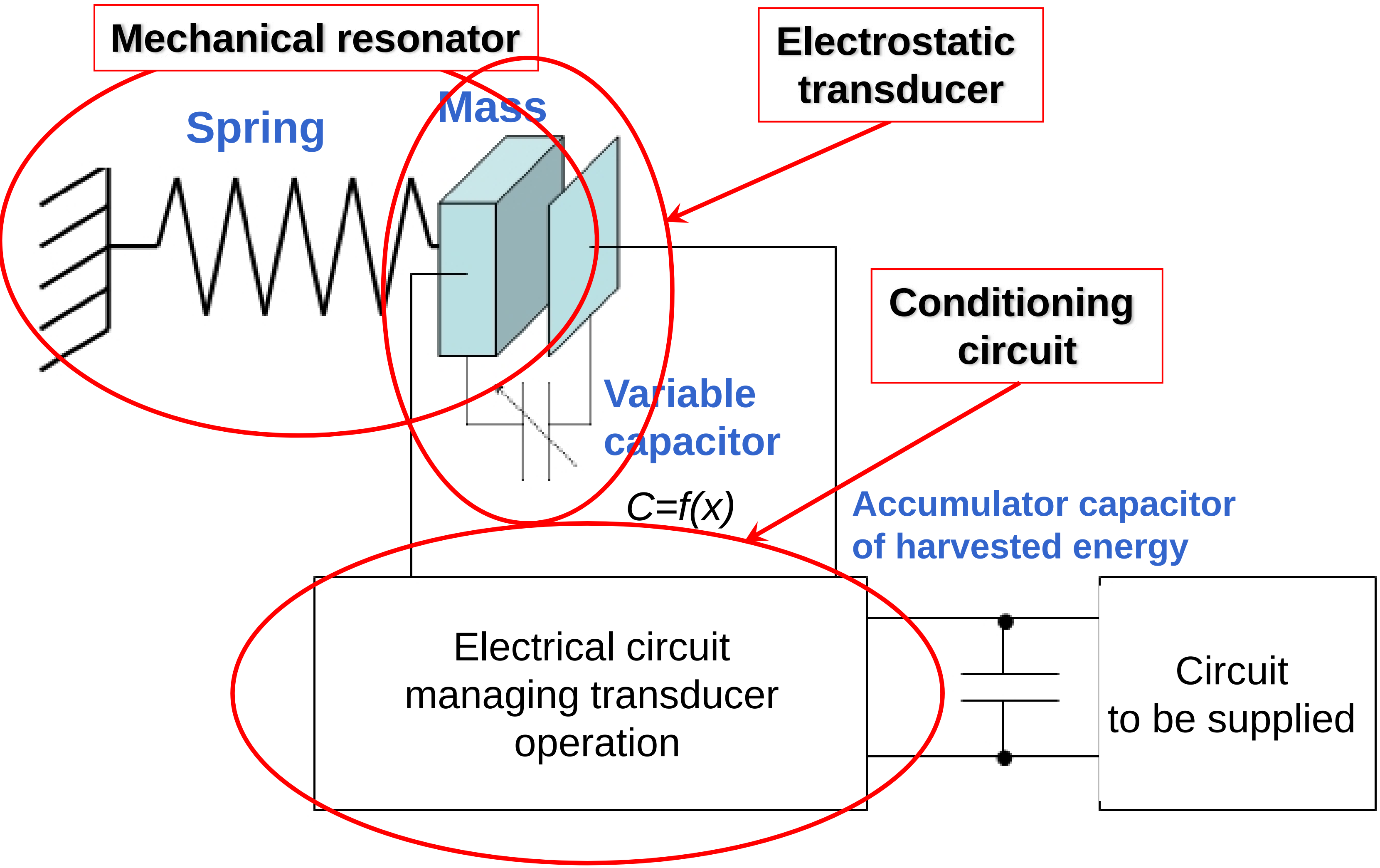
Vibration energy harvester



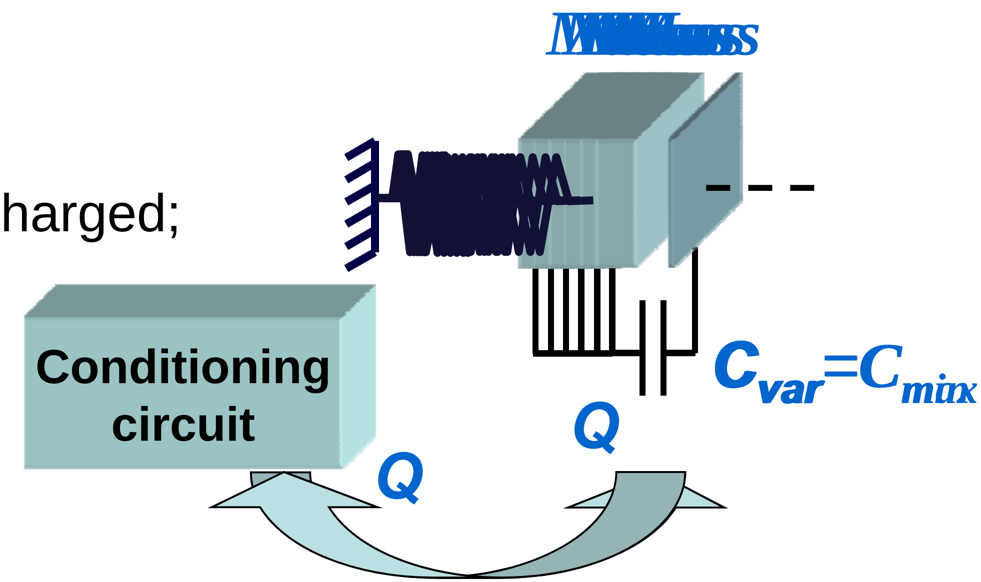
Vibration energy harvesting with a capacitive transducer

- When $C=C_{max}$, capacitance is charged; spent energy is:

$$W_1 = \frac{Q^2}{2C_{max}}$$

- When $C=C_{min}$, capacitance is discharged; returned energy is:

$$W_2 = \frac{Q^2}{2C_{\min}}$$



- Since $C_{min} < C_{max}$:

$$W_2 > W_1$$

Converted energy is:

$$\Delta W = W_2 - W_1$$

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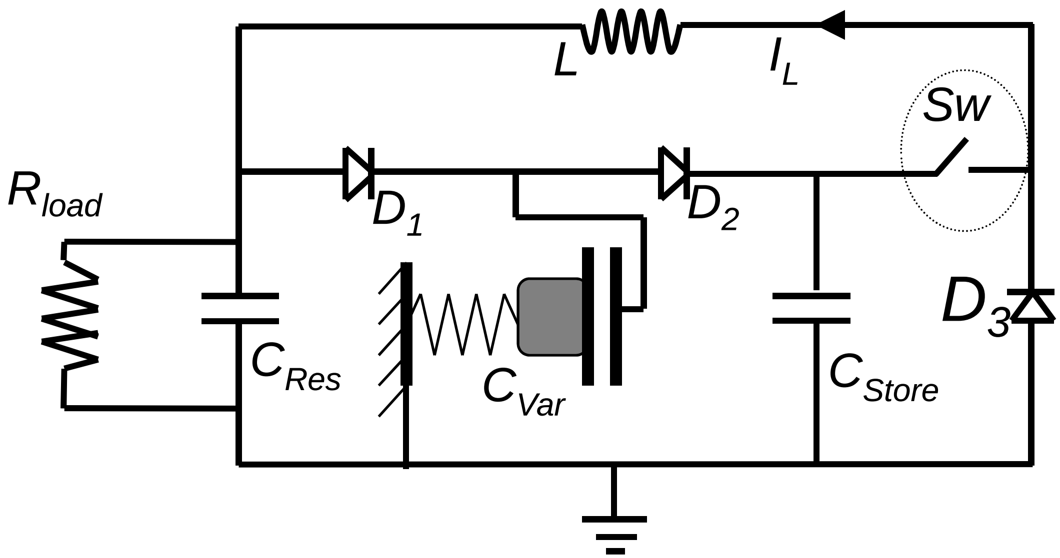
Conditioning circuit architecture

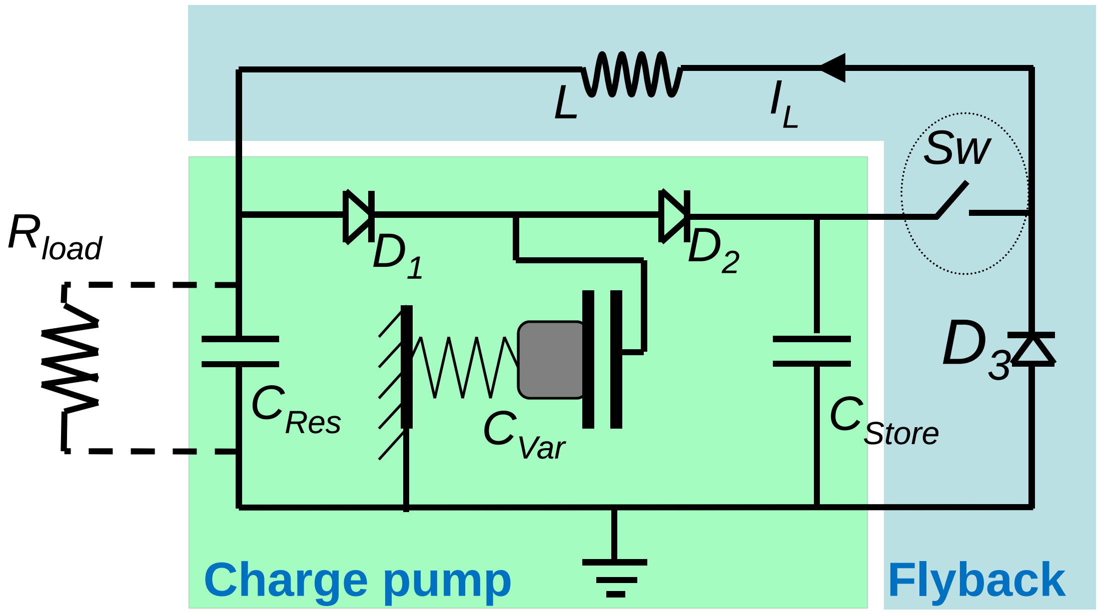


[Yen et al., 2006]

Advantages:

- Only one inductor and only one switch
- Switch doesn't need to be synhronized with Cvar variation
- Switch commutates rarely relatively to the Cvar variation frequency

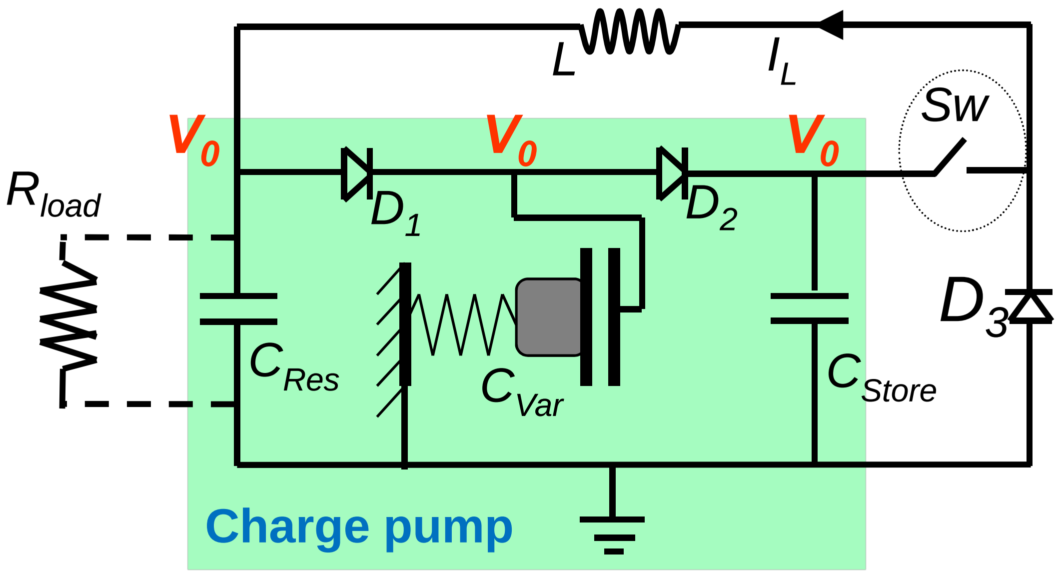
Conditioning circuit architecture



Consists of :

- a charge pump;
- a flyback circuit (Buck DC-DC converter).

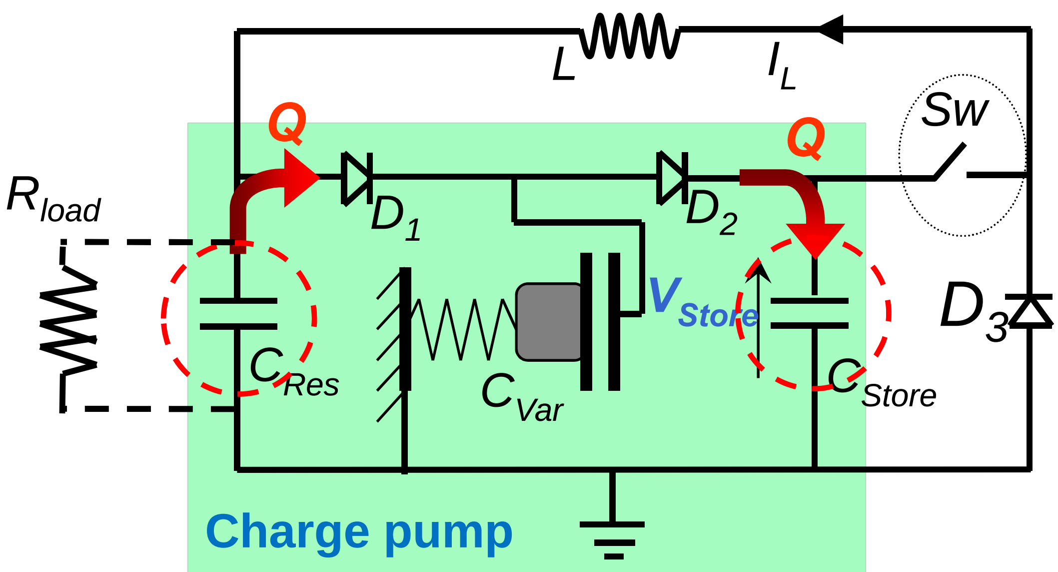
Charge pump operation



$C_{res} >> C_{store} > C_{var}$

The role of the charge pump circuit:
To generate a voltage difference between C_{res} and C_{store}.

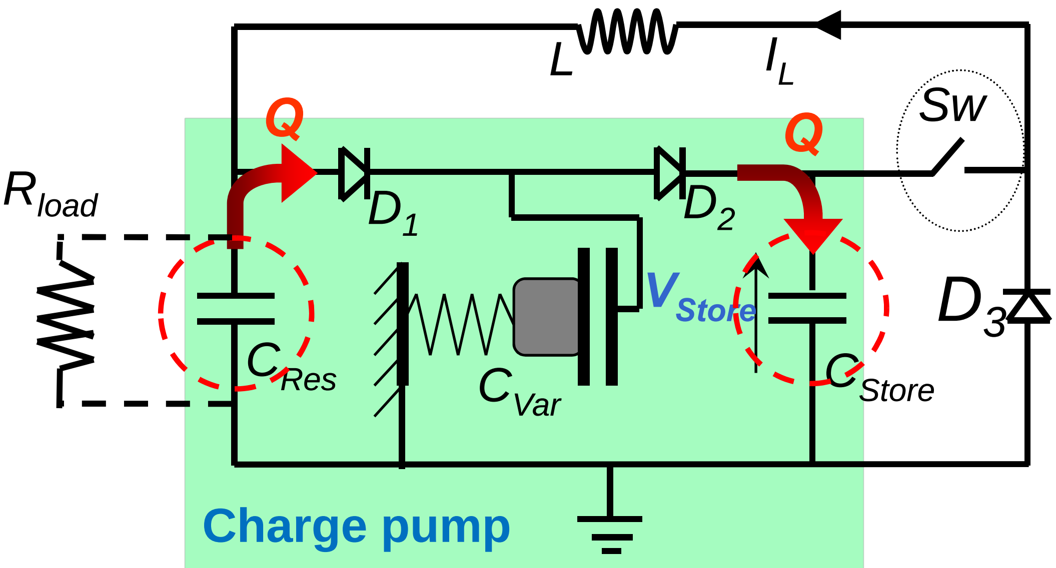
Charge pump operation



$C_{res} >> C_{store} > C_{var}$

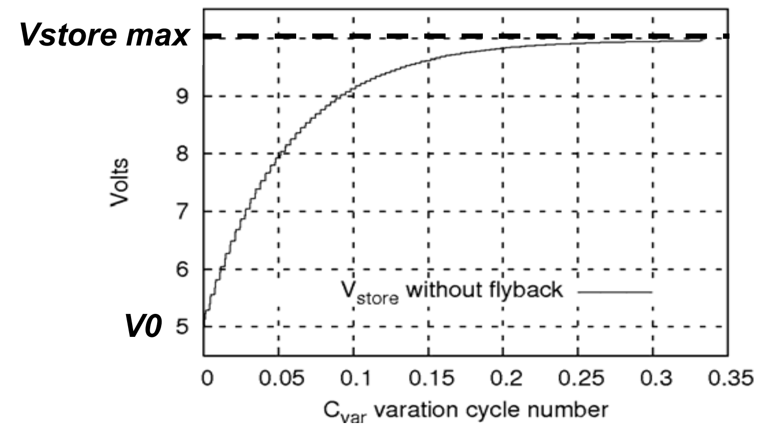
Transfer electrical charges from C_{res} to C_{store} making use of variation of C_{var} as a charge pump.

Charge pump operation



$$C_{res} >> C_{store} > C_{var}$$

Vstore



$$V_{store\ max} = V_0 C_{max} / C_{min}$$

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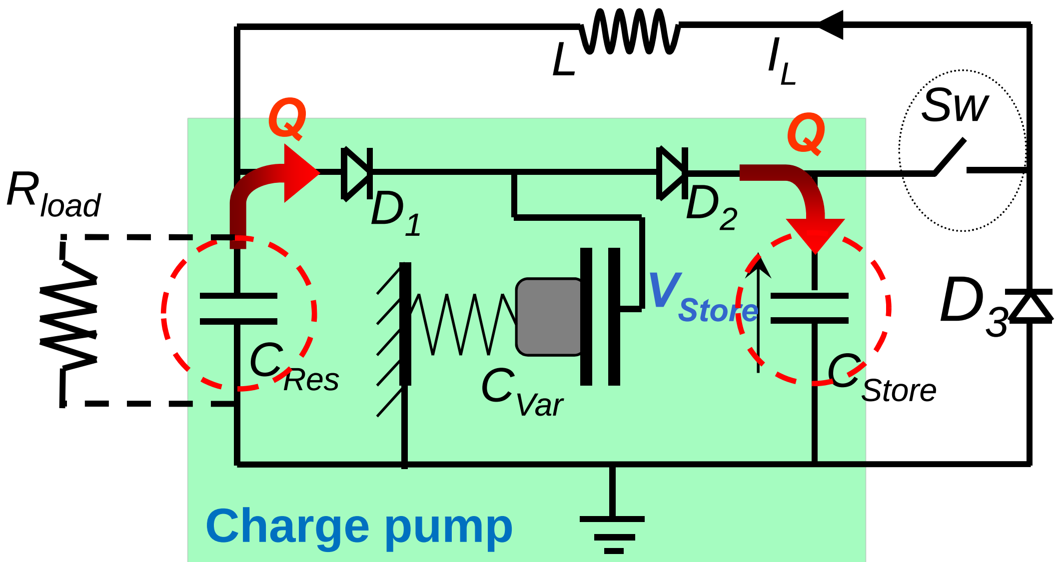
Charge pump operation



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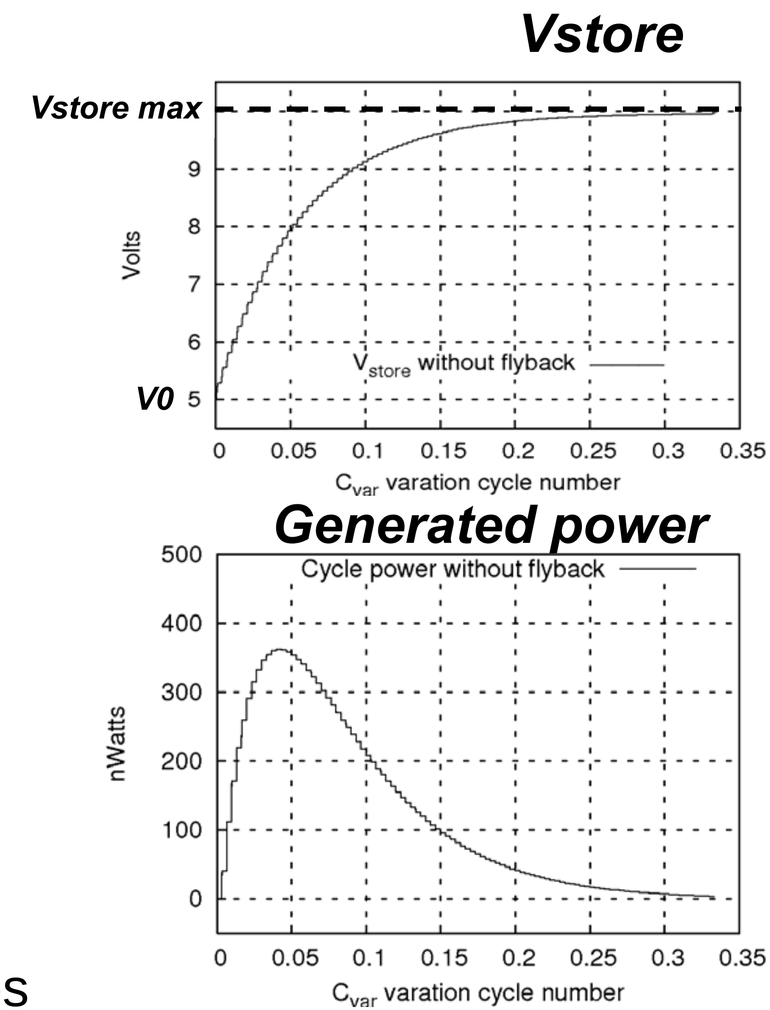
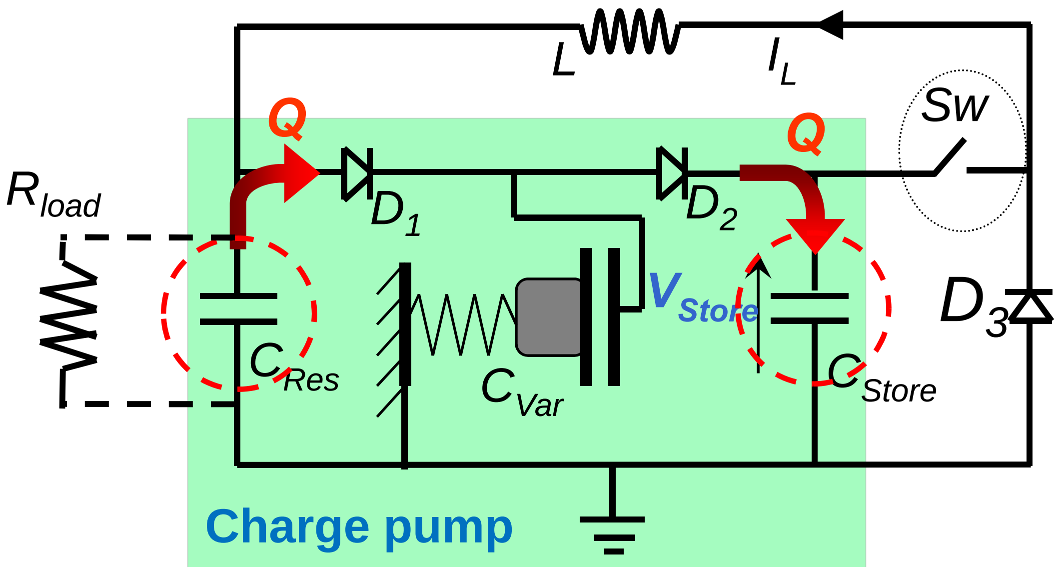


- Vstore increases quickly – average power increases and becomes maximal;
- Vstore saturates – average power decreases and drops to zero.

Charge pump operation



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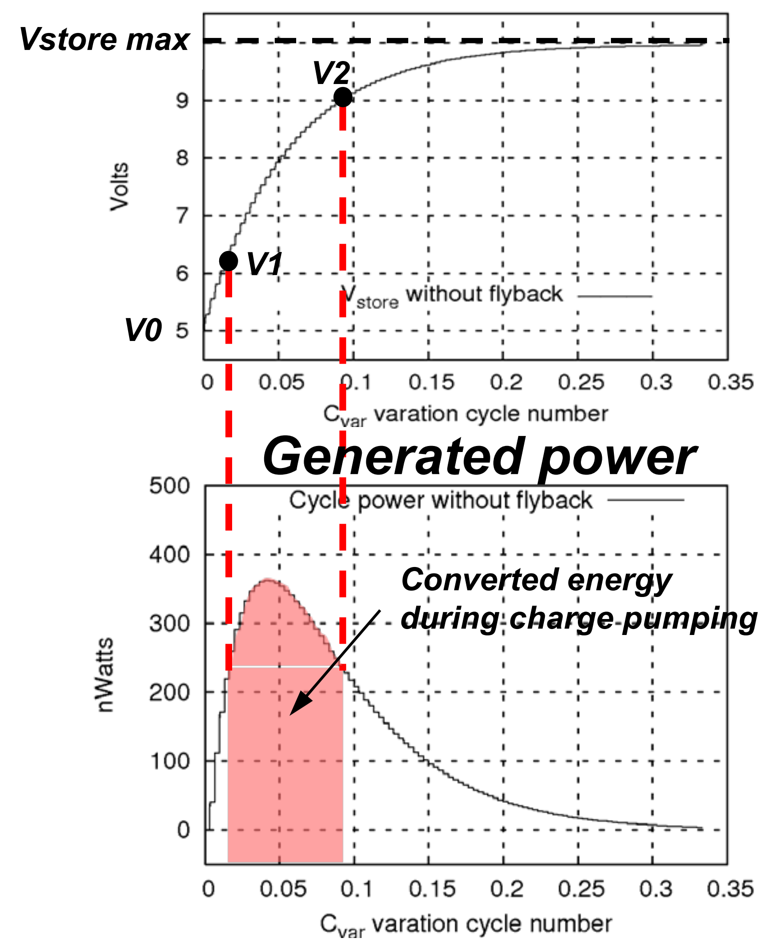

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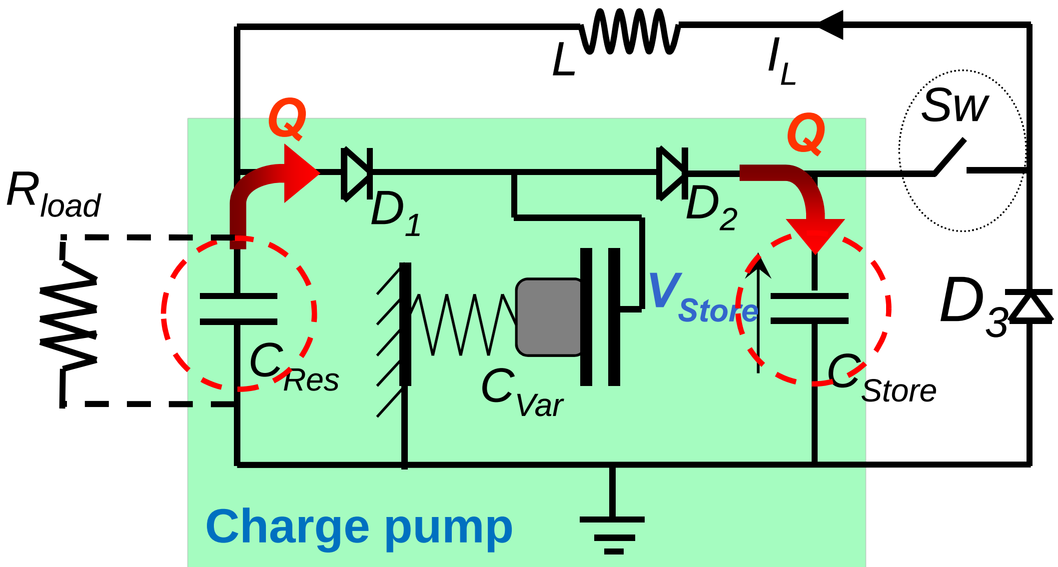

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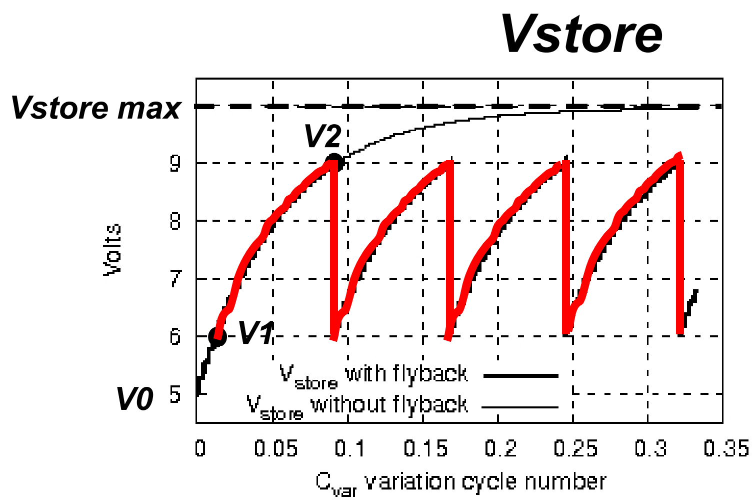
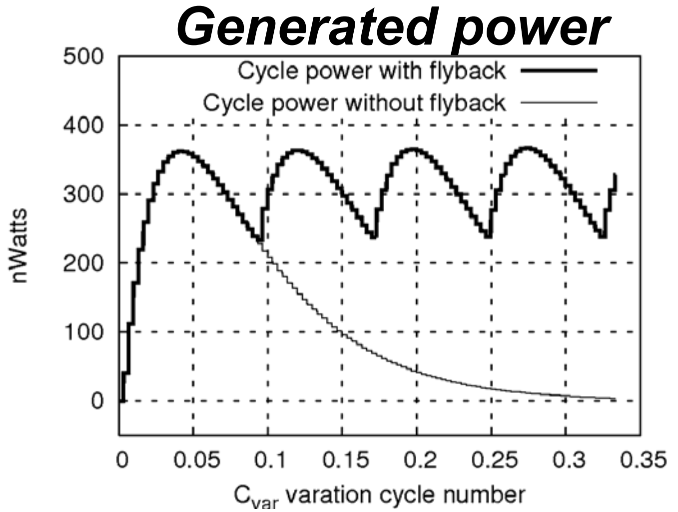
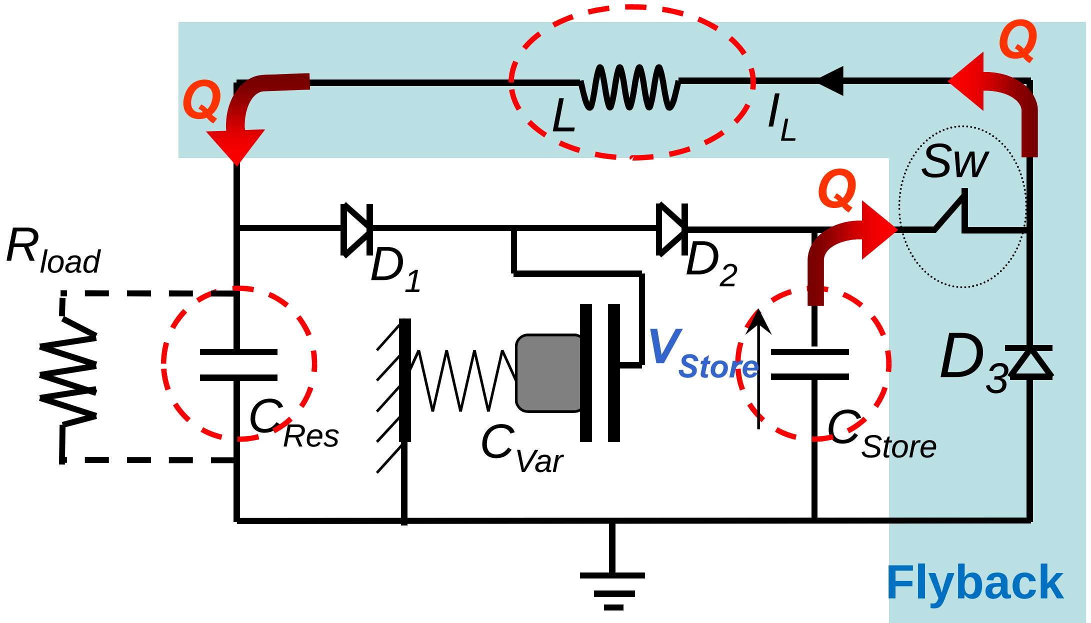
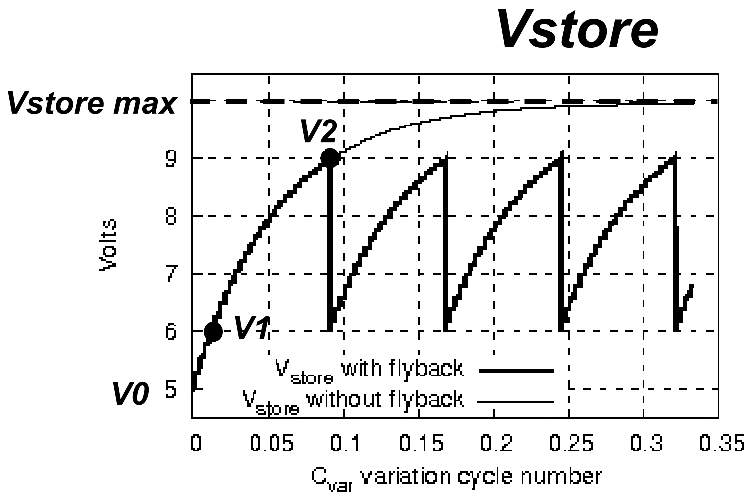
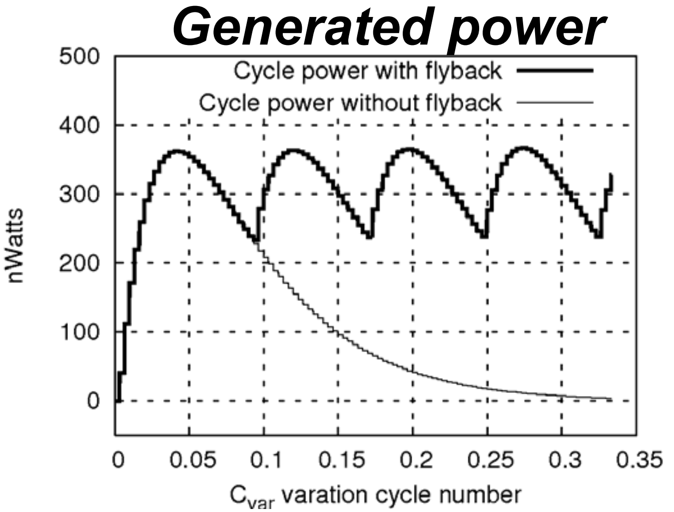




Flyback circuit operation

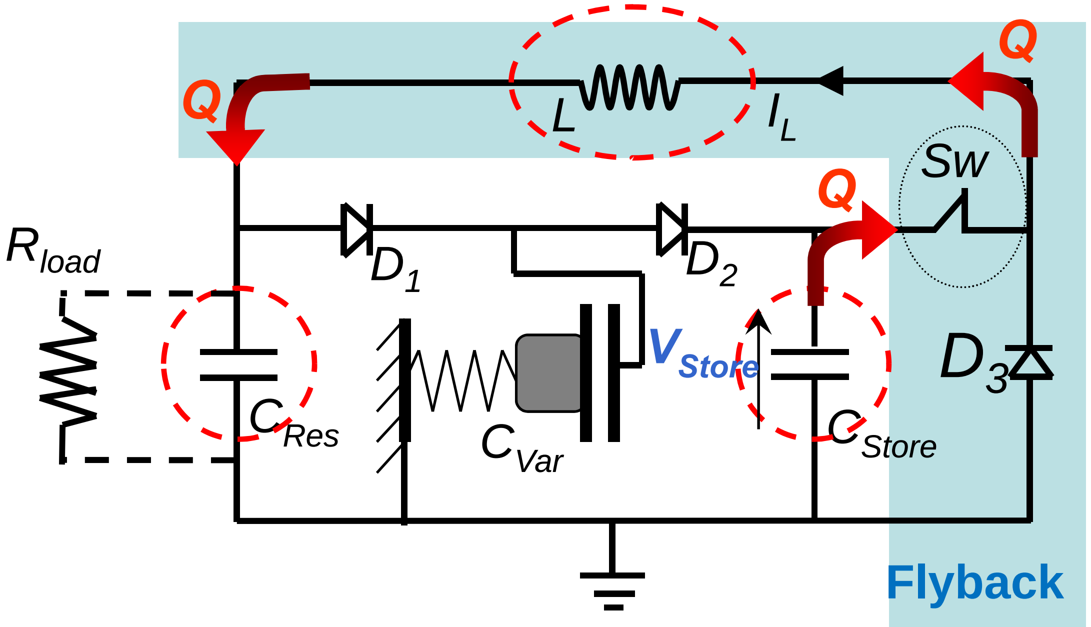


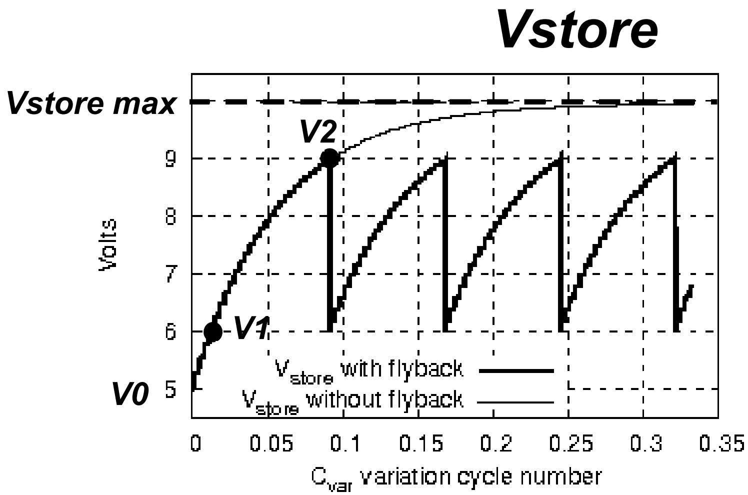


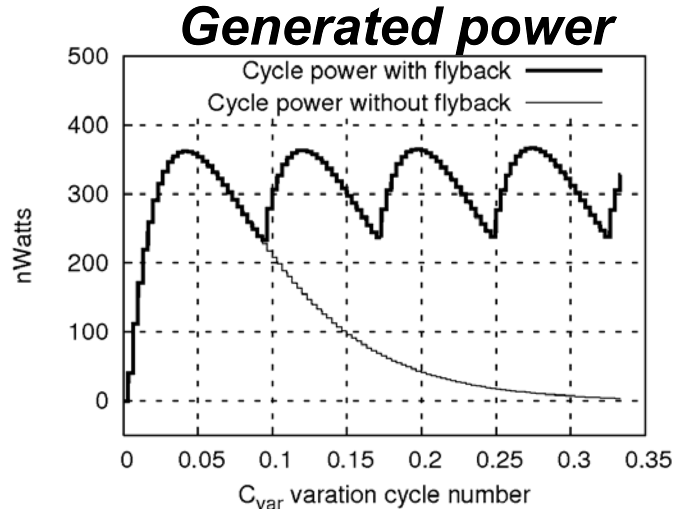


Composed of a BUCK DC-DC Converter

Flyback circuit operation

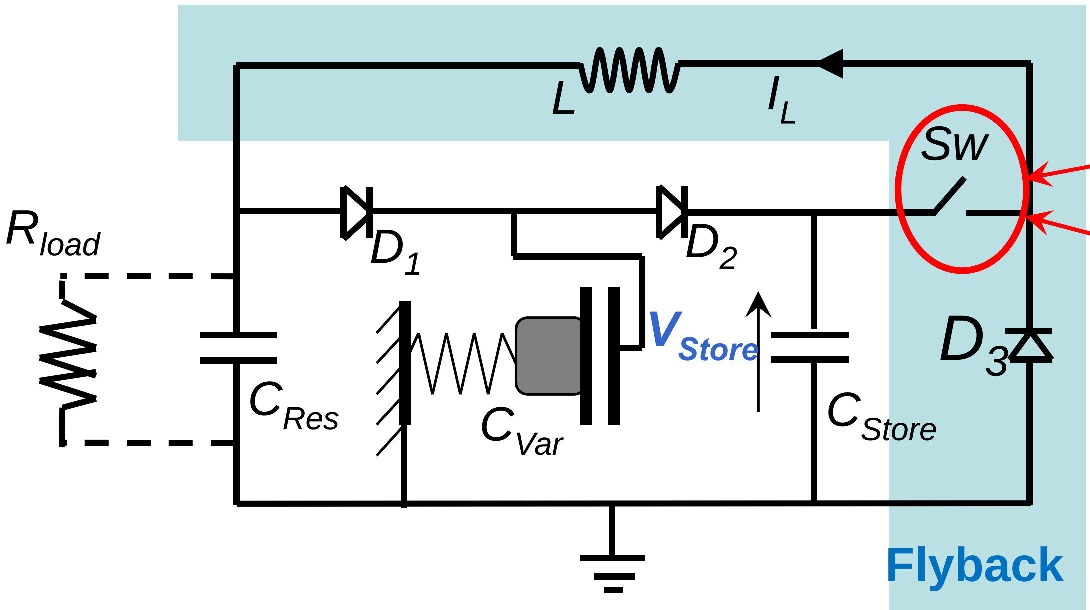


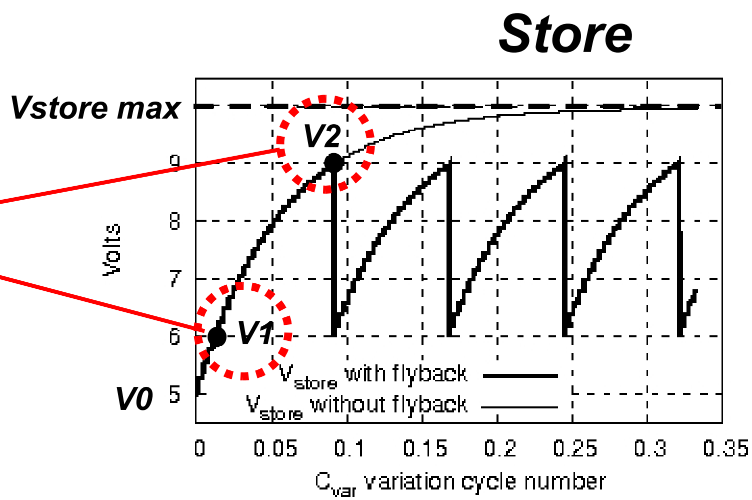


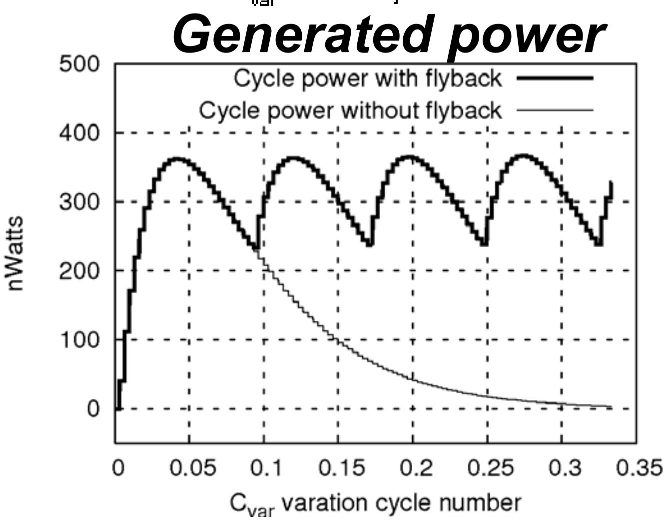


The role of the flyback circuit:
To transfer the charges and the energy from Cstore to Cres using the inductor as an energy buffer and to reset the system to its initial state ($V_{store} = V_1$)

Flyback circuit operation







Commutation parameters V_1 and V_2 are calculated with emperical formula:

$V_1 = V_{res} + 0.1(V_{store\ max} - V_{res});$

$V_2 = V_{res} + 0.6(V_{store\ max} - V_{res}),$

where $V_{store\ max} = V_{res} C_{max} / C_{min}$

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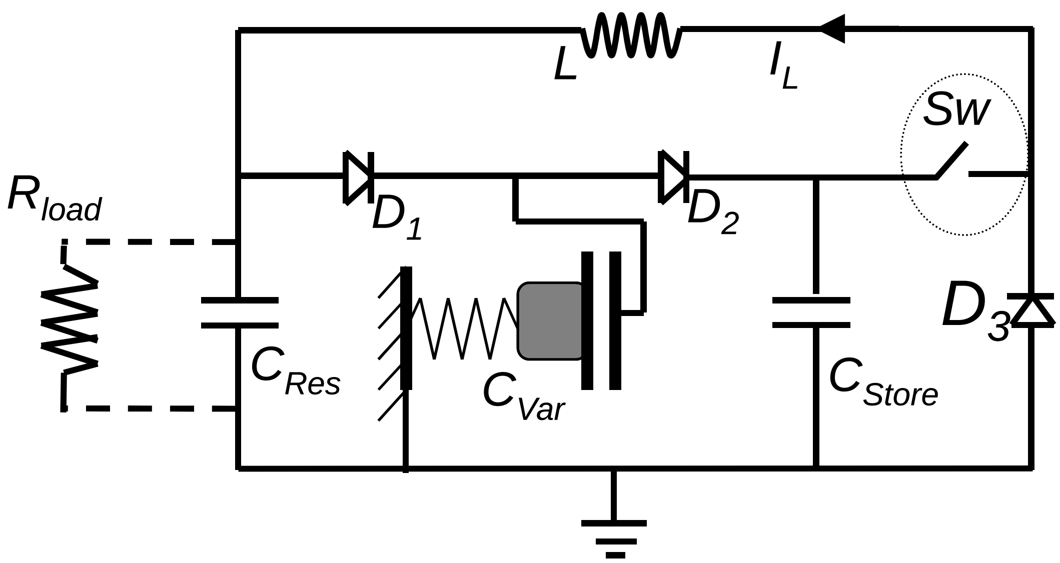
Goals of the work

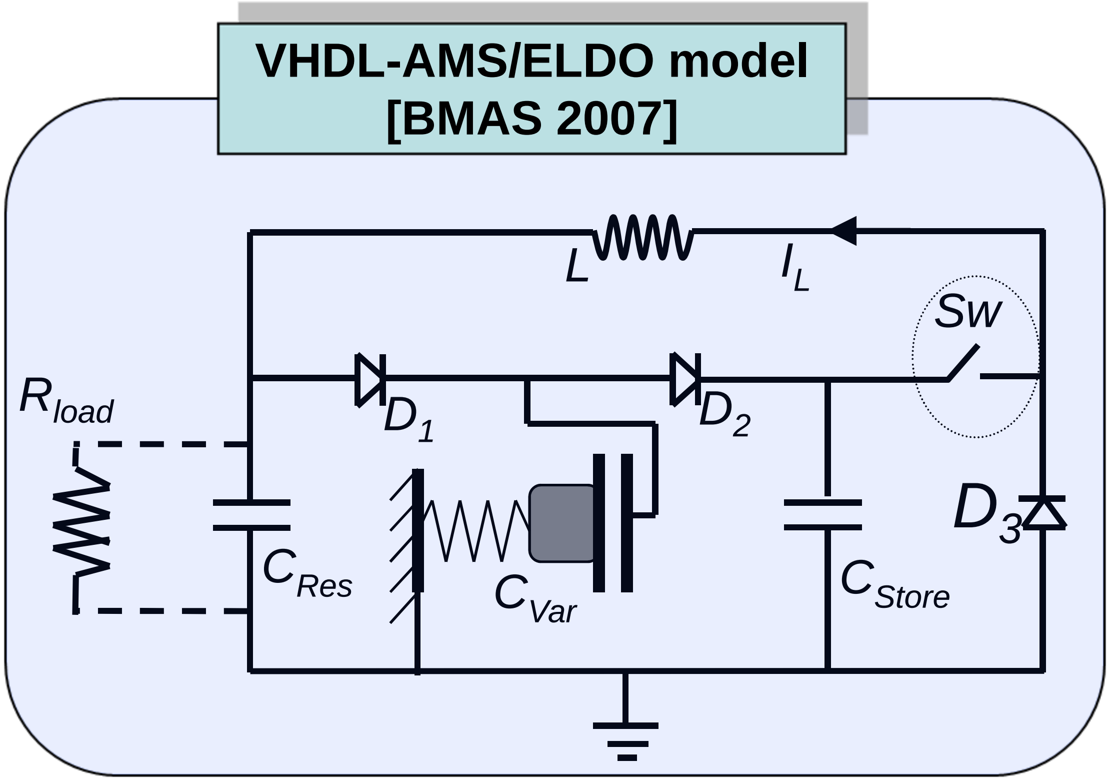
- To adapt the system to the variations of the external vibration parameters.

- To provide interface with the load



In this paper:

- We present solutions to these two problems
- We validate them through behaviour modeling by improving the existing VHDL-AMS model of the basic configuration (BMAS 2007)



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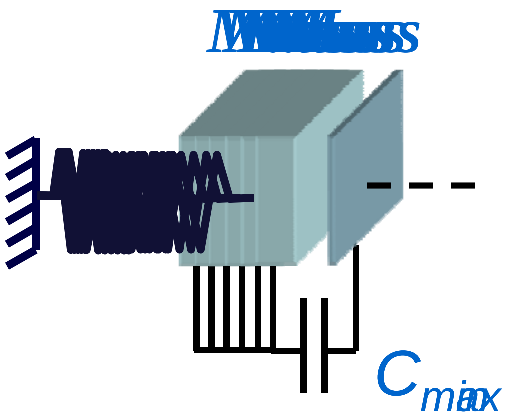
What happens when parameters of vibrations change?

$V_1, V_2 \Leftarrow V_{store\ max} \Leftarrow C_{max}/C_{min} \Leftarrow X_{max} \Leftarrow A_{ext}$

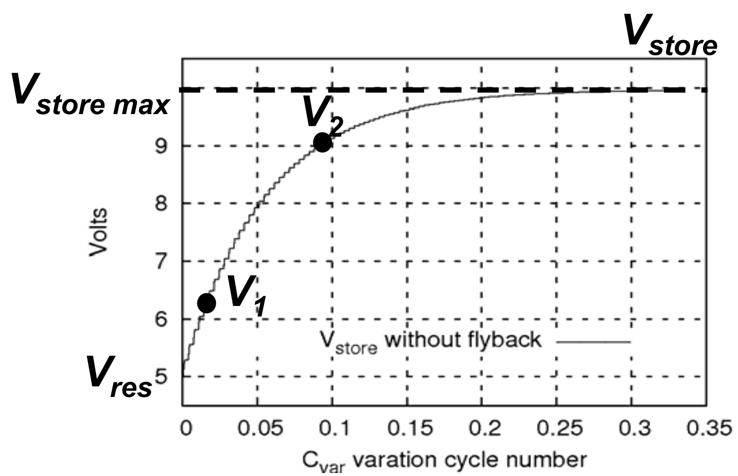


$$V_{store\ max} = V_{res}\, C_{max}/C_{min}$$

$$V_1 = V_{res} + 0.1\,(V_{store\ max} - V_{res})$$

$$V_2 = V_{res} + 0.6\,(V_{store\ max} - V_{res}),$$

Hence, V_1 and V_2 should be updated periodically

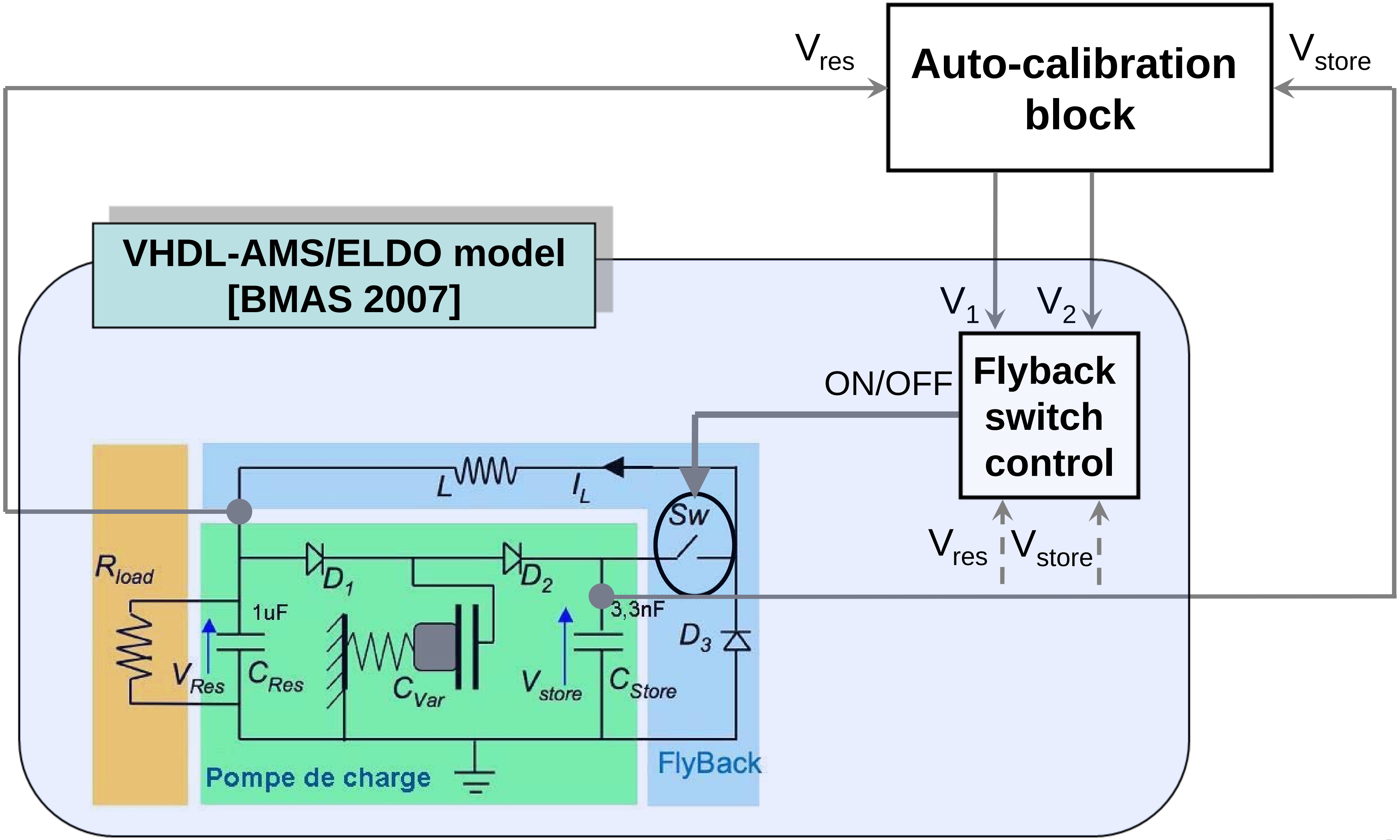


How to measure $V_{store\ max}$?

Solution:

Periodic AUTO-CALIBRATION phase.

Modeling blocks of the system



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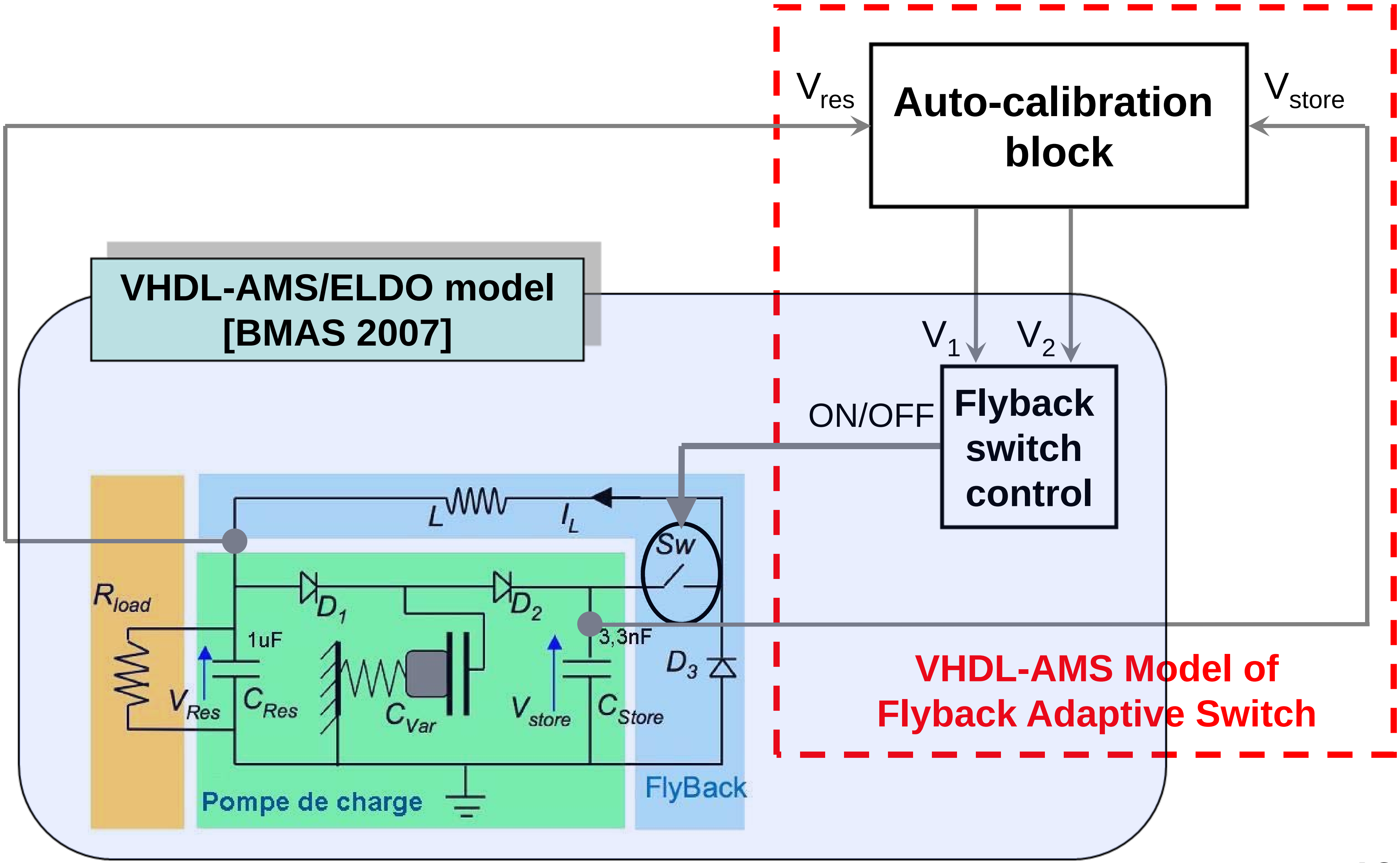
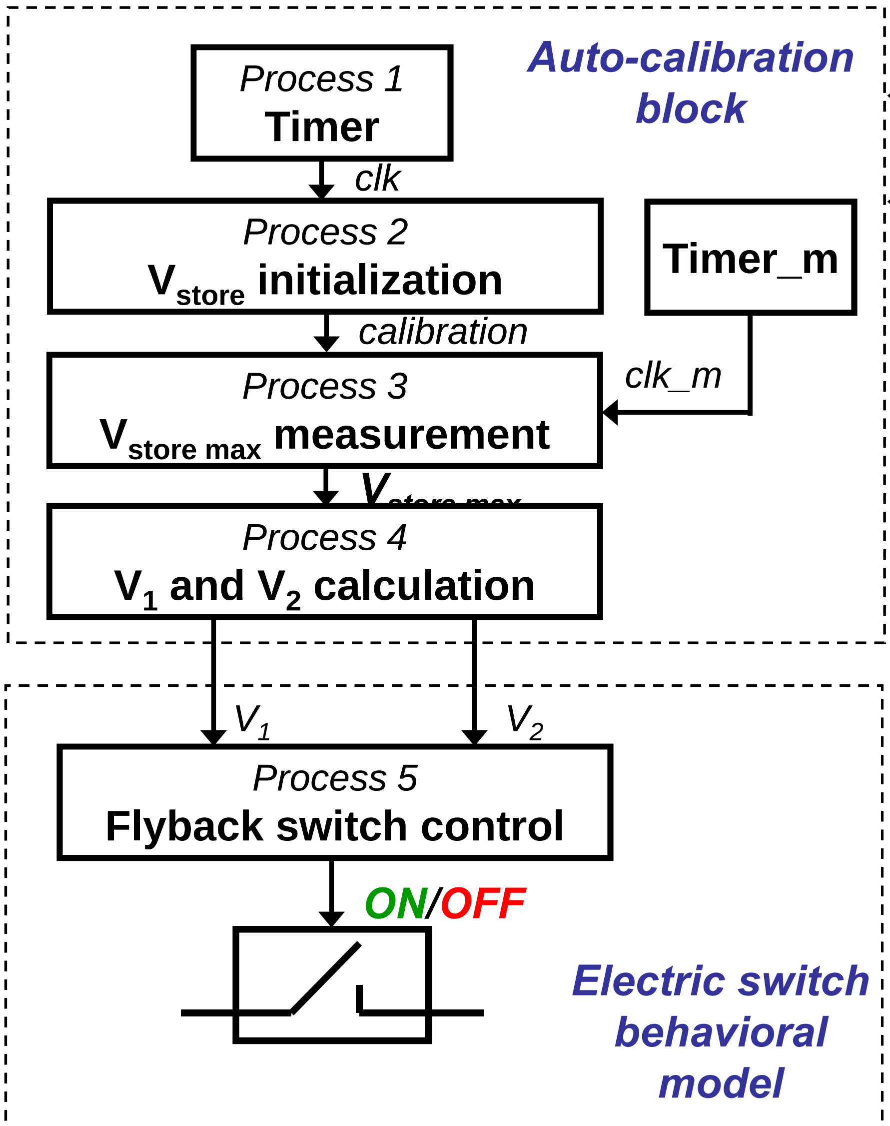
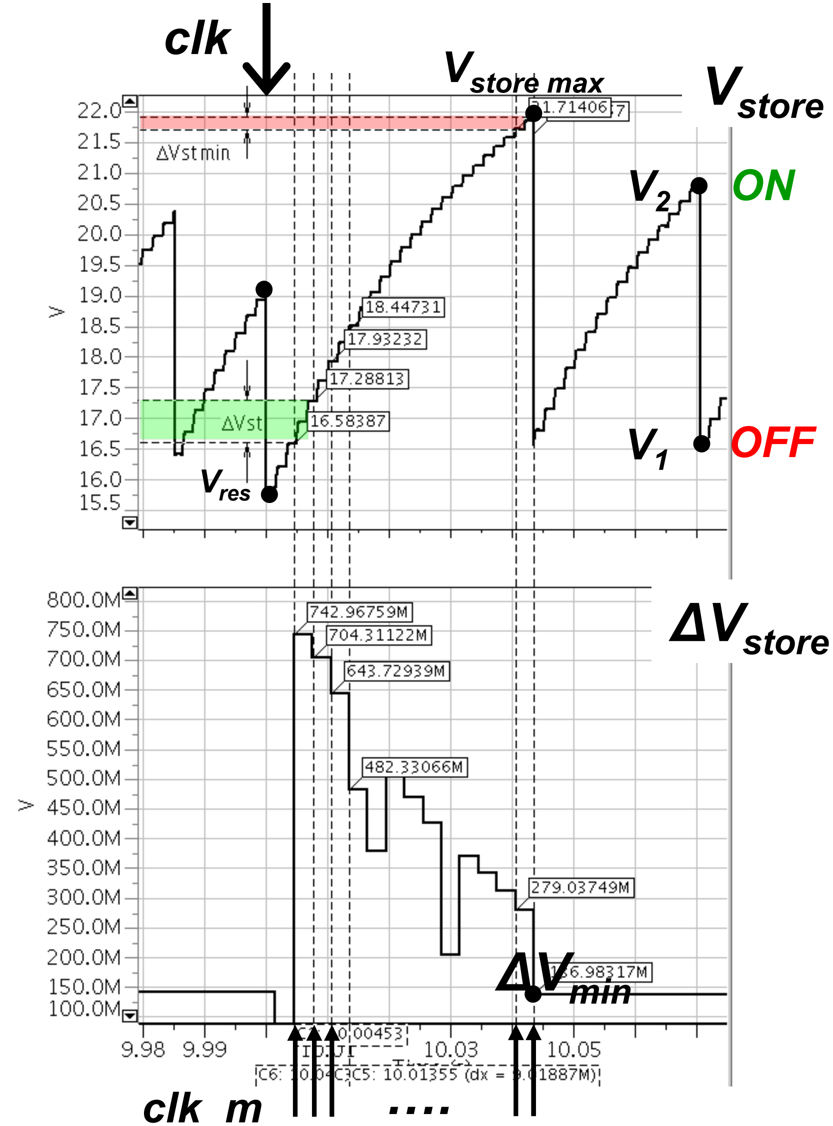


Structure of VHDL-AMS model of the adaptive switch





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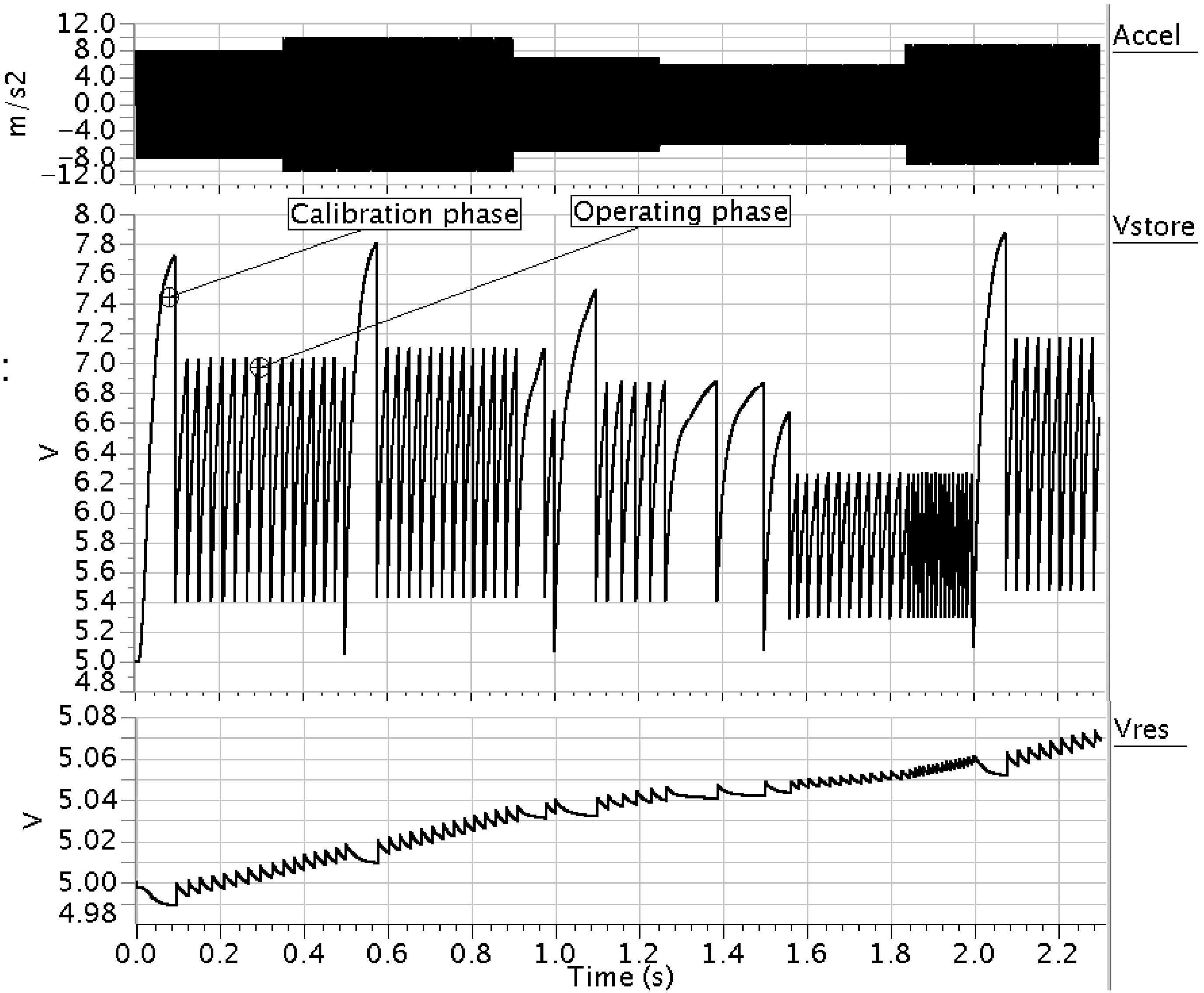
Simulation results of model with adaptive switch (Example)

- Acceleration
  - amplitude: 4.5 to 10 m/s²
  - frequency: 300 Hz

- Calibration phase: every 500 ms

Increasing of Vres corresponds to the energy harvesting



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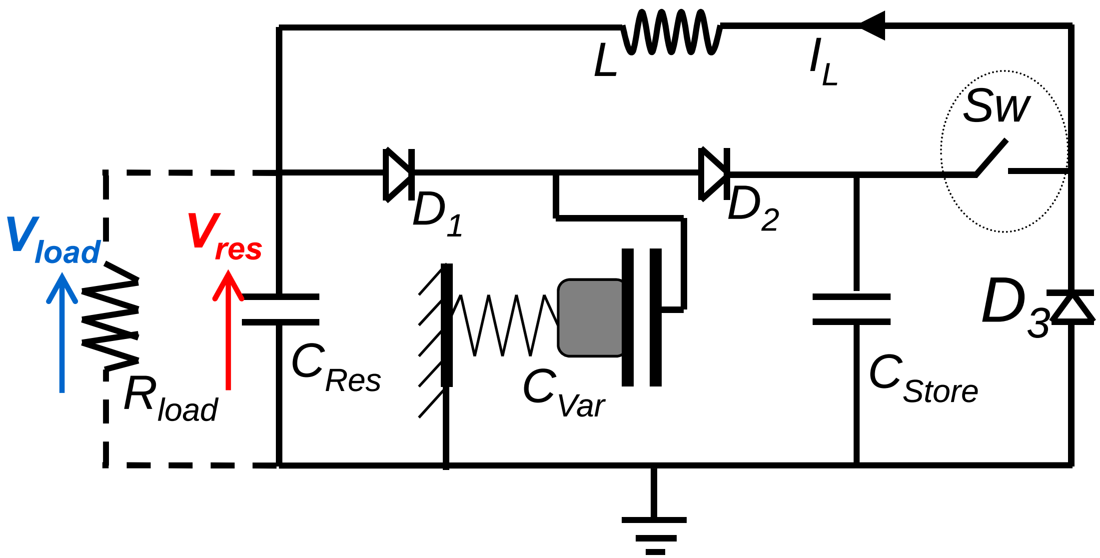
Motivation for Improved architecture of the conditioni

V_{res} – needs High Voltages
V_{load} – needs Low Voltages

} The load interface is required



Improved architecture of the conditioning circuit

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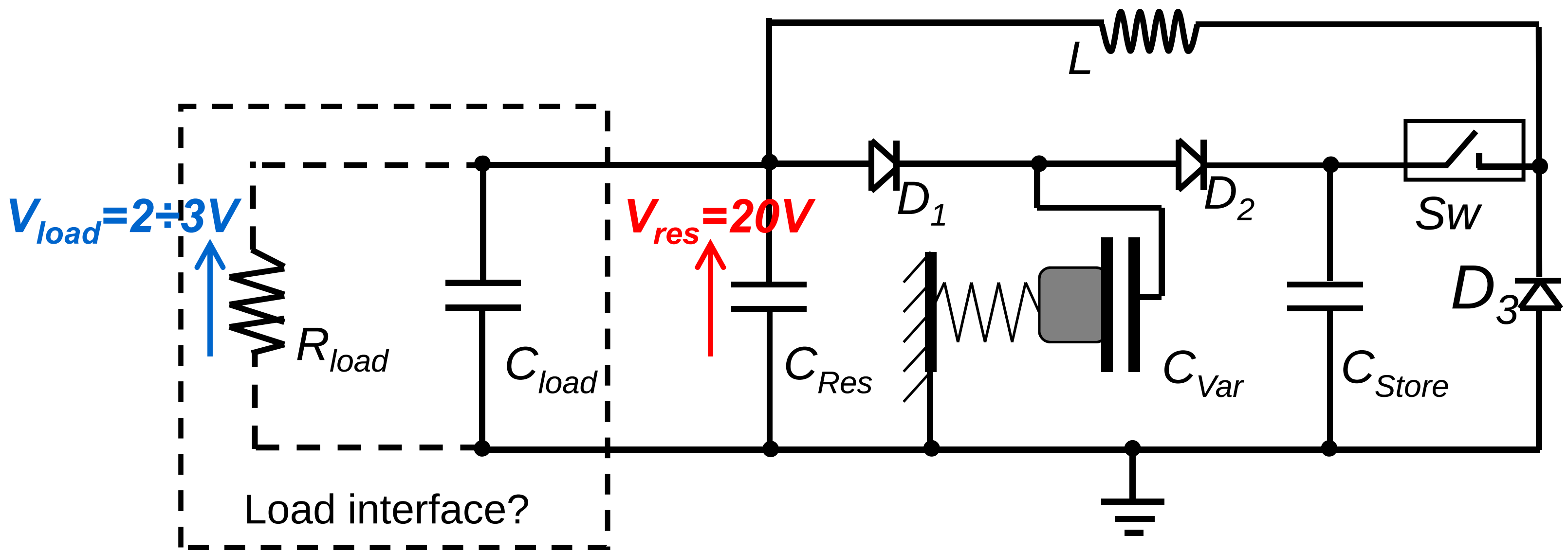
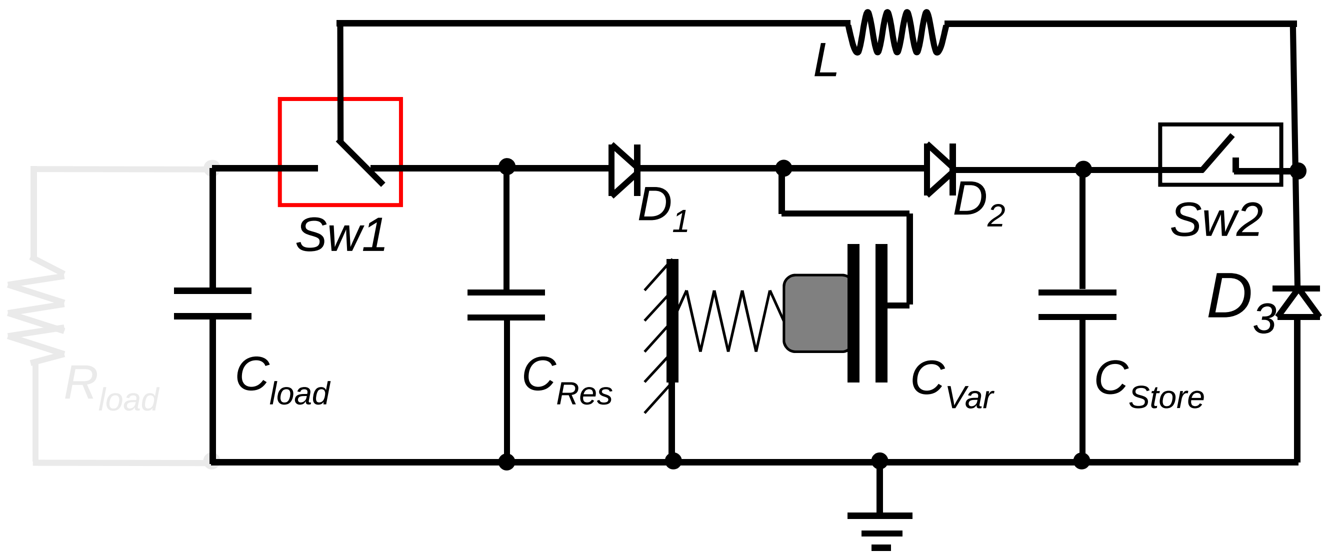


Improved architecture of the conditioning circuit

Decision: reuse the existing DC-DC converter



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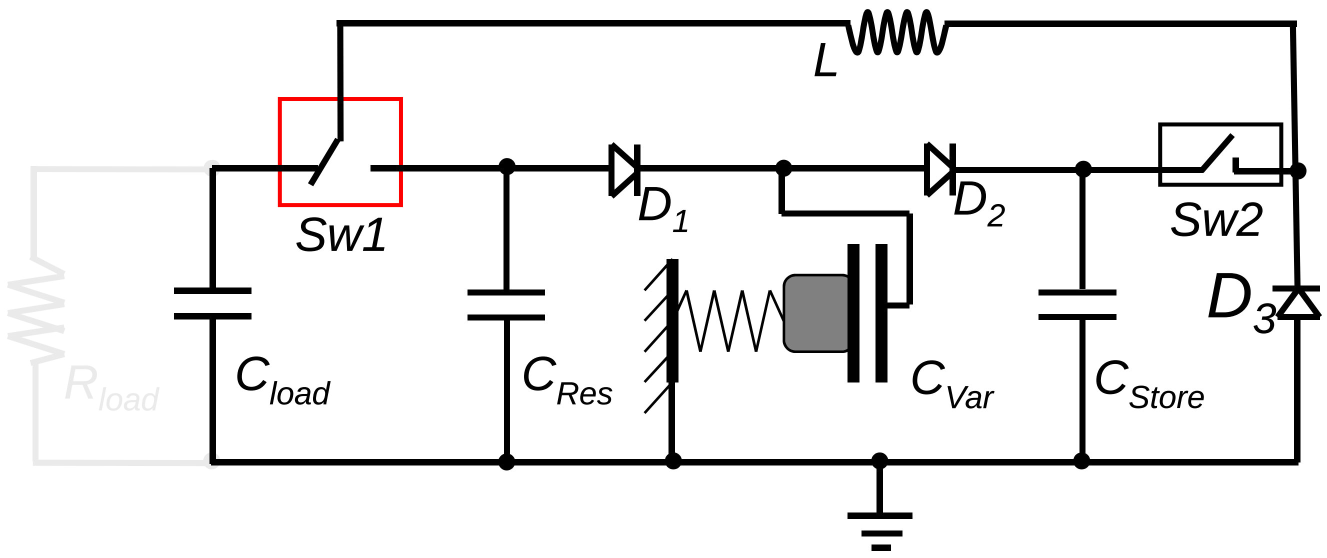

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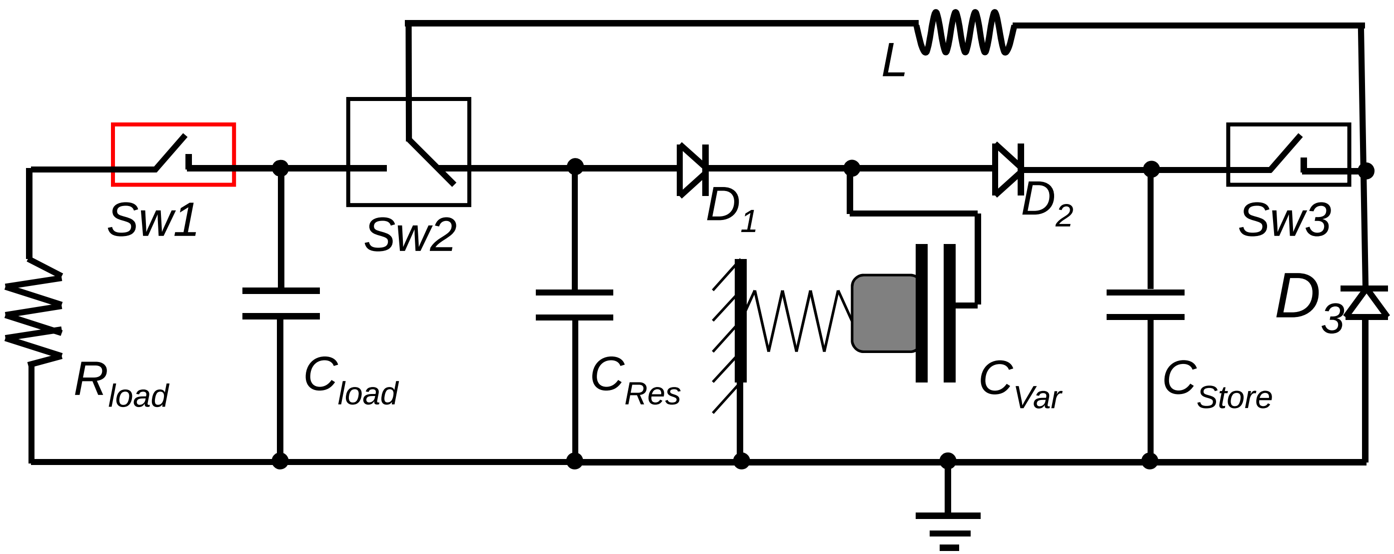
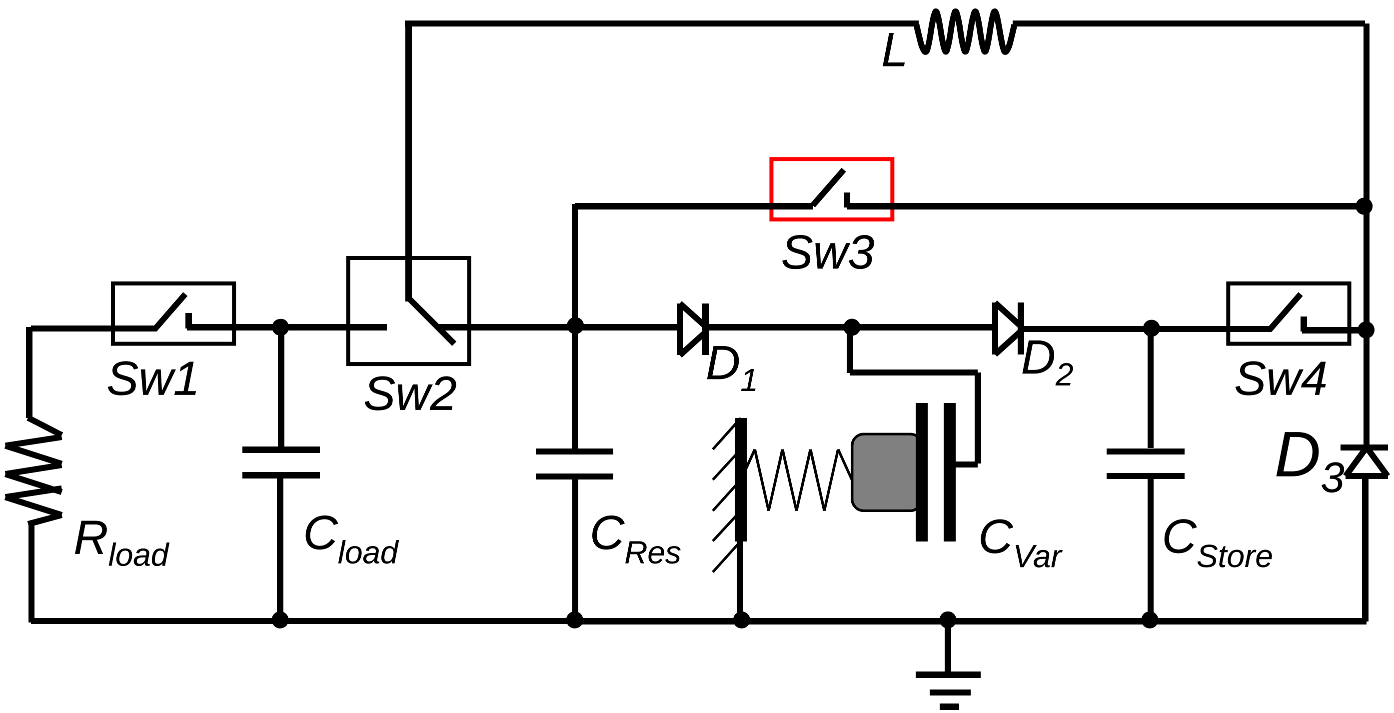


Improved architecture of the conditioning circuit



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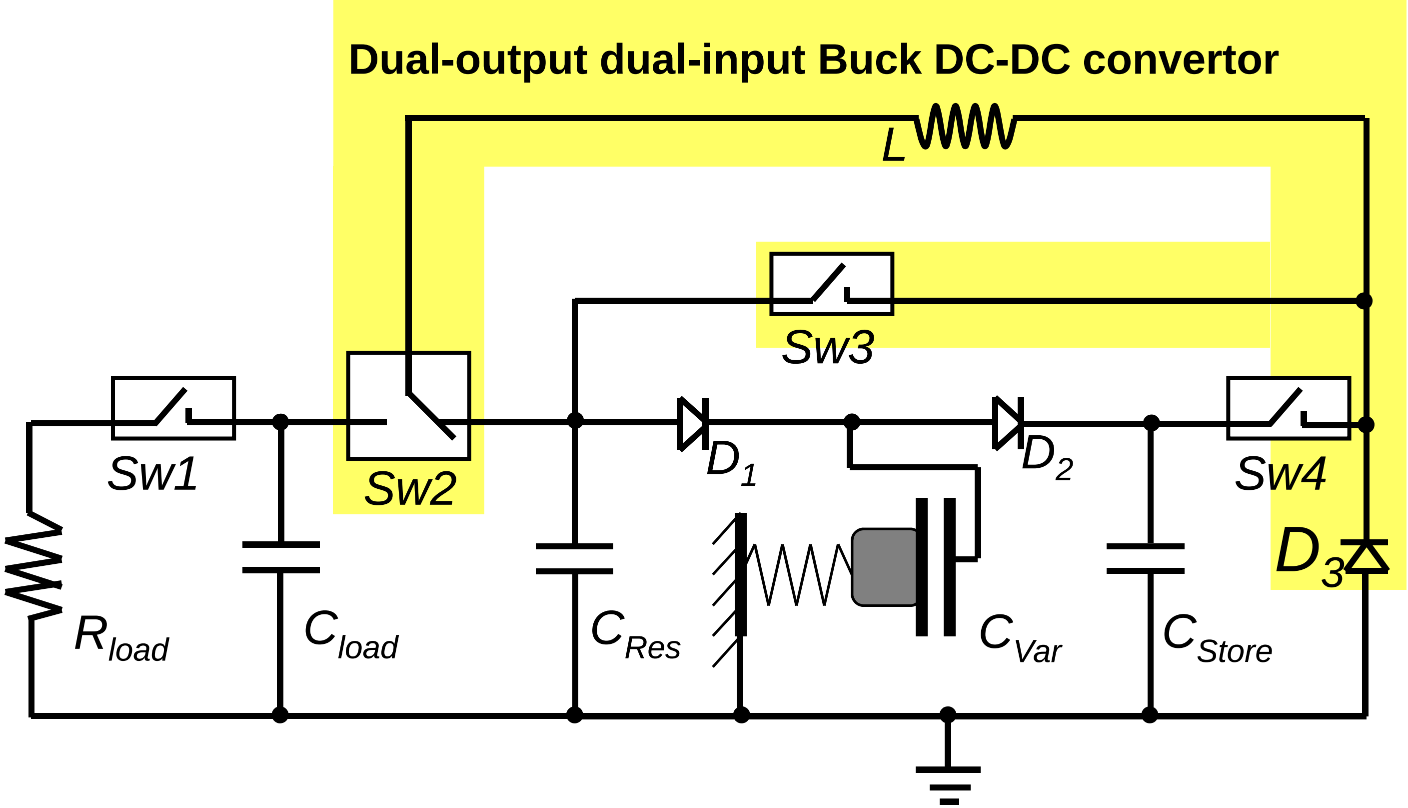

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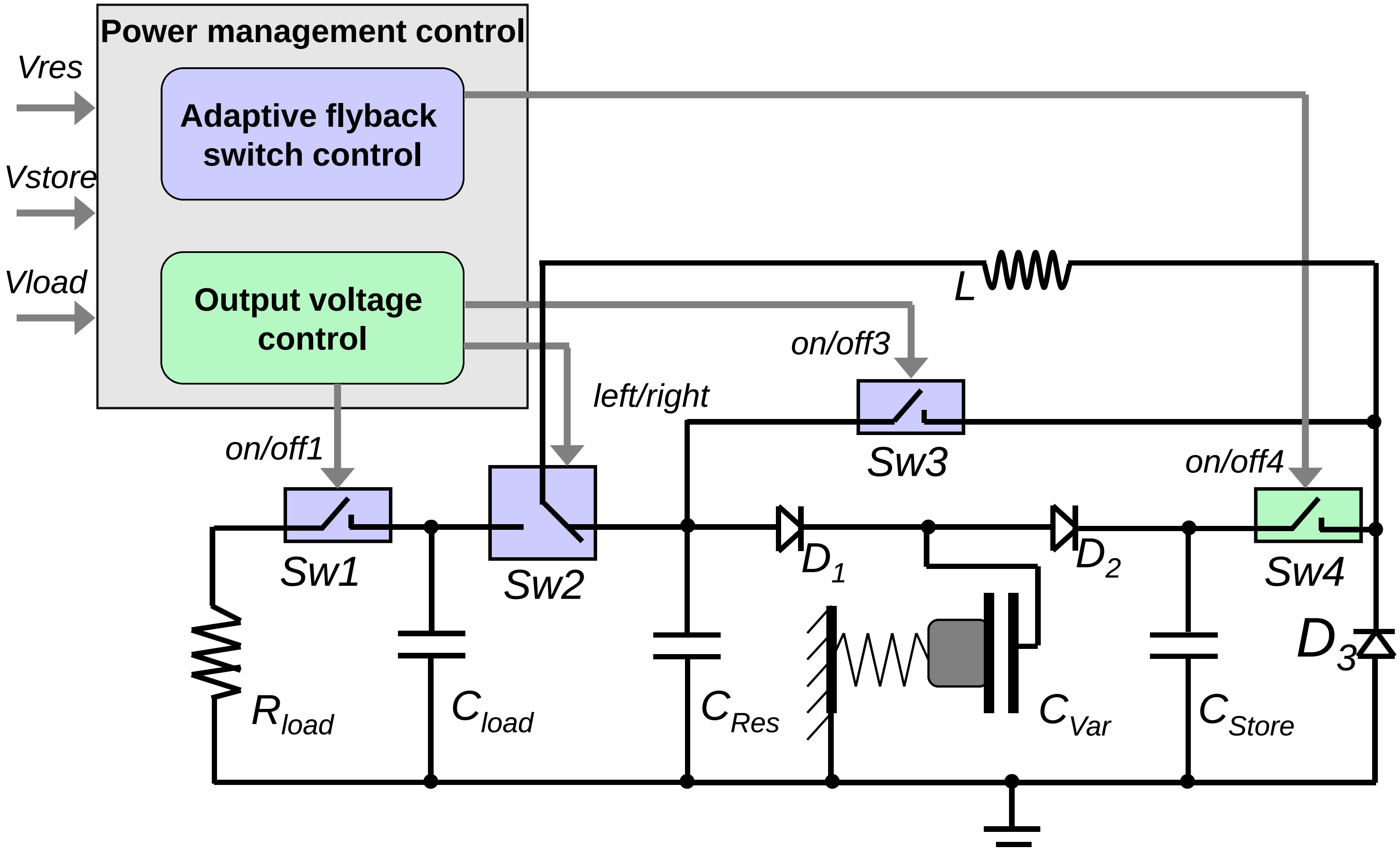

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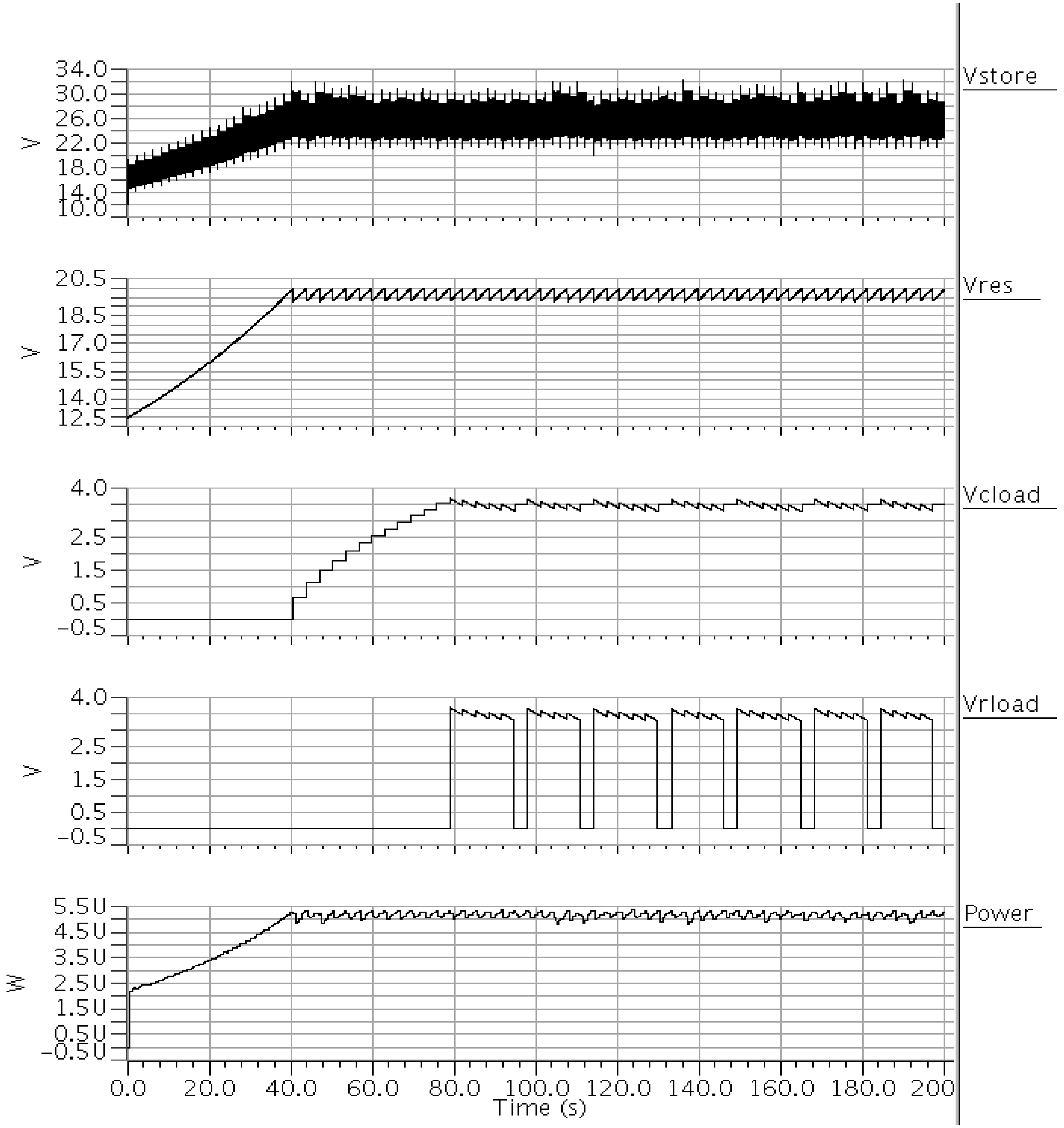
Simulation results of model with power management (Example)

3 operation phases:

- Accumulation of internal energy
- Charging of Cload capacitor aimed for the load supplying
- Load supplying phase

Power generated by harvester →



Modeling results – Example

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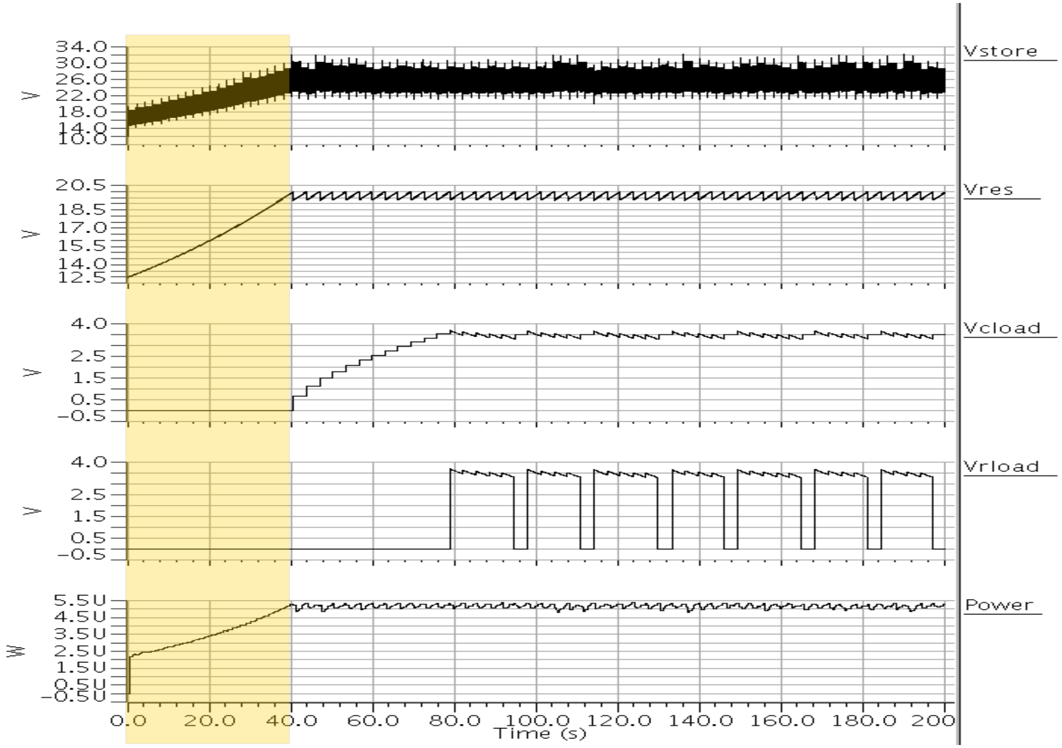

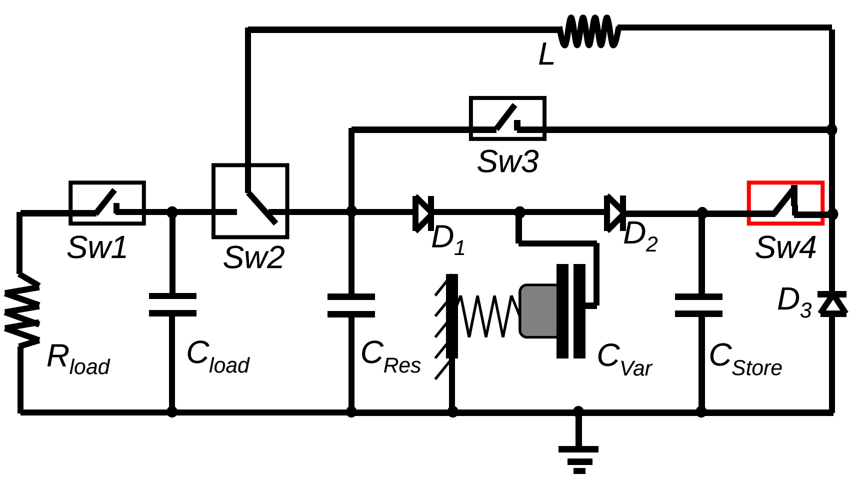

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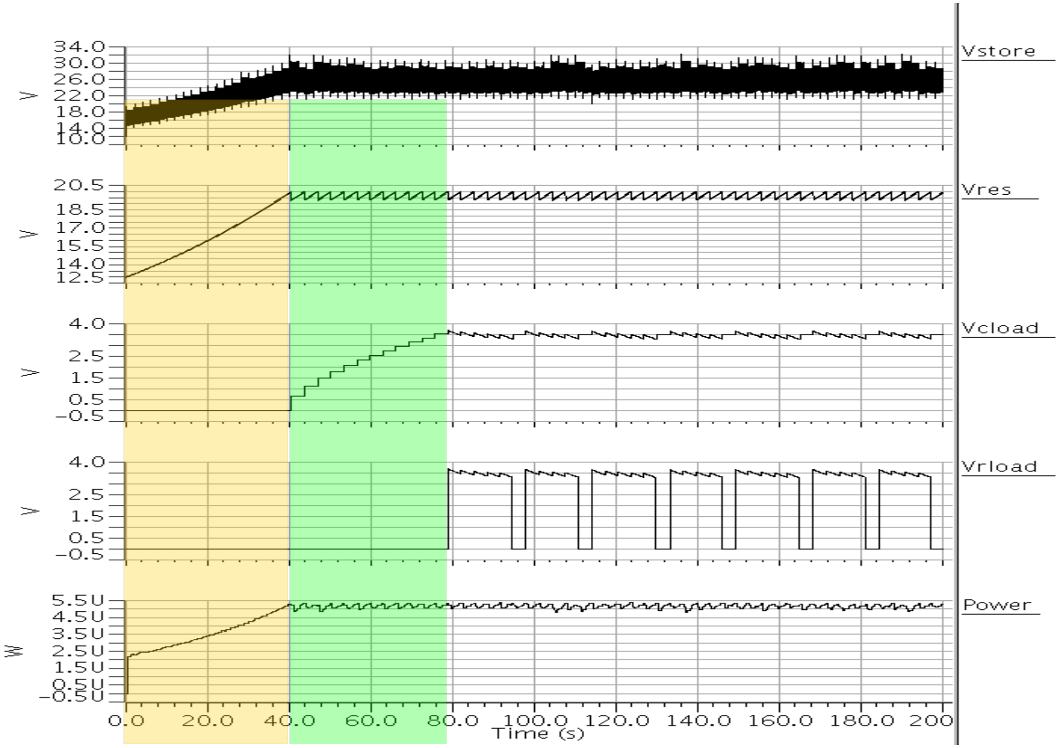

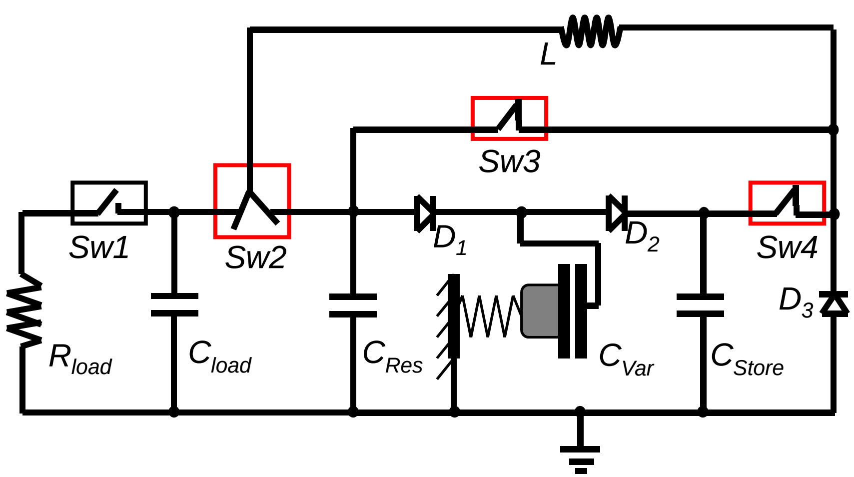

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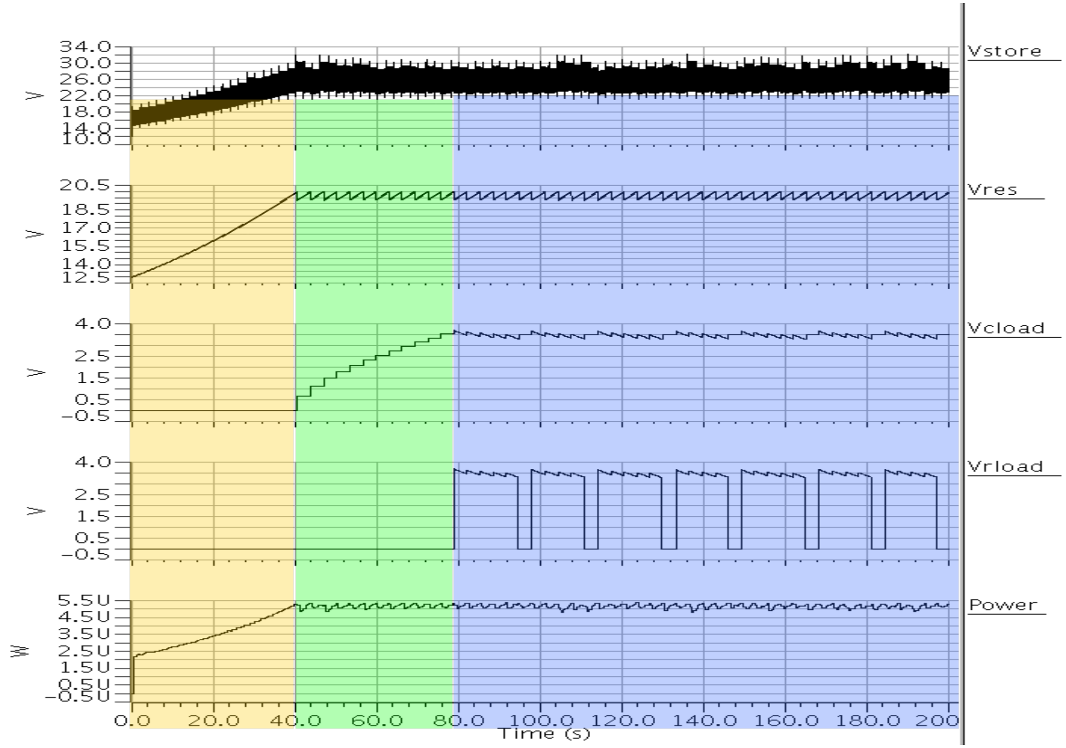

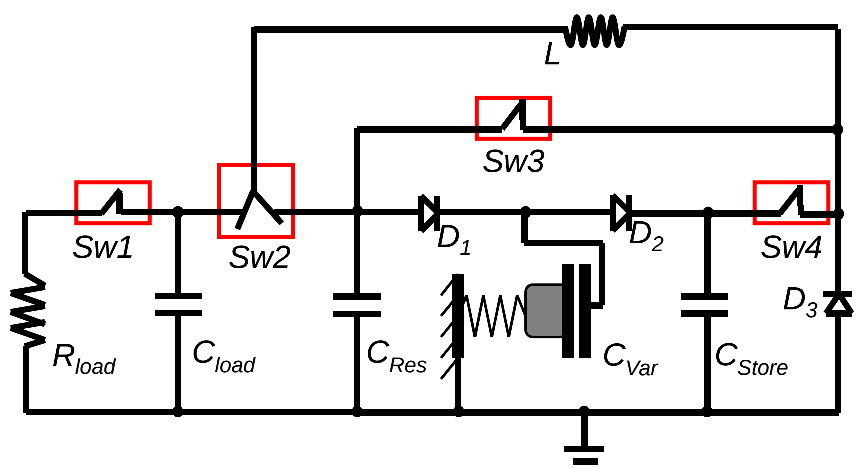

Conclusions

- Developed algorithm allows to adapt the system to the environment conditions.
- Proposed hardware architecture with power management facilities can operate following different algorithms.
- The switches should be implemented by high-voltage transistors.
- Average power from simulation results:
  5uW with 20V of Vres.