AMS modeling of controlled switch for design optimization of capacitive vibration energy harvester

Dimitri Galayko, Rodrigo Pizarro, Philippe Basset, Ayyaz Mahood Paracha, Gilles Amendola

Outline

- Introduction
- Operating and design of conditionning circuit
  - Charge pump
  - Flyback circuit
  - Optimization issues
- Modeling
  - Resonator + transducer modeling
  - Switch modeling
  - Principle of mechanical energy harvesting
- Results and conclusion

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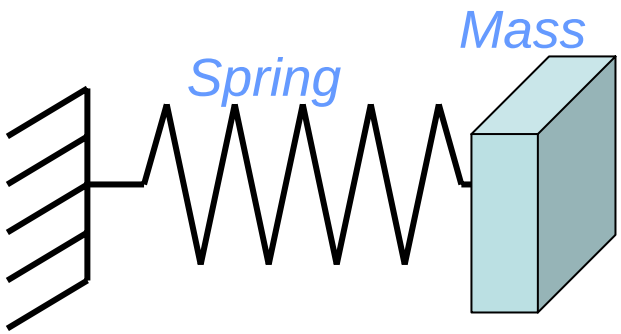
Introduction

- Motivations
  - Ambiant energy harvesting for supply of embedded low power integrated systems (wireless sensor networks…)

- Nature of energy: vibrational (mechanical)
  - Application : transportation (sensor networks in aircrafts, cars…)

Introduction

Mechanical energy harvesting principle



Resonant element

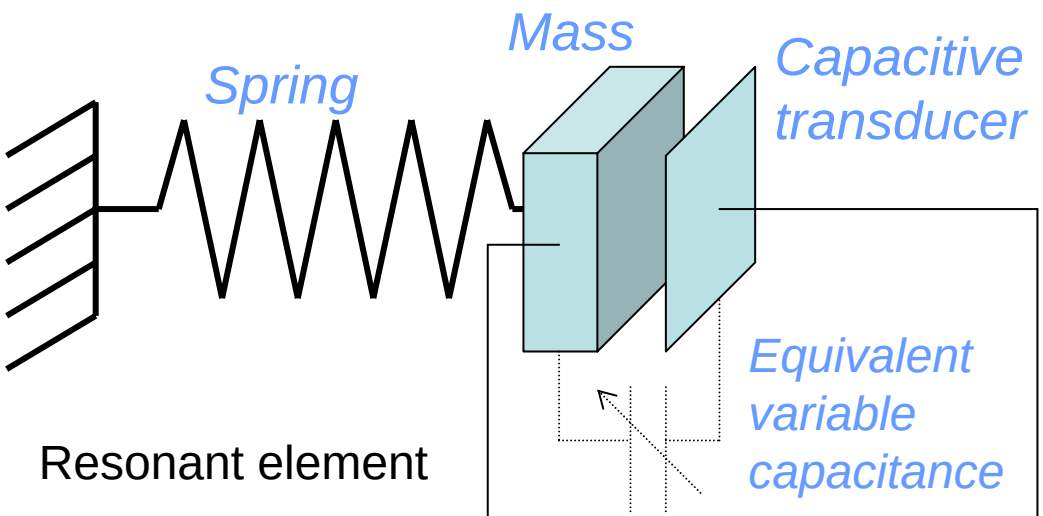
Electromechanical conversion

Conditionning circuit
Transfert of electrical charges

Load

Introduction

Mechanical energy harvesting principle



$$W = \frac{Q^2}{2C}$$

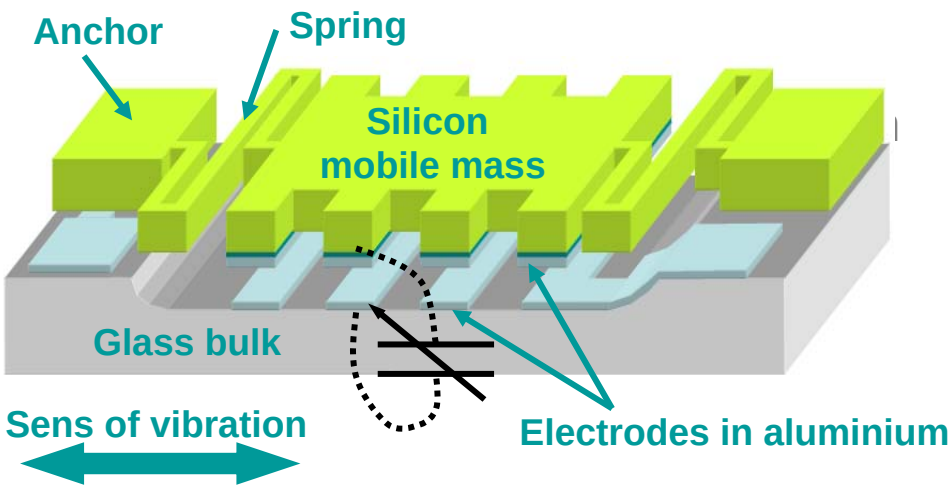
Capacitive accumulator of harvested energy

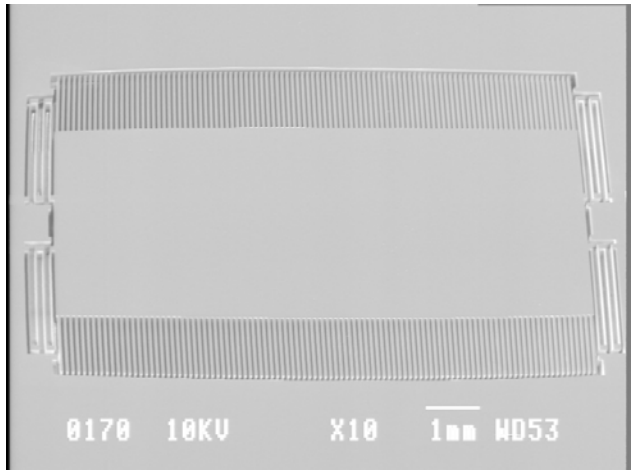
Conditionning circuit : transfert of electrical charges

Load

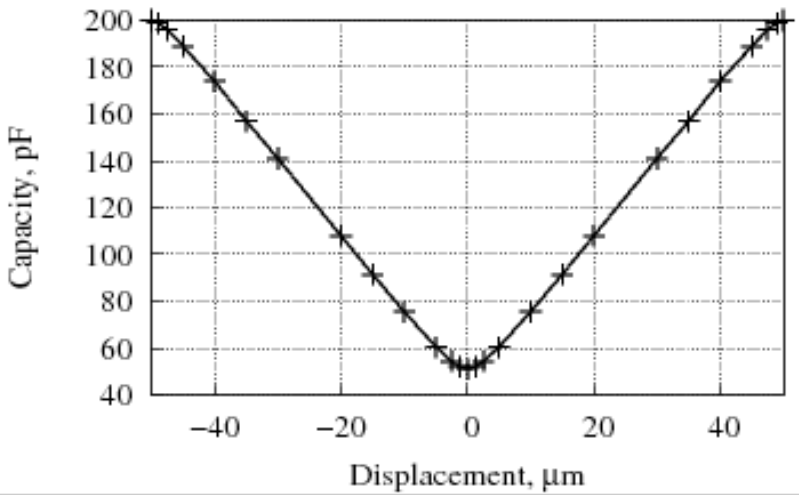
Introduction

Resonator for energy harvesting





Designed, fabricated and characterized in in ESYCOM laboratory (ESIEE)



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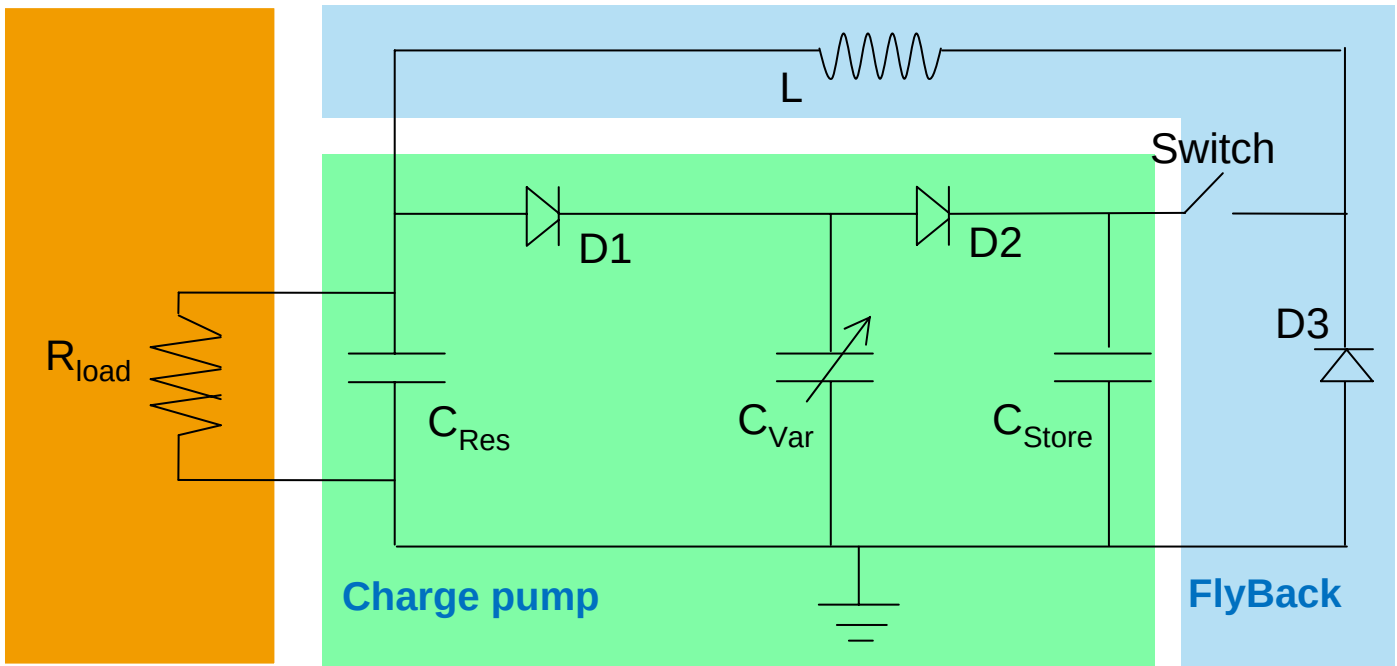
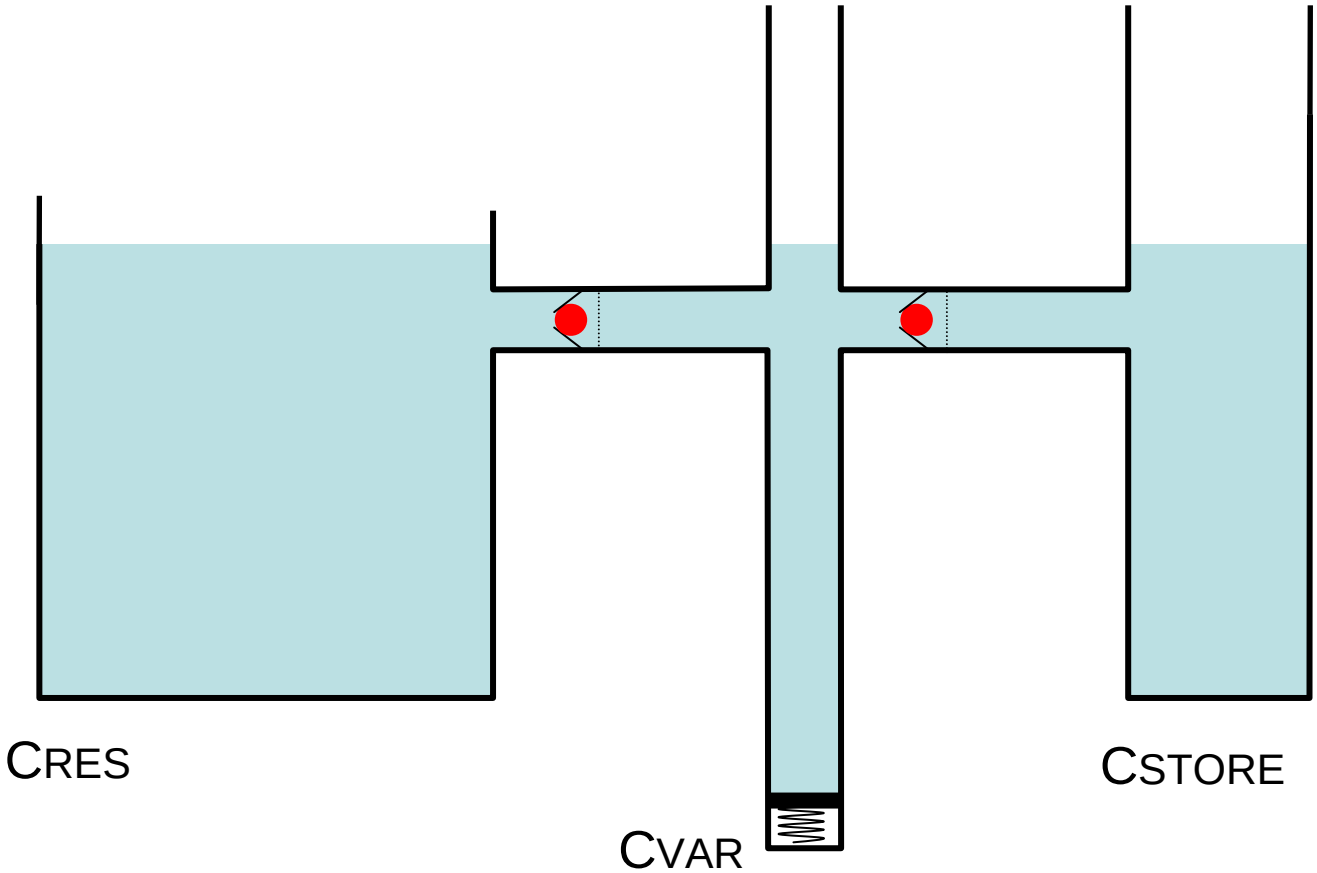
Conditionning circuit

- Circuit architecutre proposed at MIT
- Inspired by BUCK converter network



Conditionning circuit

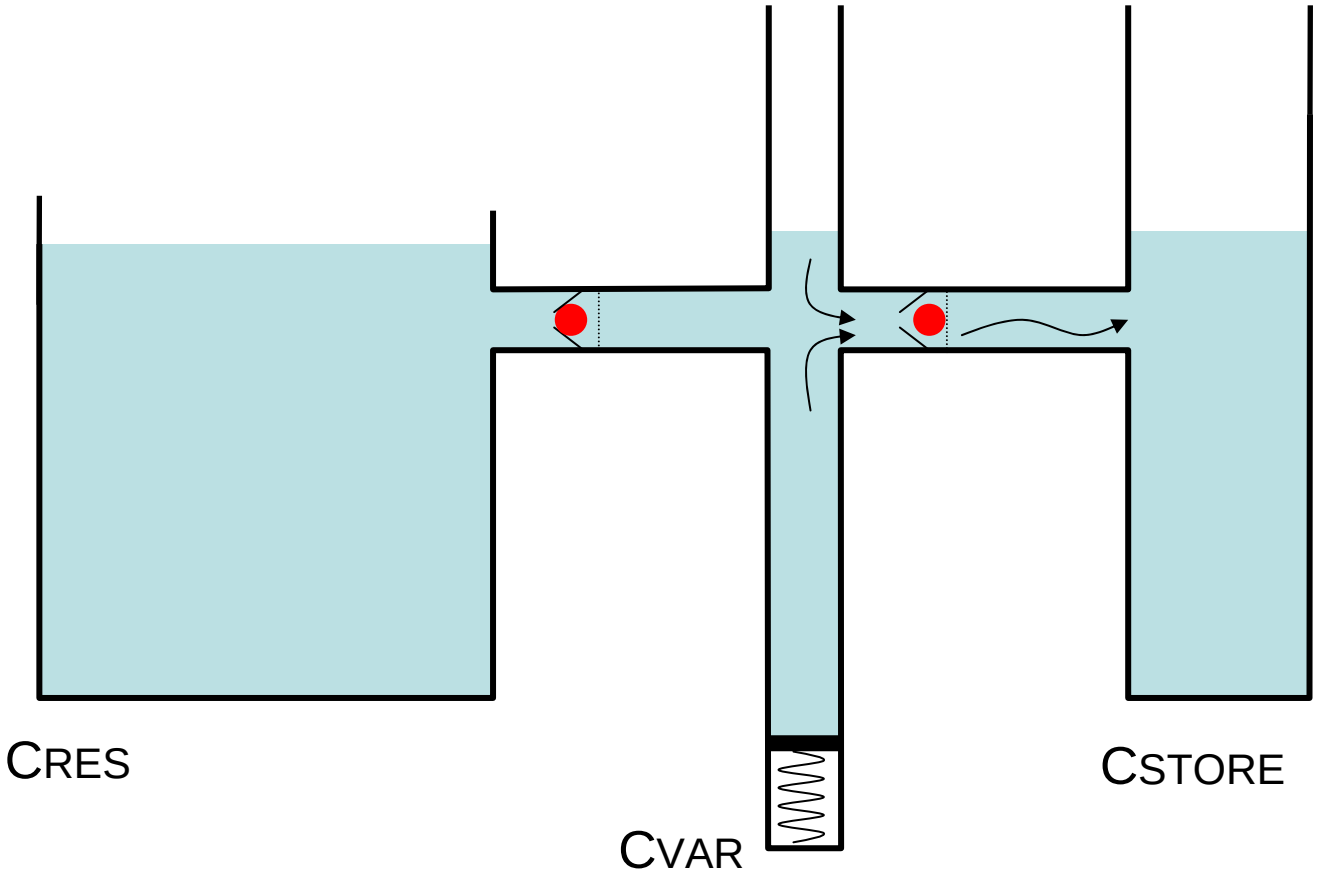
Charge pump operation



Cvar =Cmax

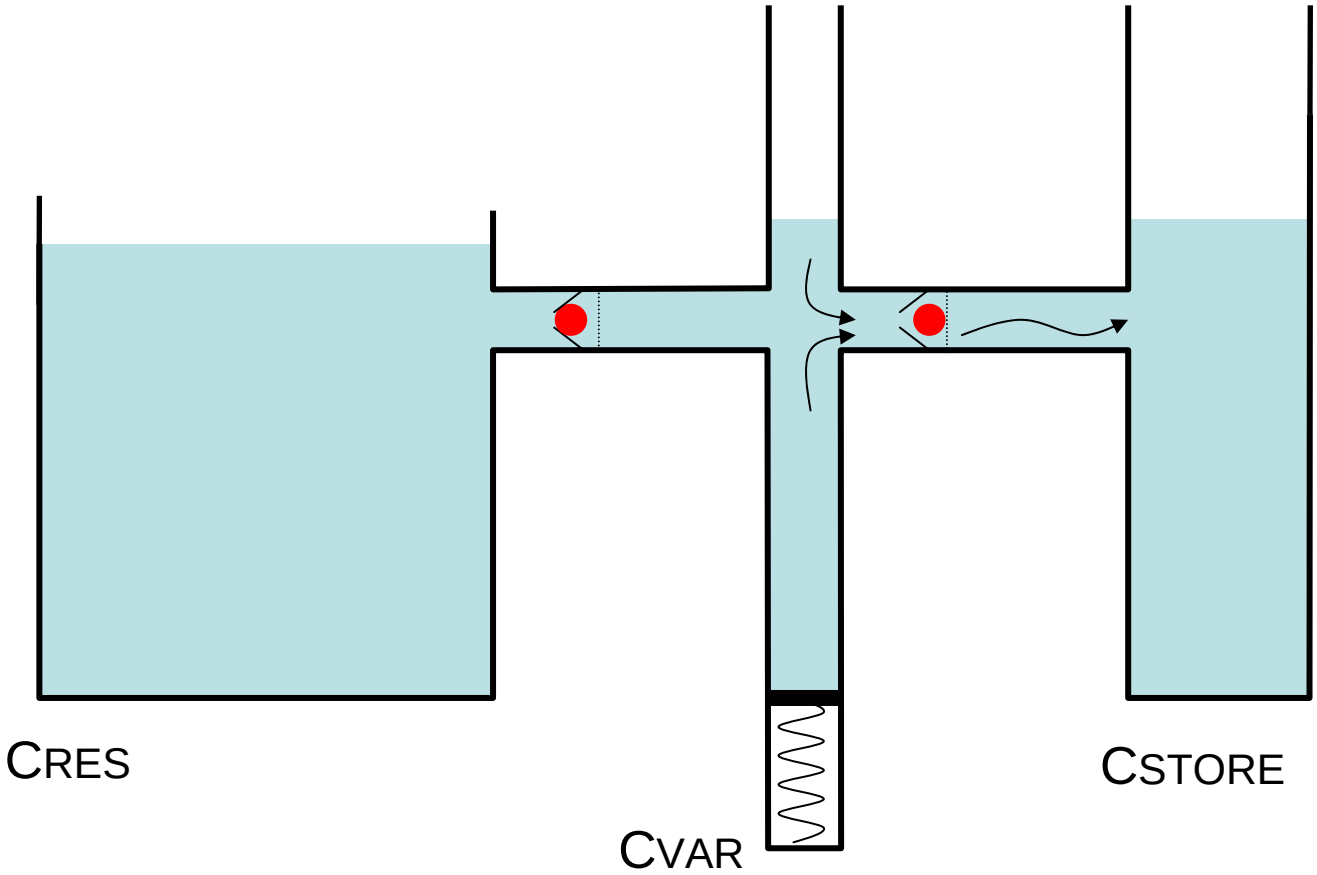
Conditionning circuit

Charge pump operation



Conditionning circuit

Charge pump operation



Conditionning circuit

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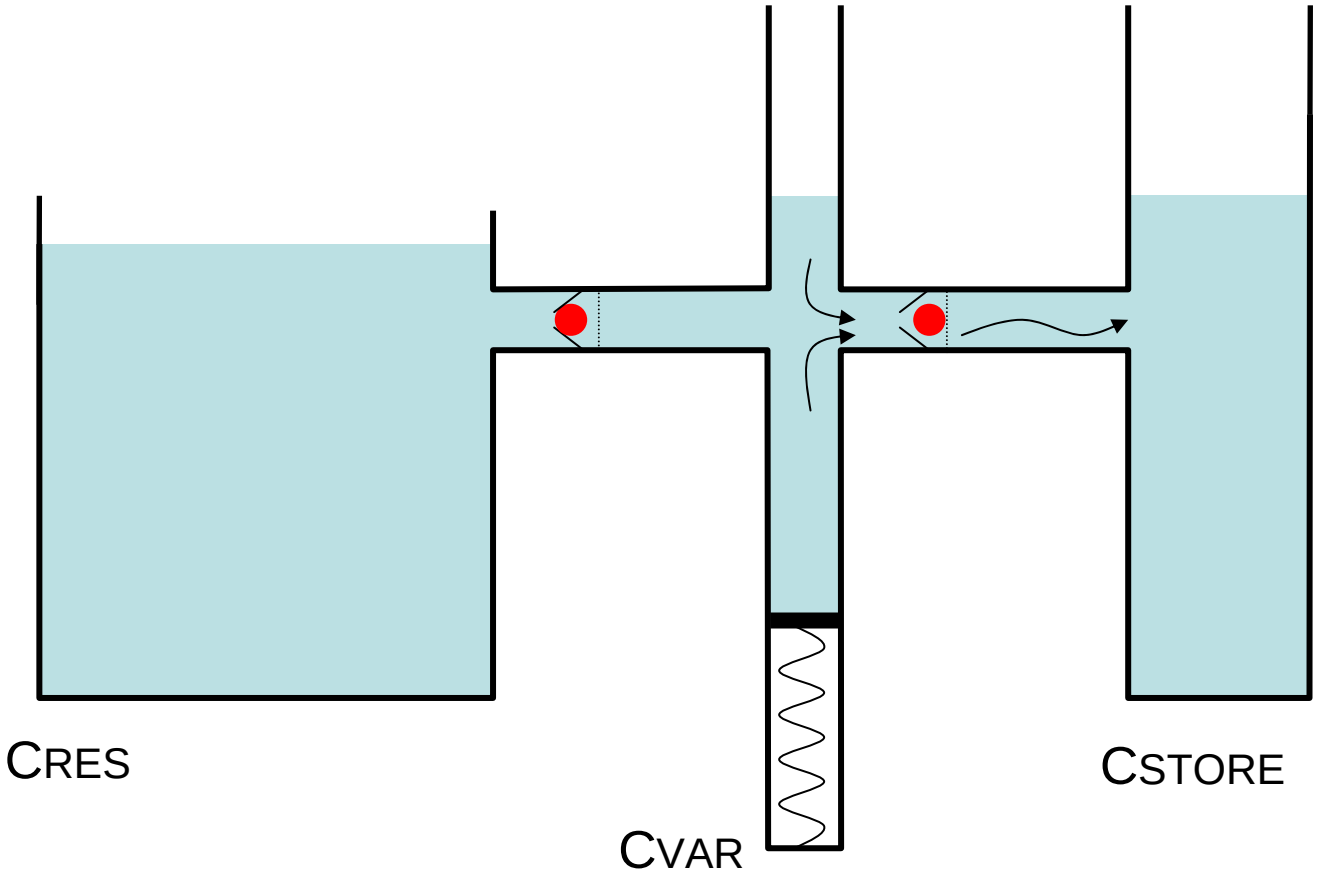
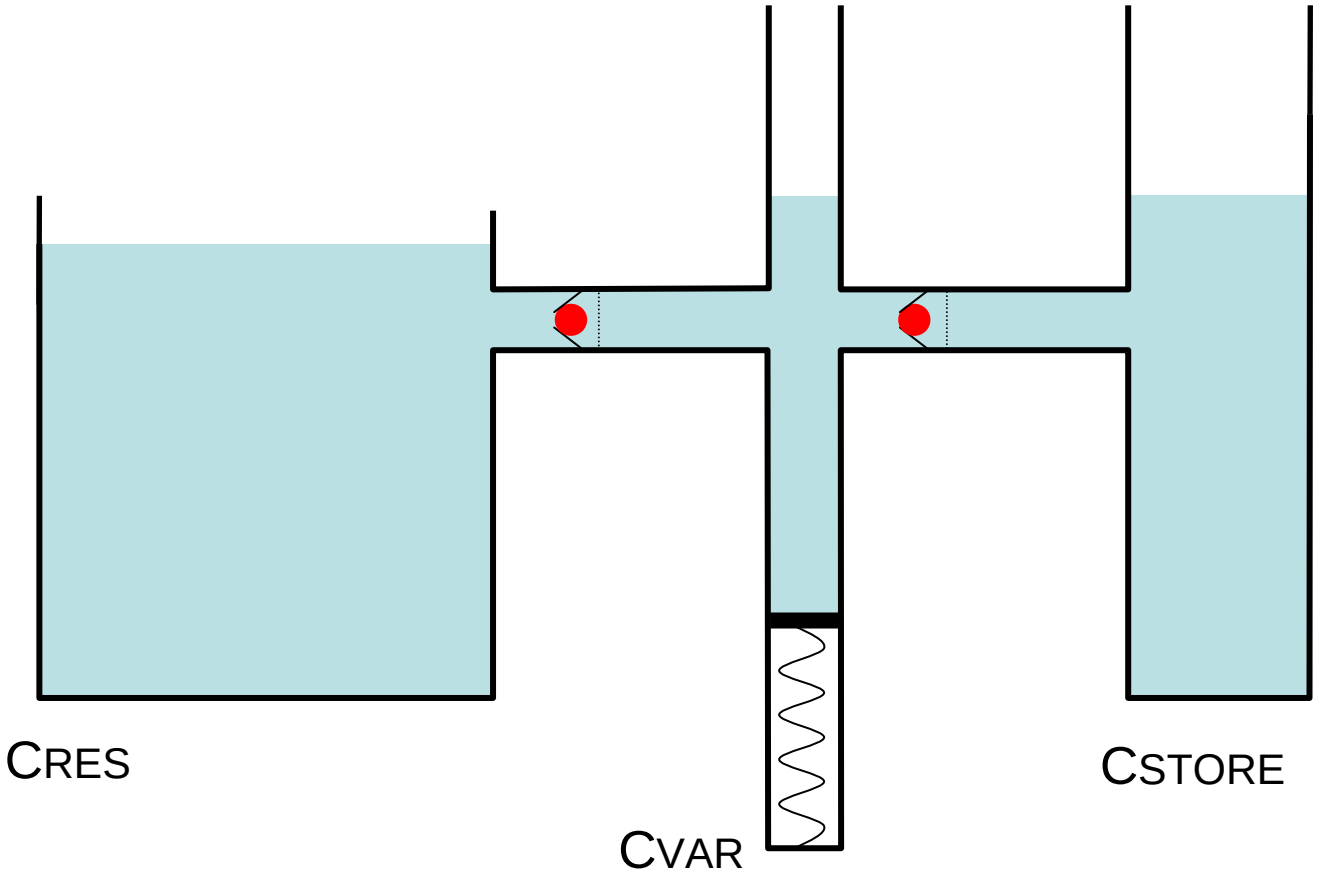


Conditionning circuit

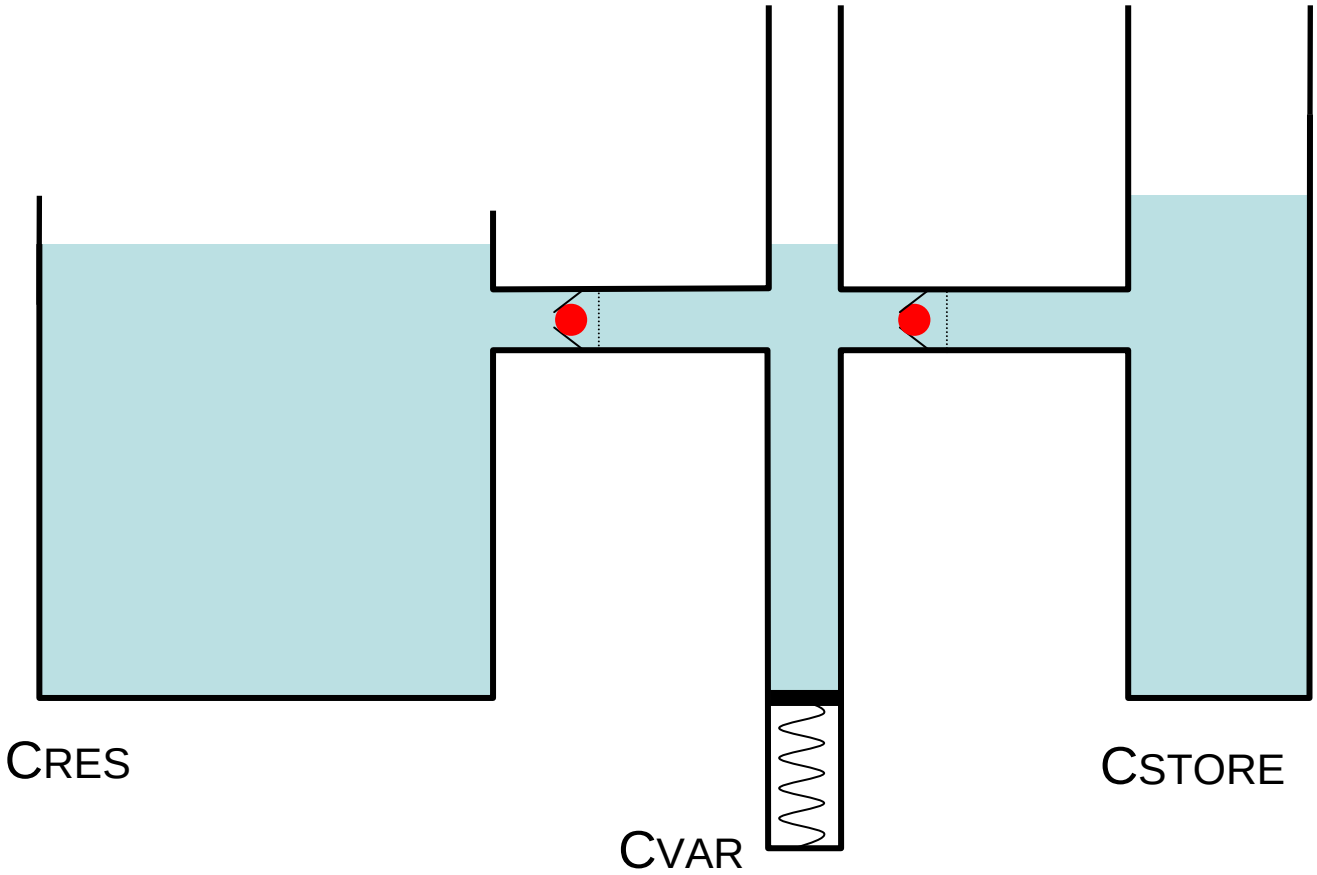
Charge pump operation



Cvar =Cmin

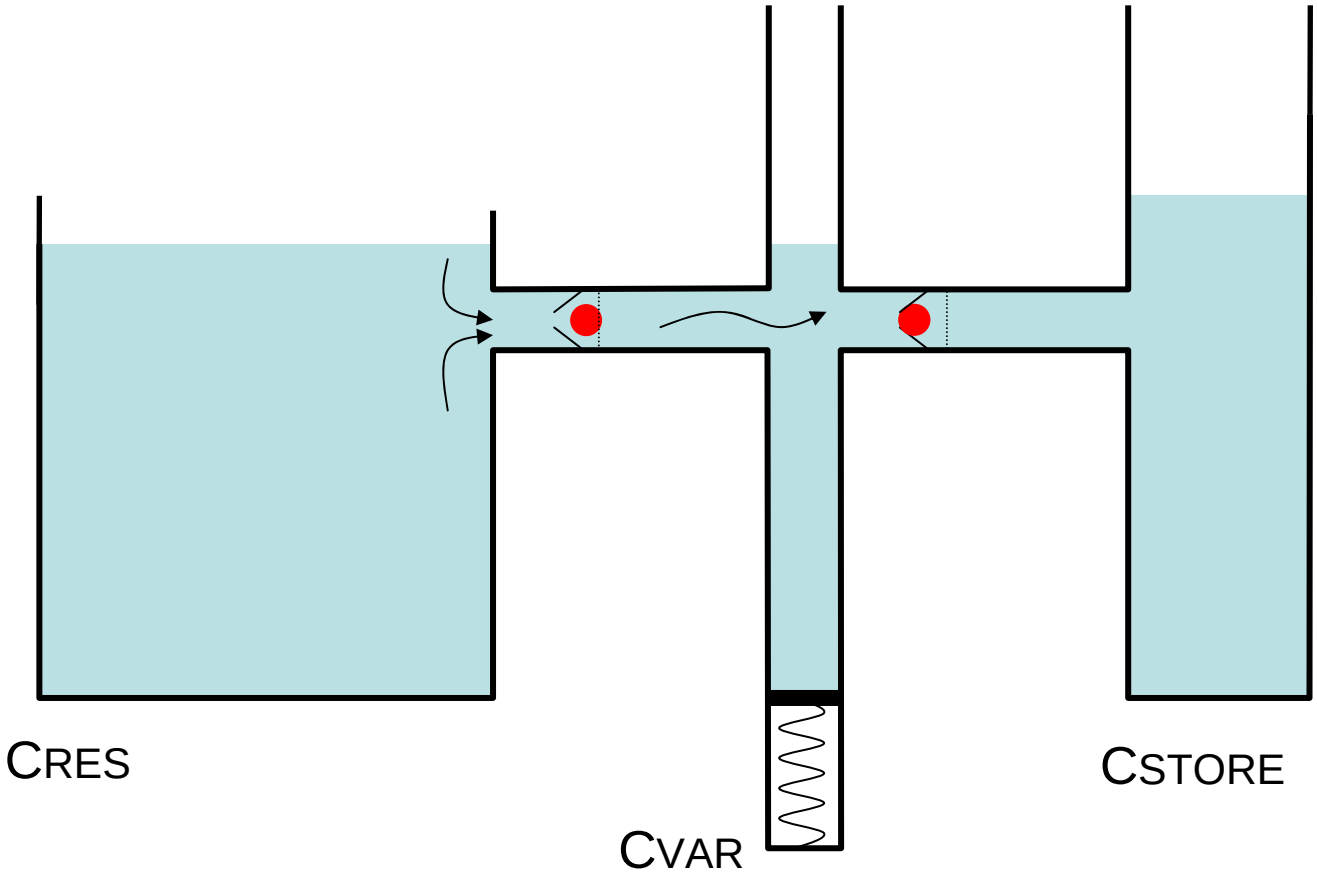
Conditionning circuit

Charge pump operation



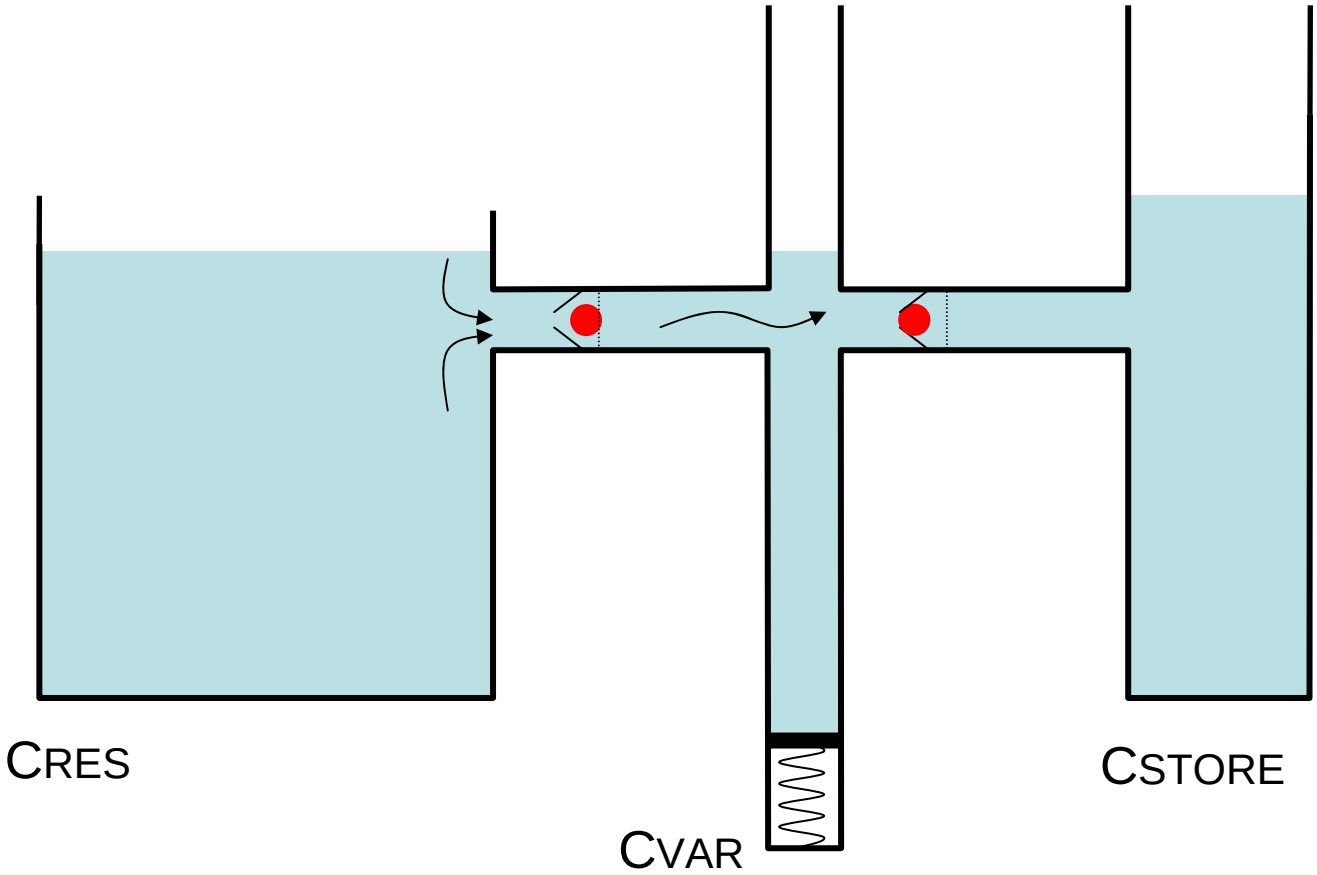
Conditionning circuit

Charge pump operation



Conditionning circuit

Charge pump operation



Conditionning circuit

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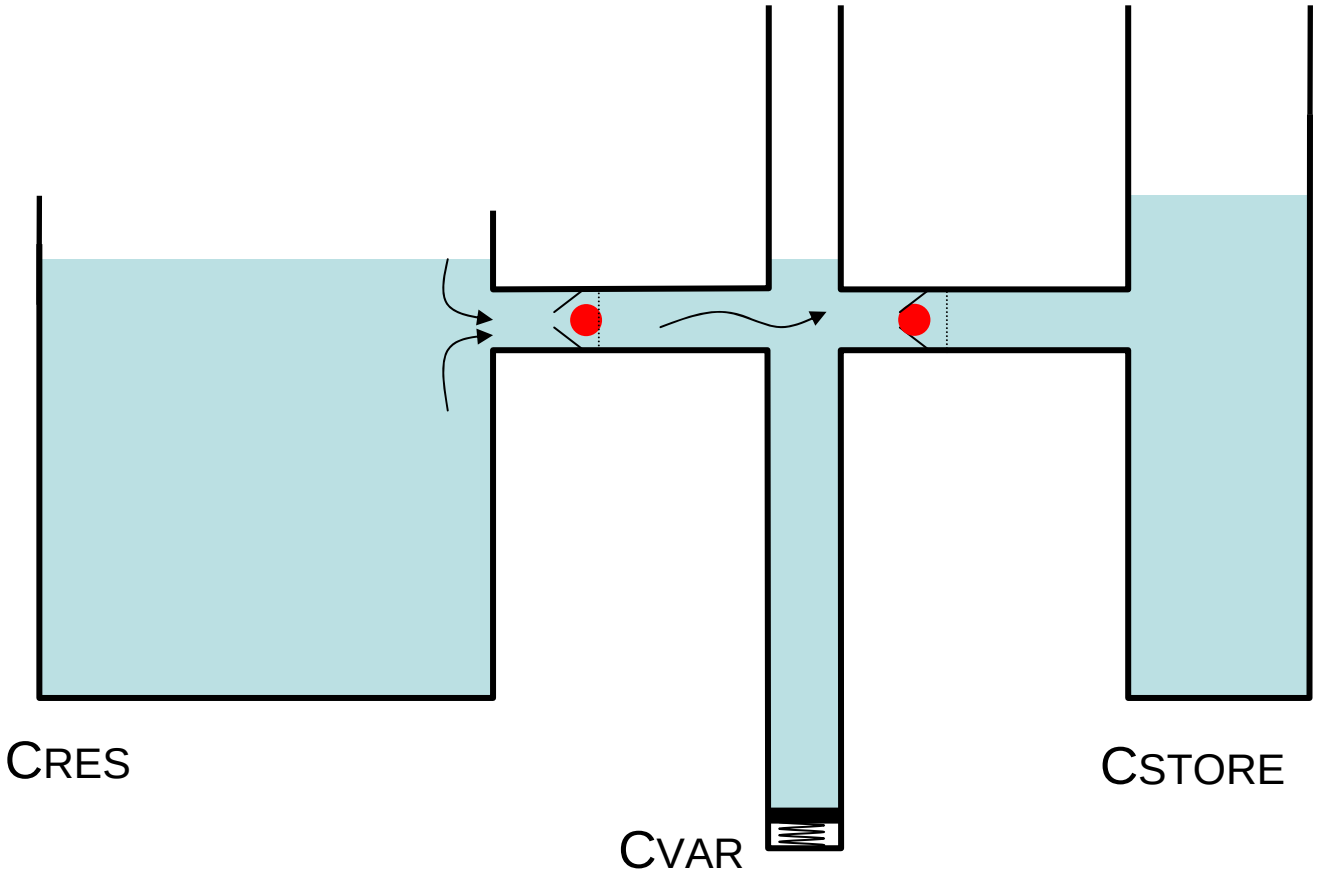
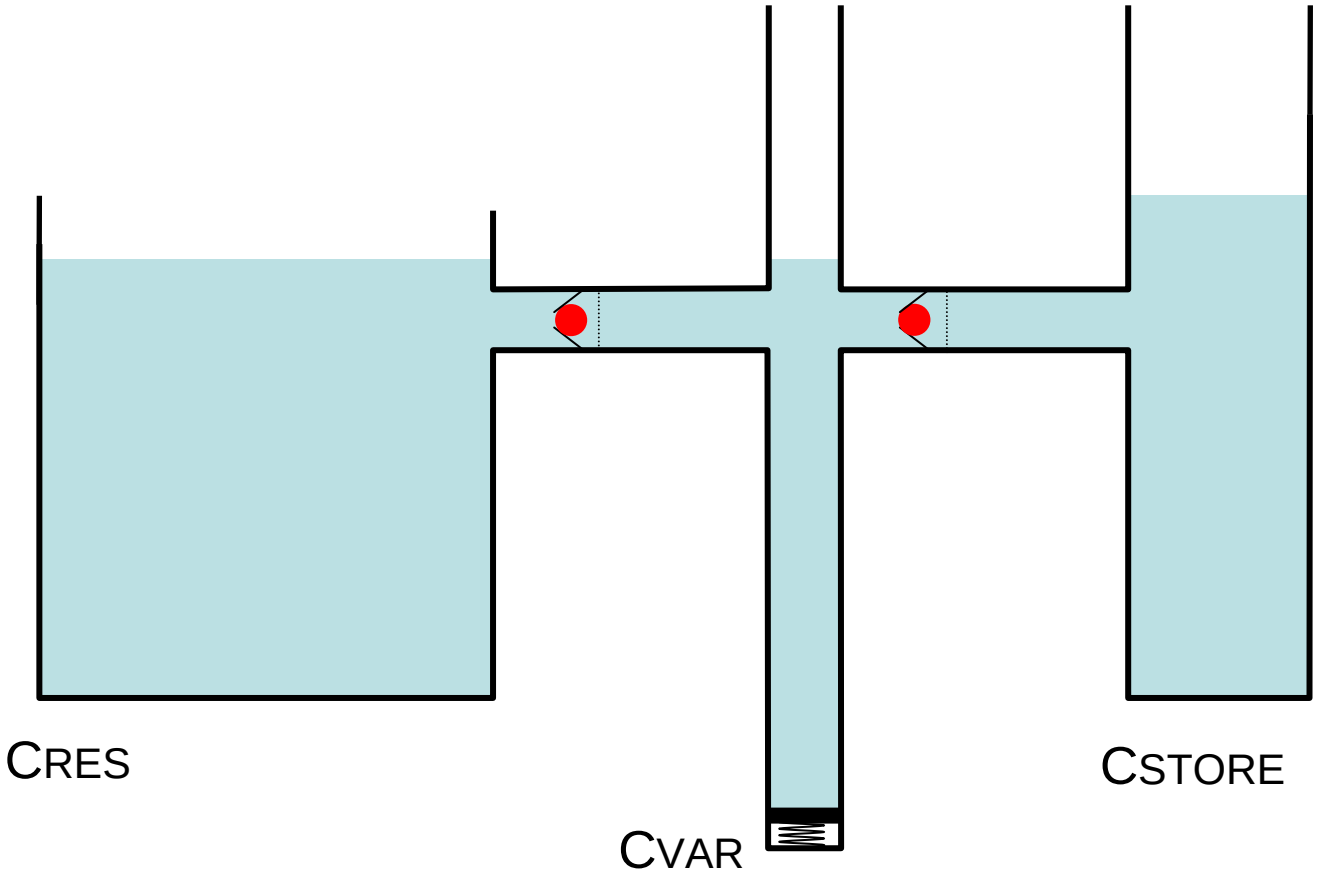


Conditionning circuit

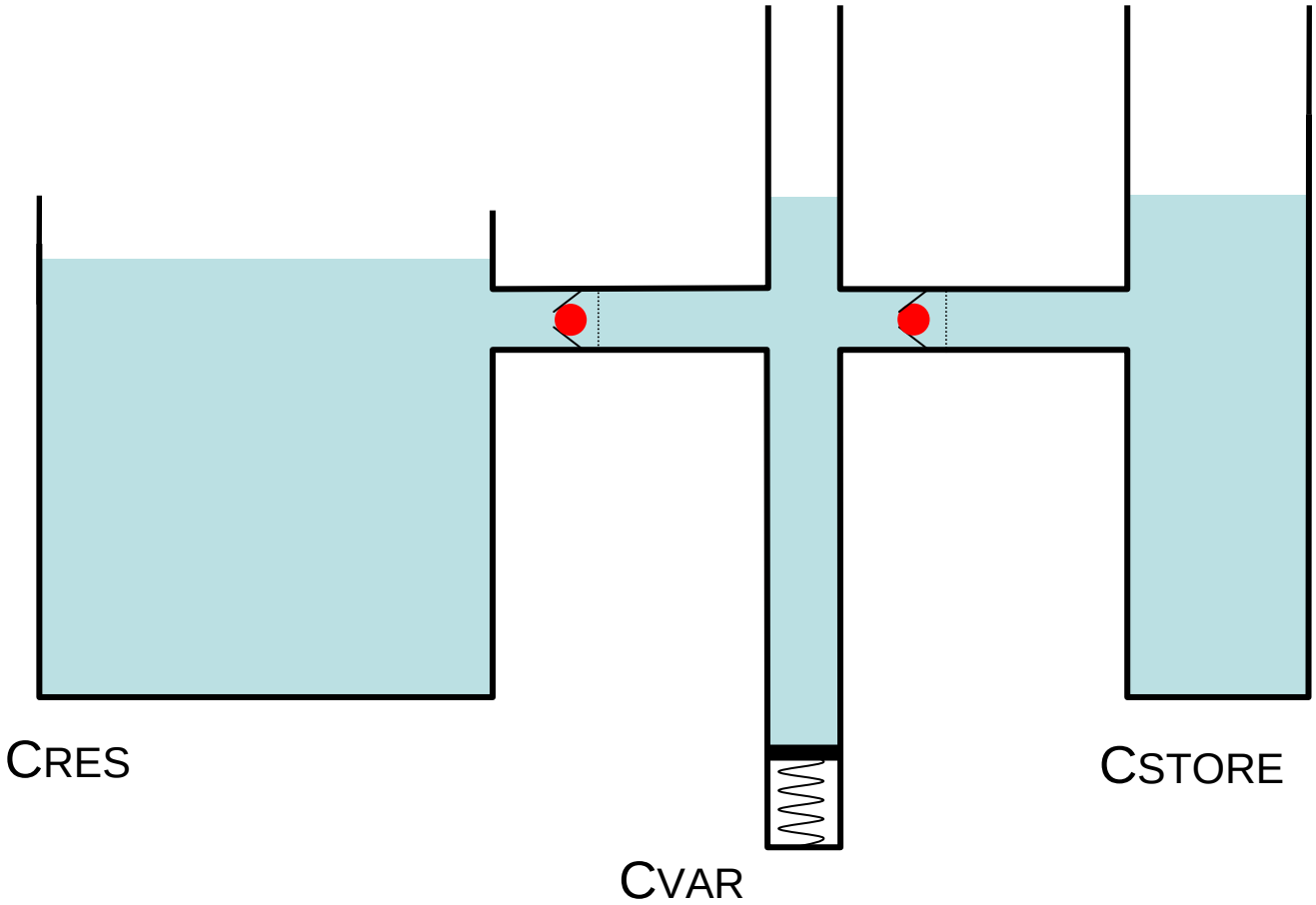
Charge pump operation



Cvar =Cmax

Conditionning circuit

Charge pump operation



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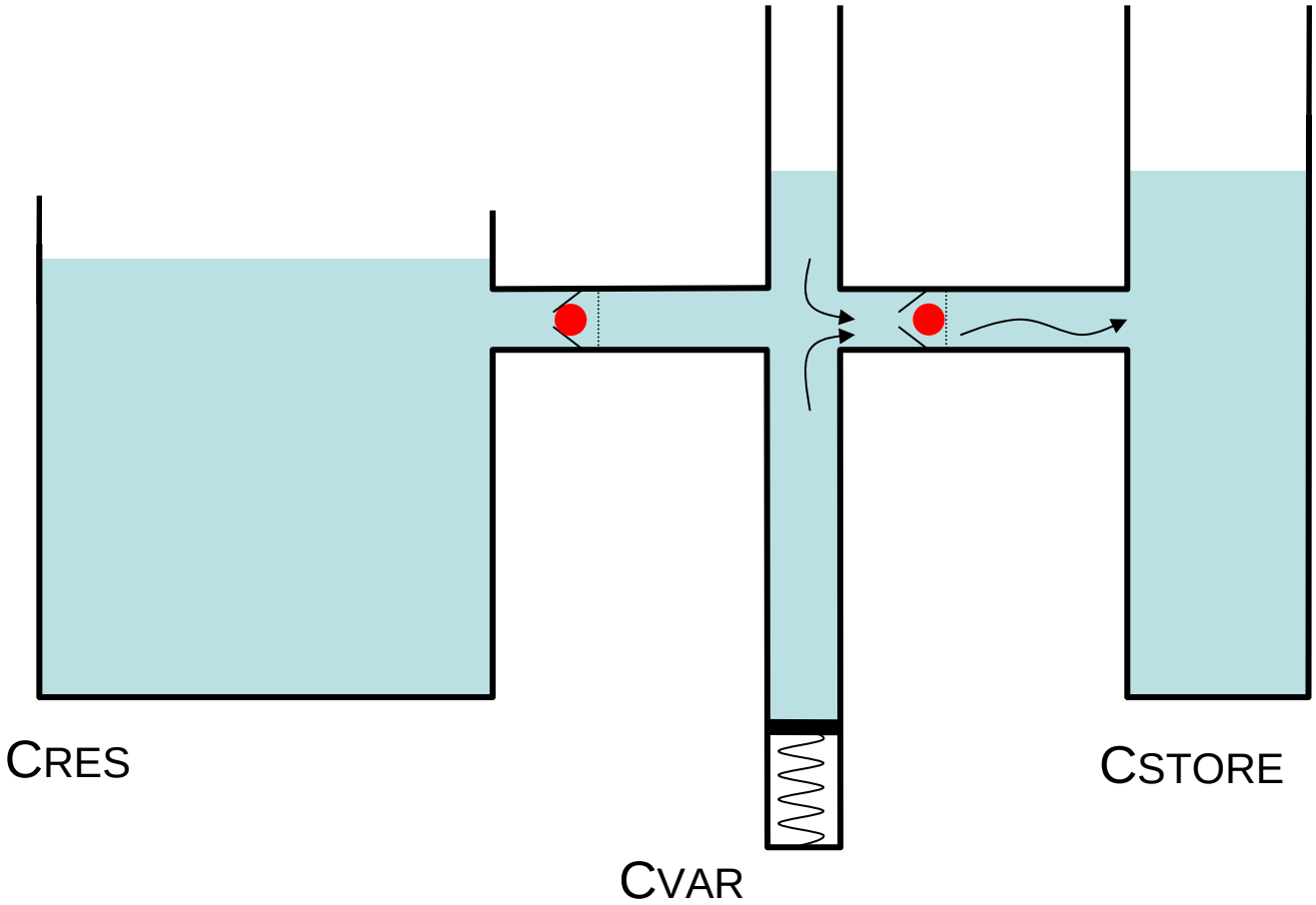

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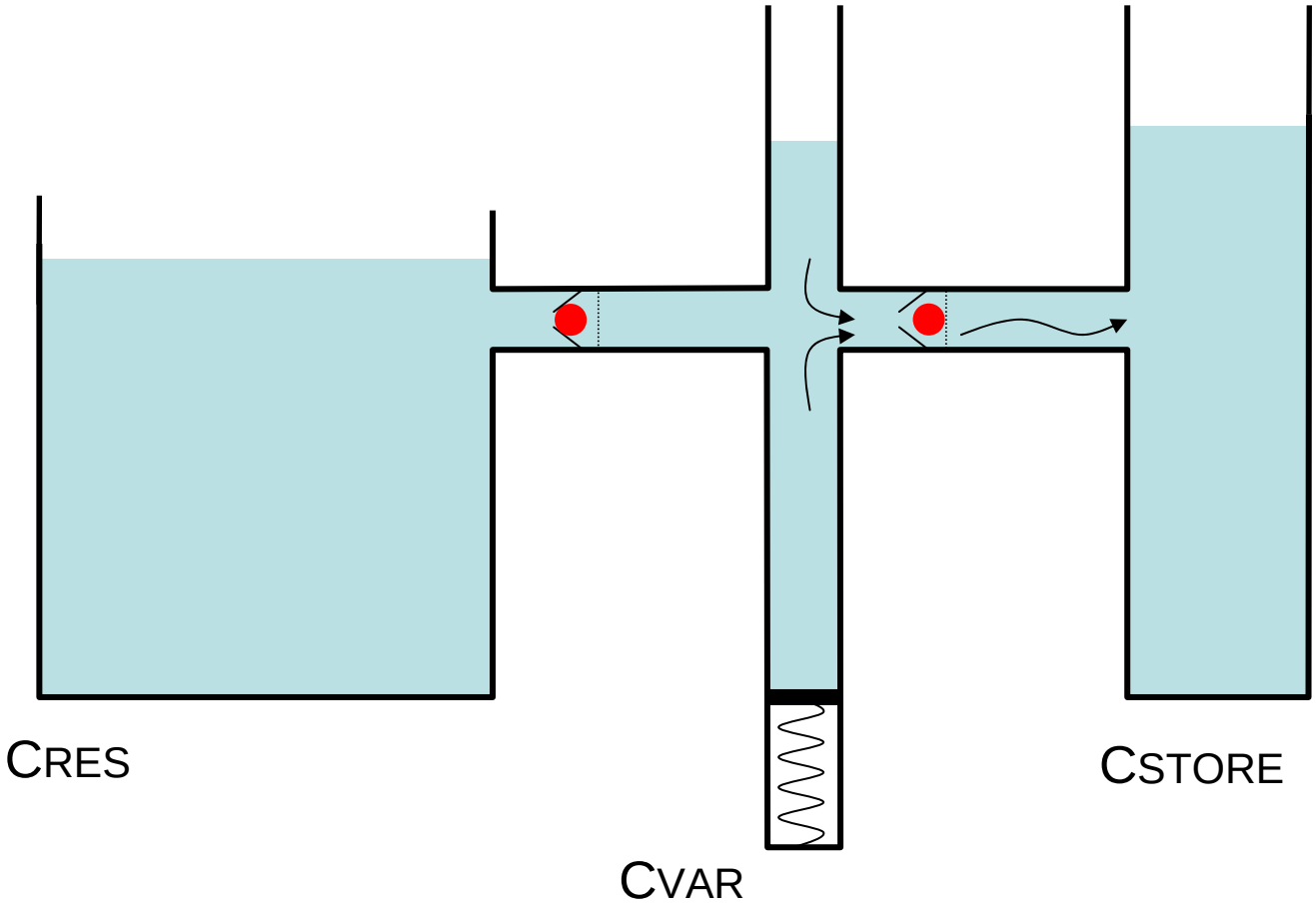

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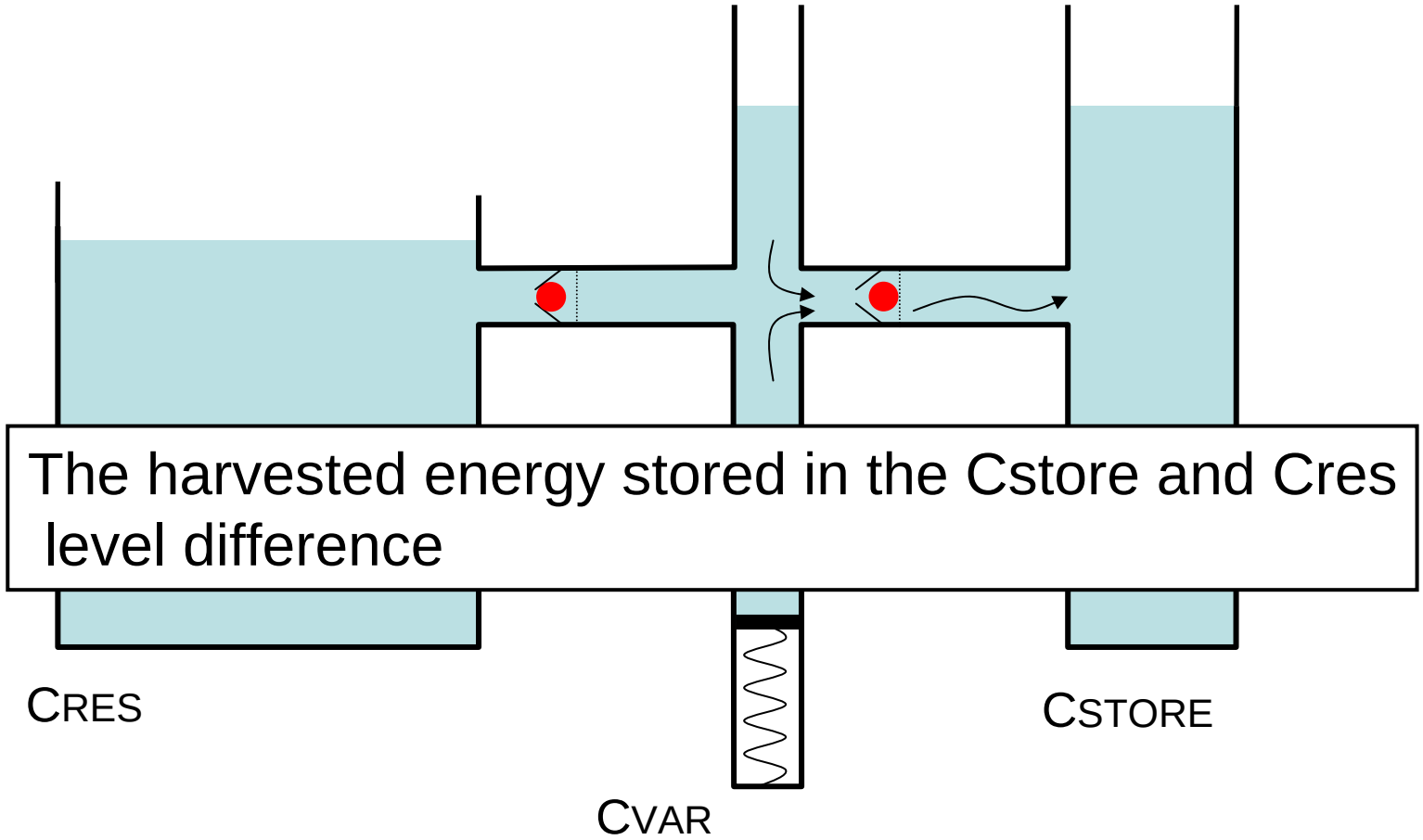

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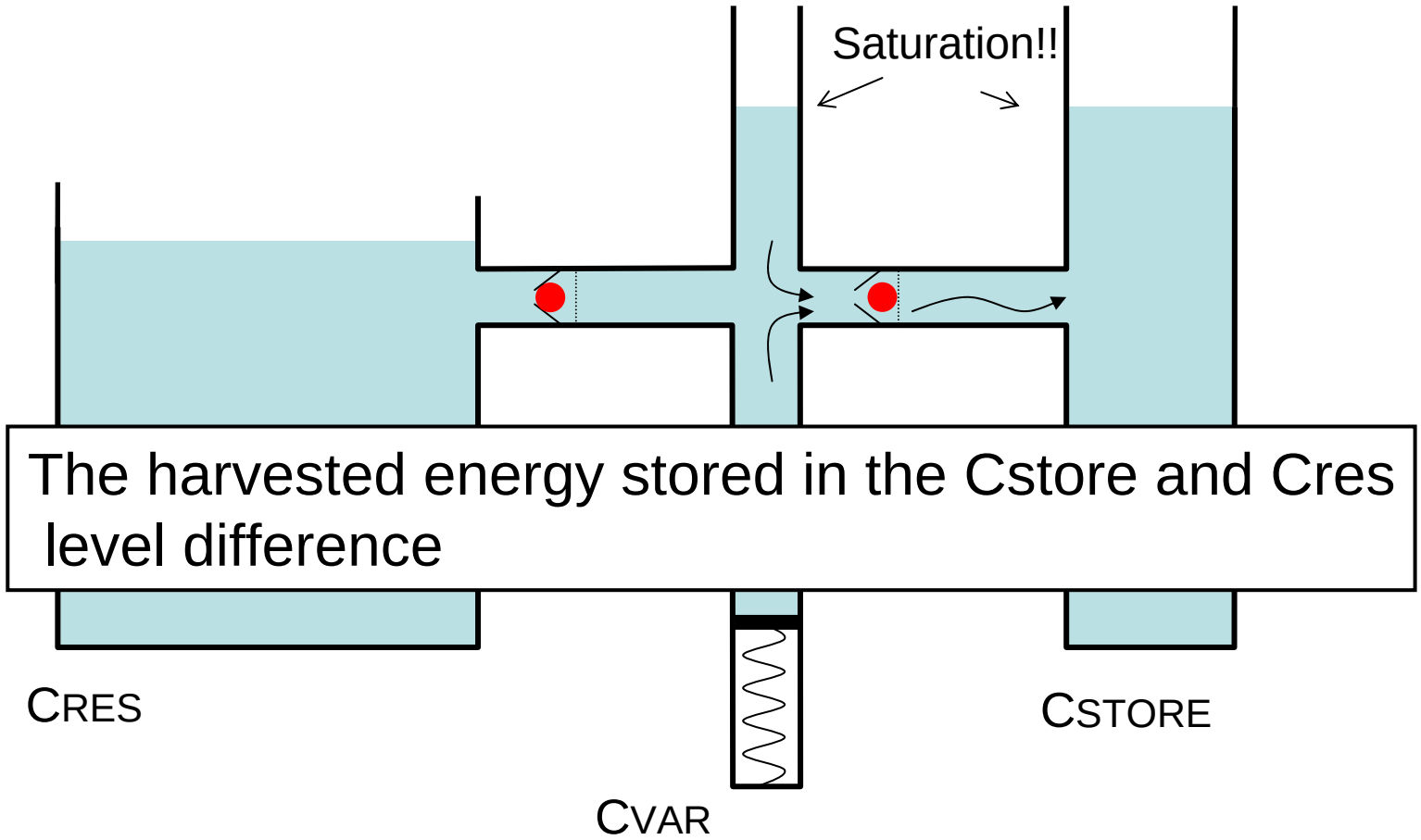

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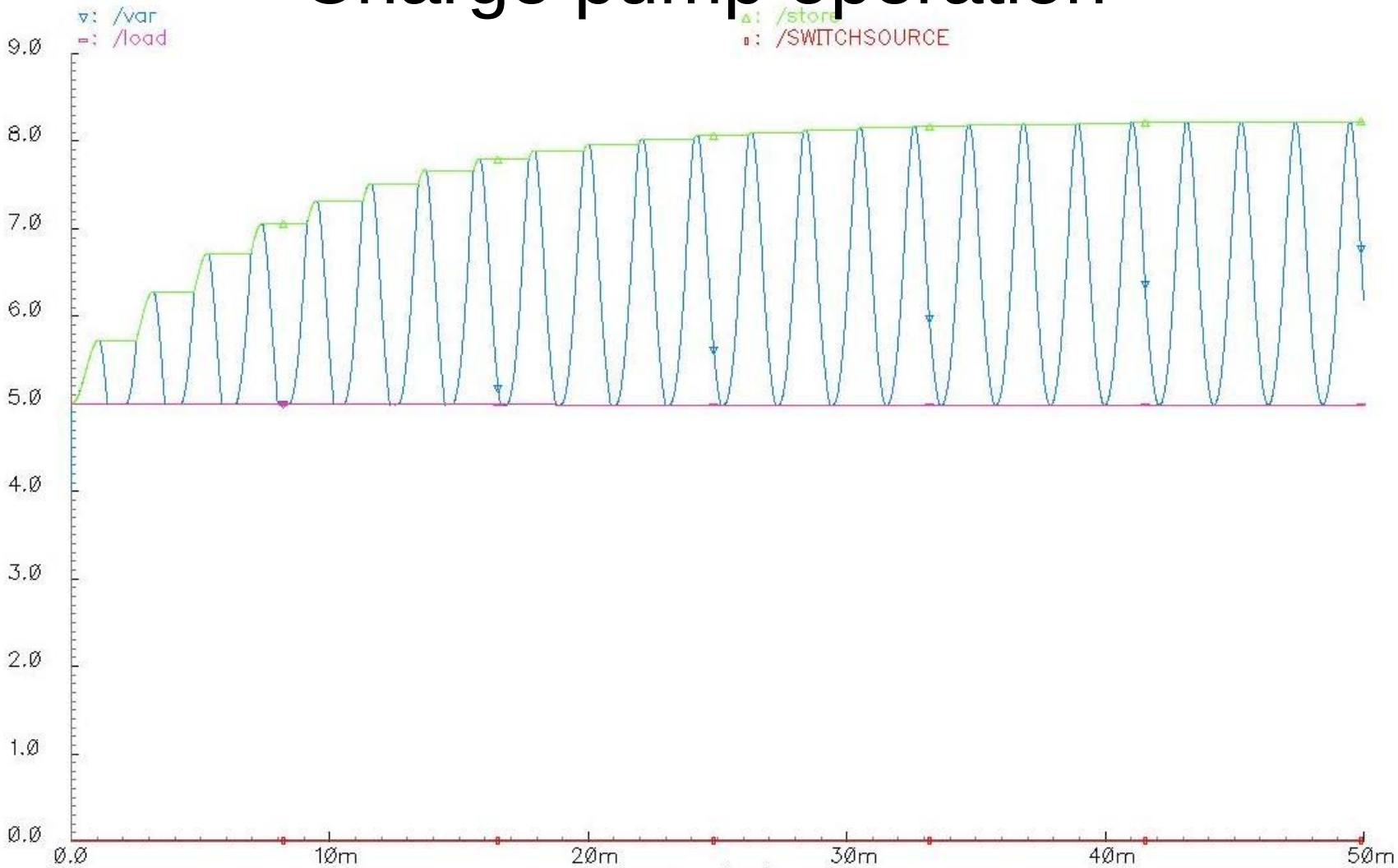
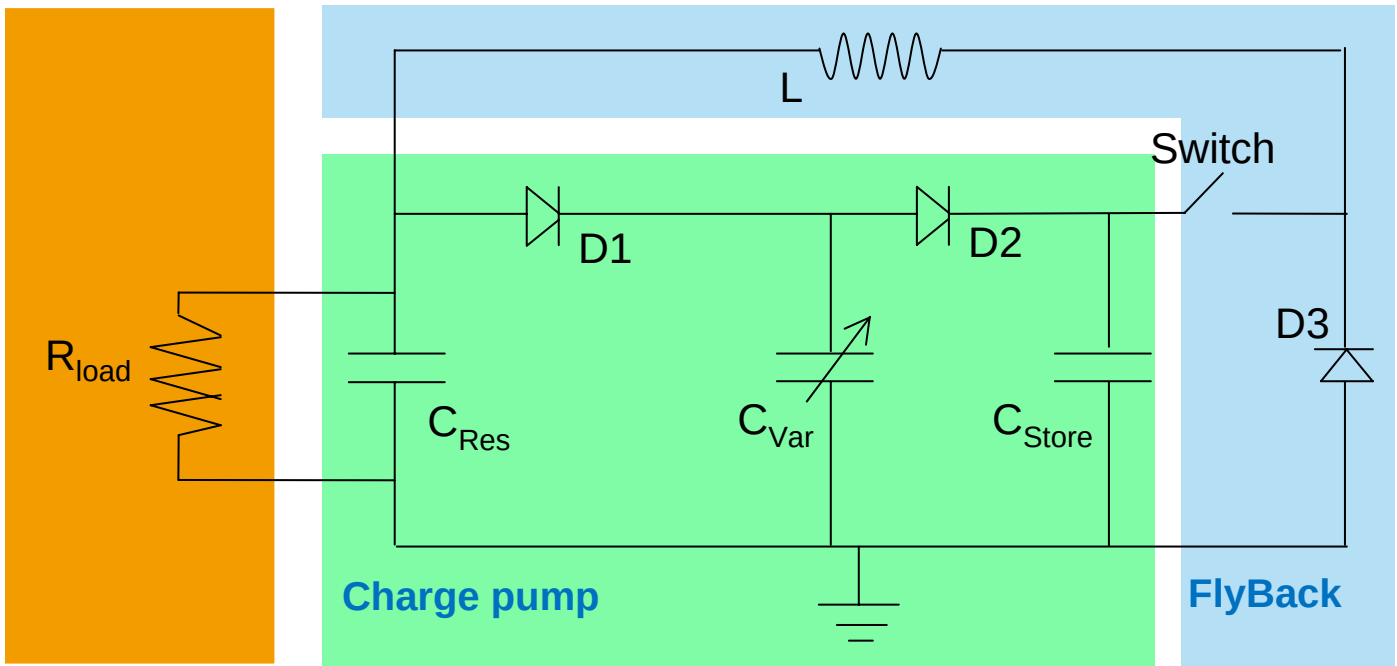
Conditionning circuit

Charge pump operation



Conditionning circuit
Charge pump operation

- Charge return needed (flyback circuit !)

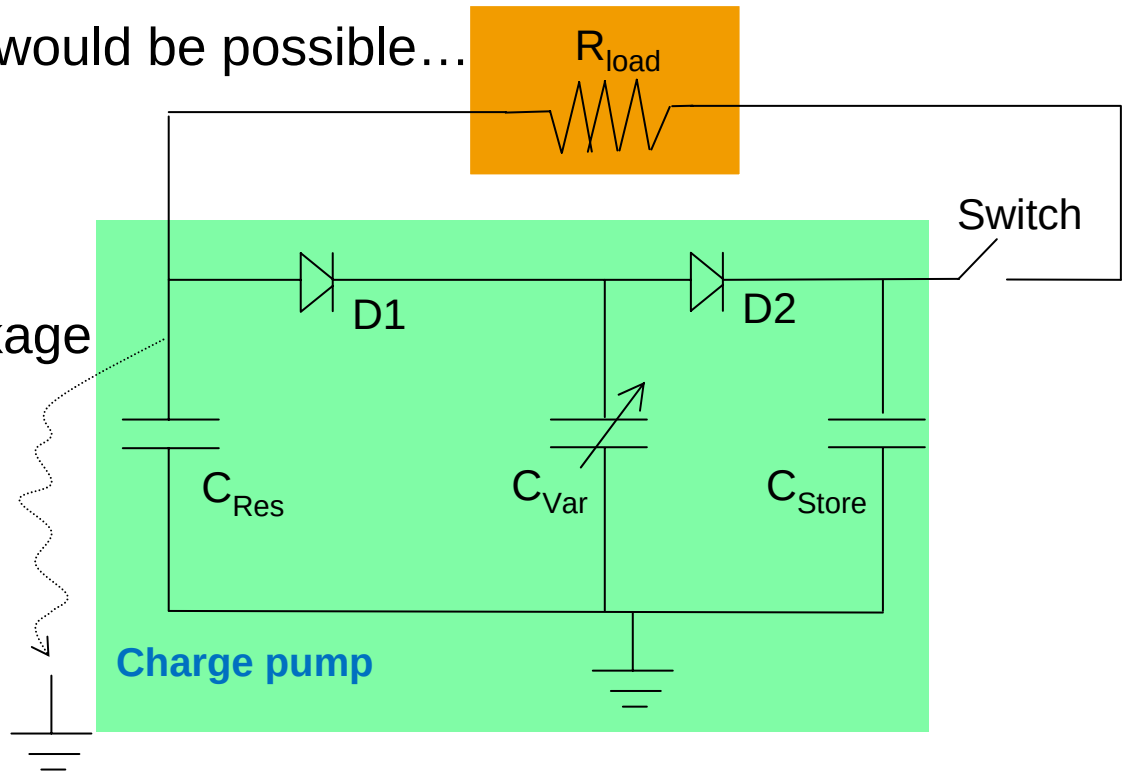


Conditionning circuit
Charge pump operation

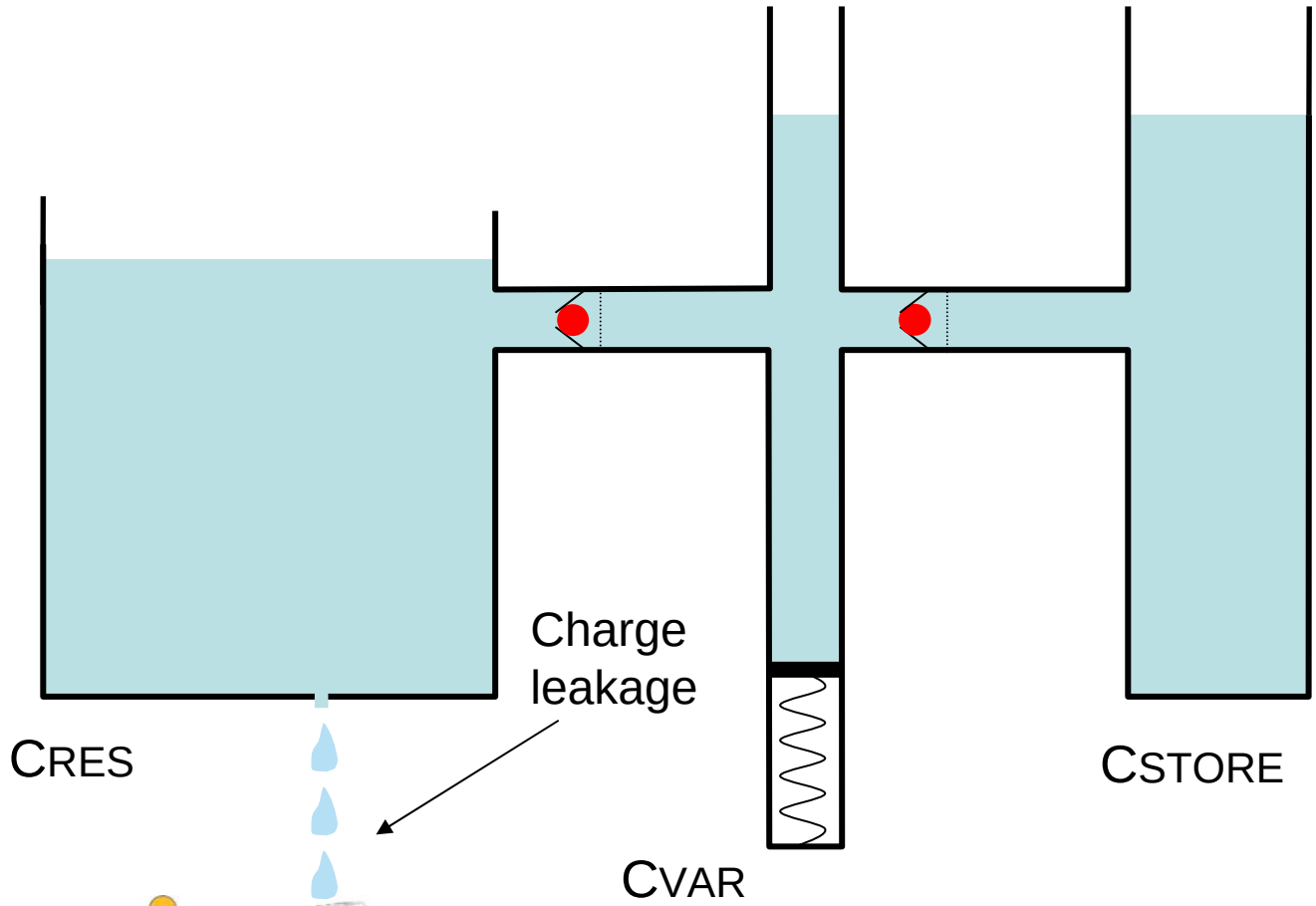
- Charge return needed (flyback circuit !)

Such scheme would be possible…

if it was no leakage

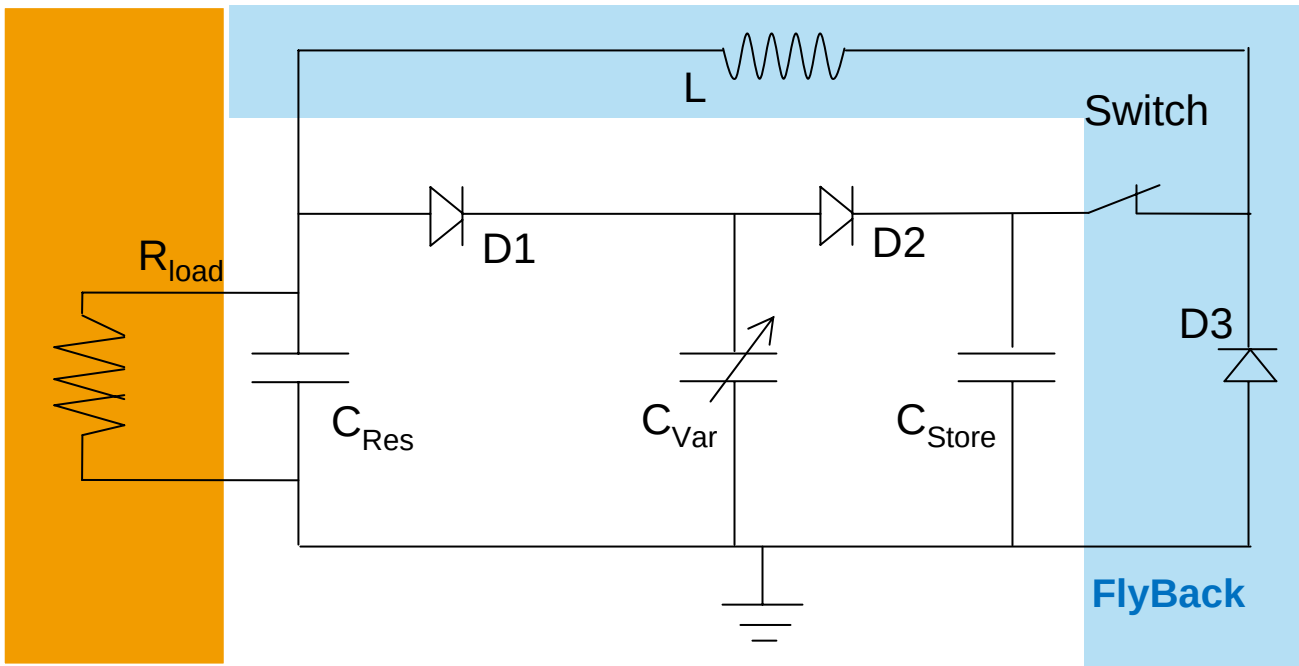


Conditionning circuit
Charge pump operation



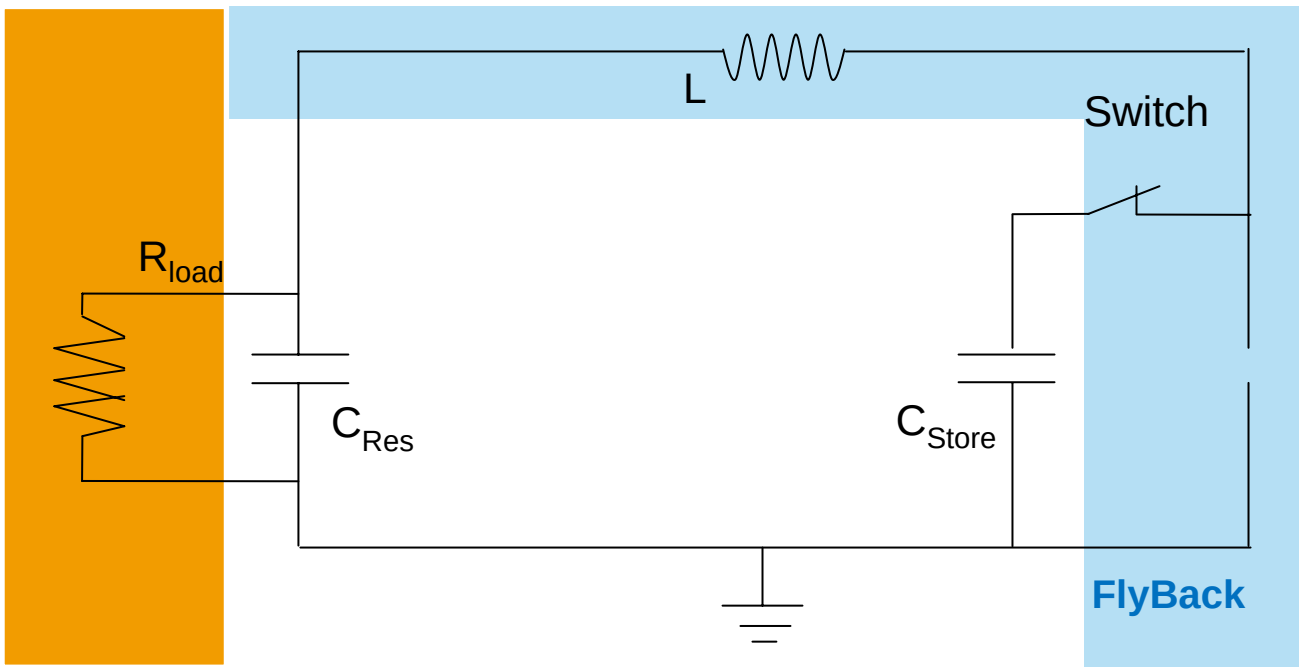
Conditionning circuit
Flyback operation

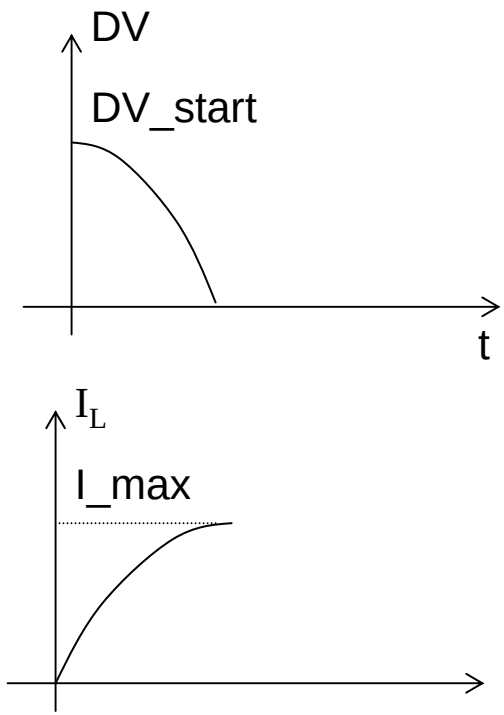
- Stores the harvested energy in the inductor
- This energy is used to recharge Cres



Conditionning circuit
Flyback operation

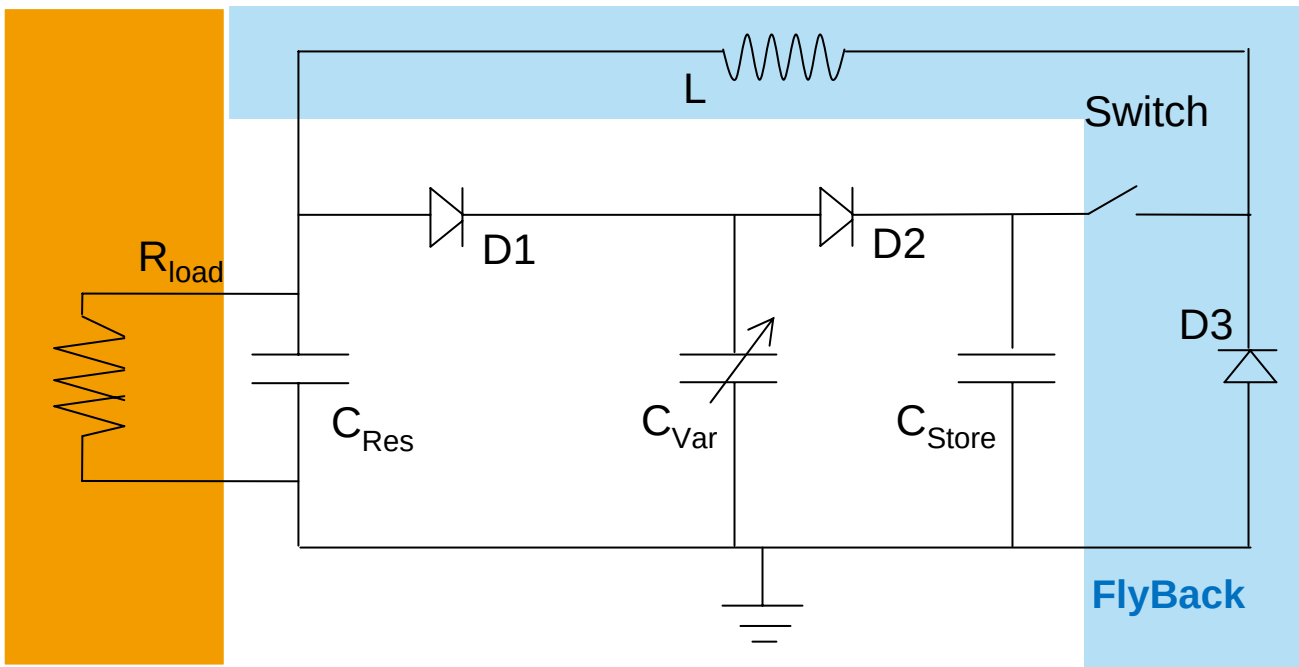
- The switch is on, Cstore discharge on Cres and on L
- L is accumulatng the harvested energy

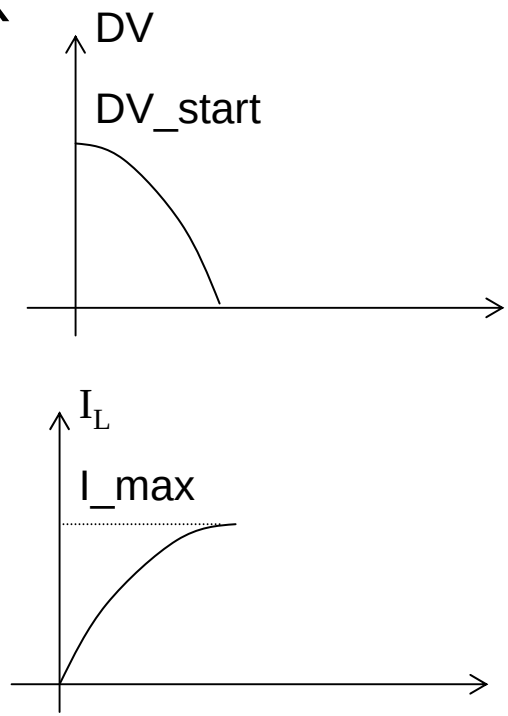




Conditionning circuit
Flyback operation

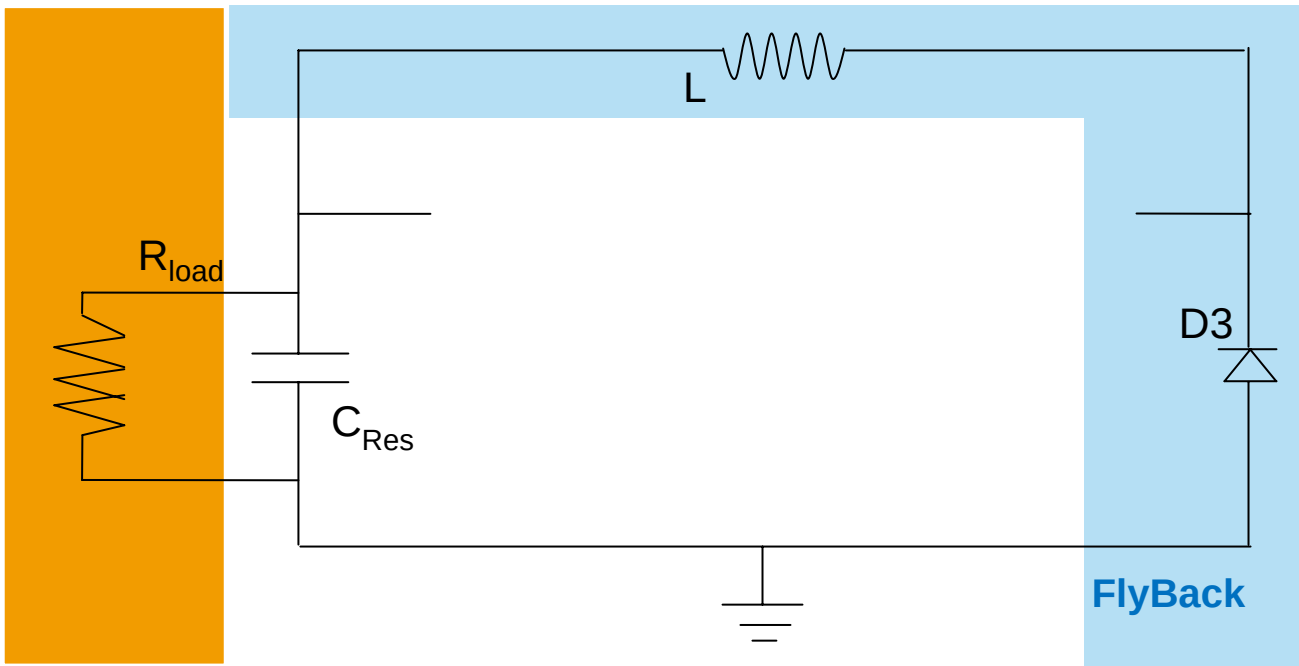
- The switch is off, inductor current continues through D3
- The circuit is equivalent to LCres network

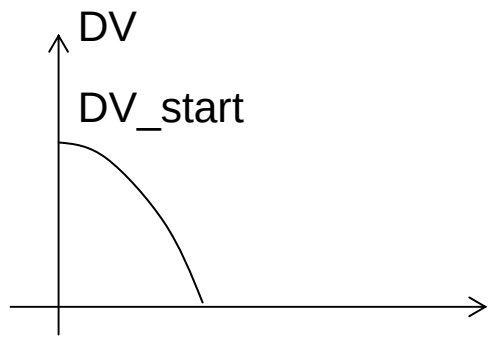


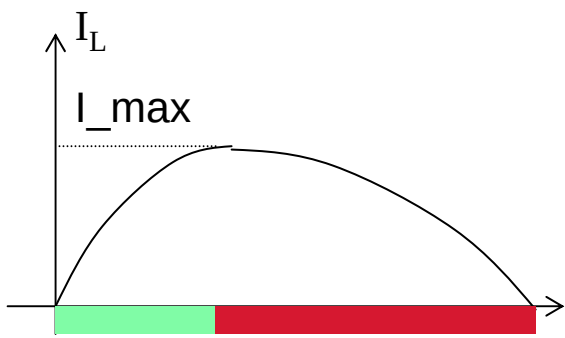


Conditionning circuit
Flyback operation

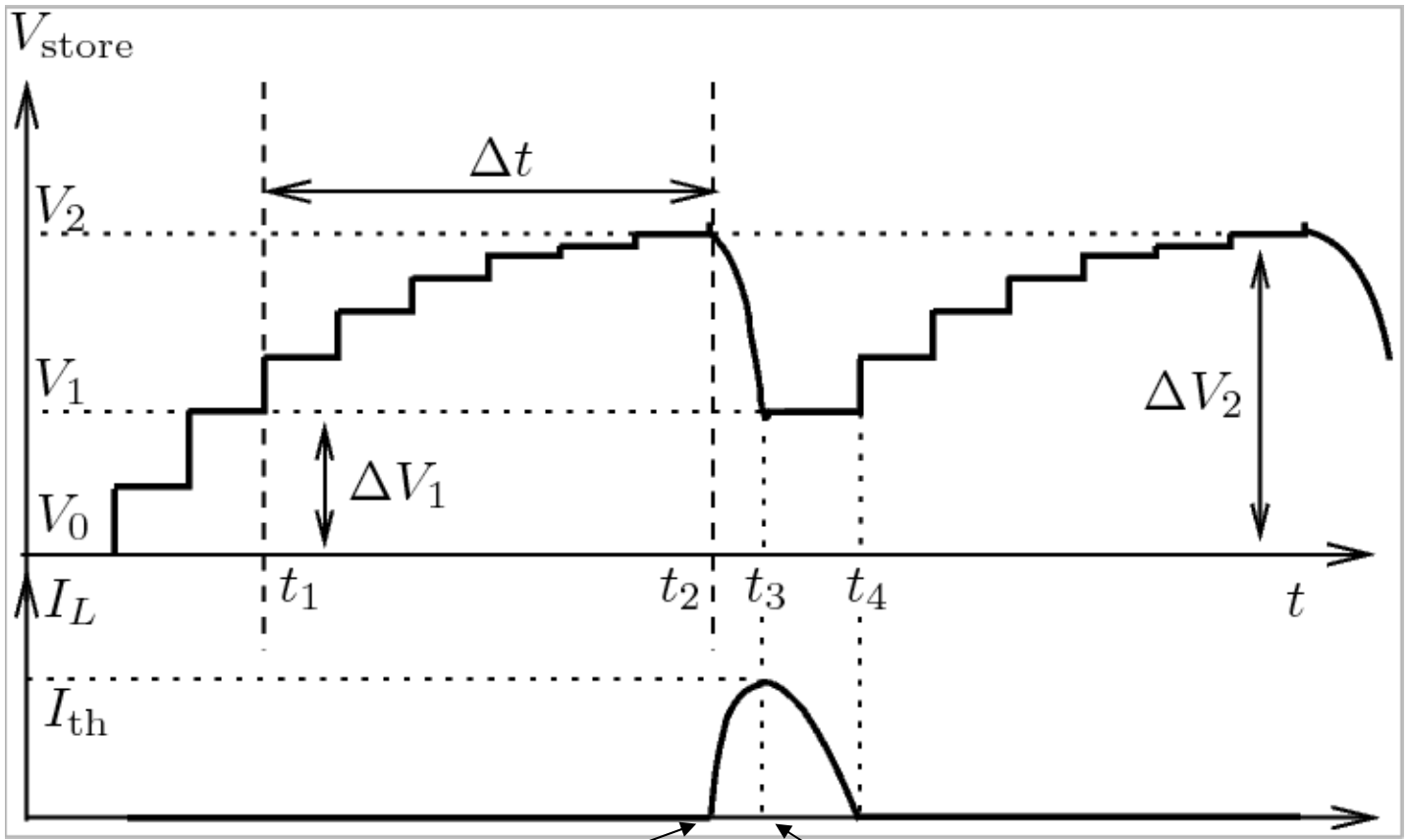
- The switch is off, inductor current continues through D3
- The circuit is equivalent to LCres network
- The energy in L is used to add charges to Cres



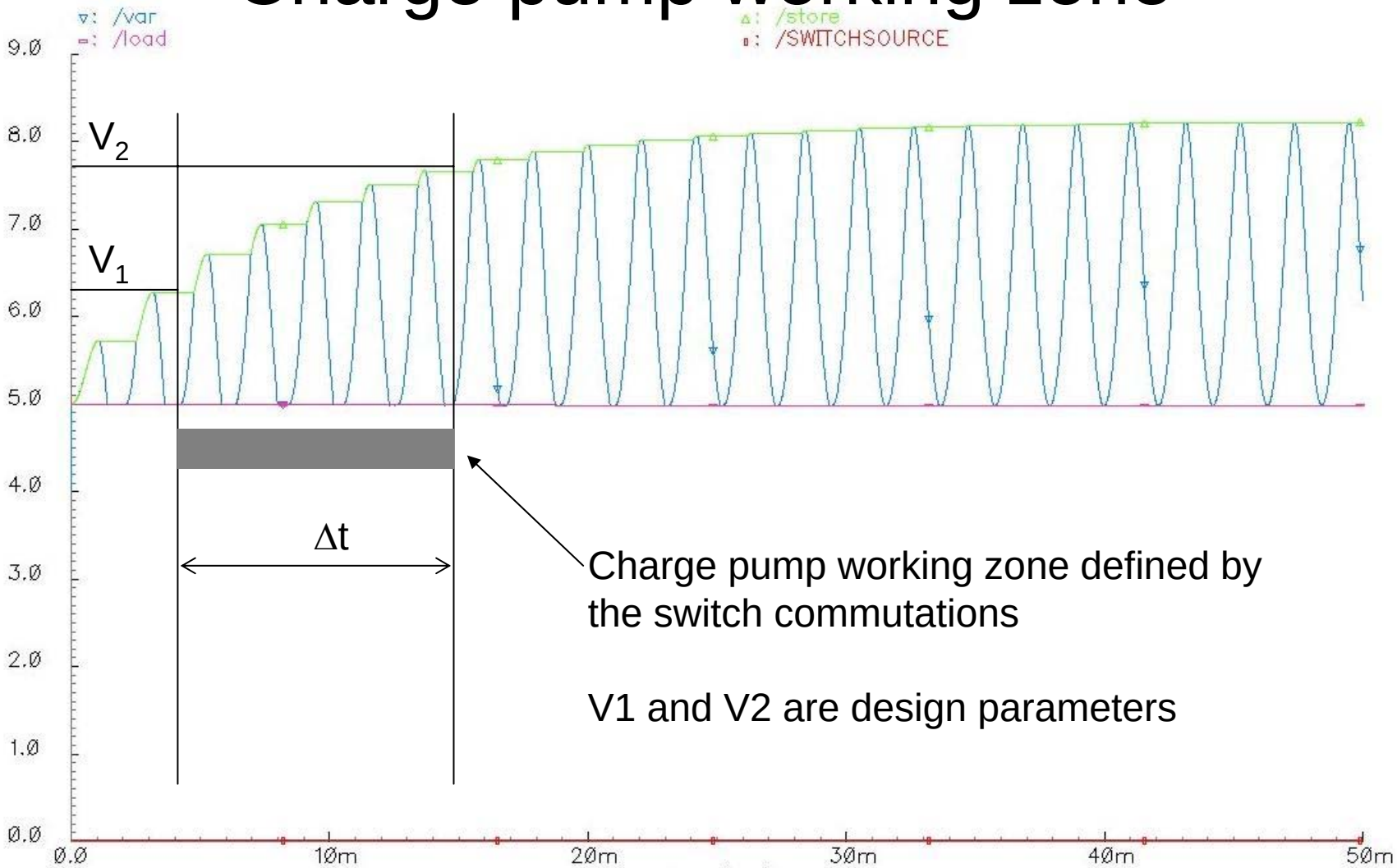




Conditionning circuit
Global operating diagrams



Conditionning circuit
Charge pump working zone



Charge pump working zone defined by the switch commutations

V1 and V2 are design parameters

Conditionning circuit
Switch commutation scenario

- How to define the switch commutation ?
- Hard time specification : not good (variable frequency…)
- Better : energy-state driven commande of commutations
- Example : The switch goes on when V_{store} reaches some defined V_2
- The switch goes off when V_{store} reaches some defined V_2,or when the current I_L reaches some I_{max} value

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Modeling
Resonator & transducer

- Behavioural modeling, based on differential equations
- Implementation in VHDL-AMS

- For the resonator :

$$k(x - x_{system}) + \mu\dot{x} + F_{transducer} = m\ddot{x}$$

  x: coordonnee of the mobile mass,

  x_{system} : coordonnee of the spring fixed end,

  k: elastic constant, μ : damping constant

  m: resonator mass

  $F_{transducer}$: force generated by transducer

- x_{system} is found from the known external acceleration

$$x_{system} = \int\int a_{ext}(t)$$

Modeling
Resonator & trasducer

- The force generated by the transducer :

$$F_{transducer}(x) = \frac{V^2_{\text{var}}}{2}\frac{dC_{\text{var}}(x)}{dx}$$

V_{var}: voltage on C_{var} (transducer)

$C_{var}(x)$: relation between the displacement and the capacitance of the transducer, obtained experimentally

- Electrical description of transducer :

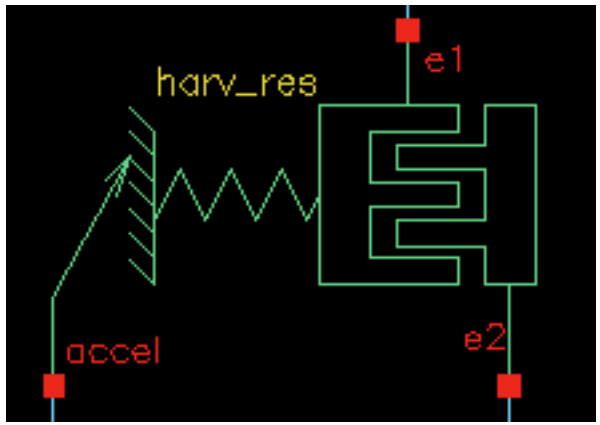
$$Q = C_{\text{var}}V_{\text{var}} + Q_0$$
$$I_{\text{var}} = \dot{Q}$$

Q: electrical charge of the transducer (Cvar), Q_0- initial charge

I: electrical current through transducer

Modeling
Resonator & trasducer

- In electrical domain seen as a variable capacitor
- External acceleration represented by input voltage



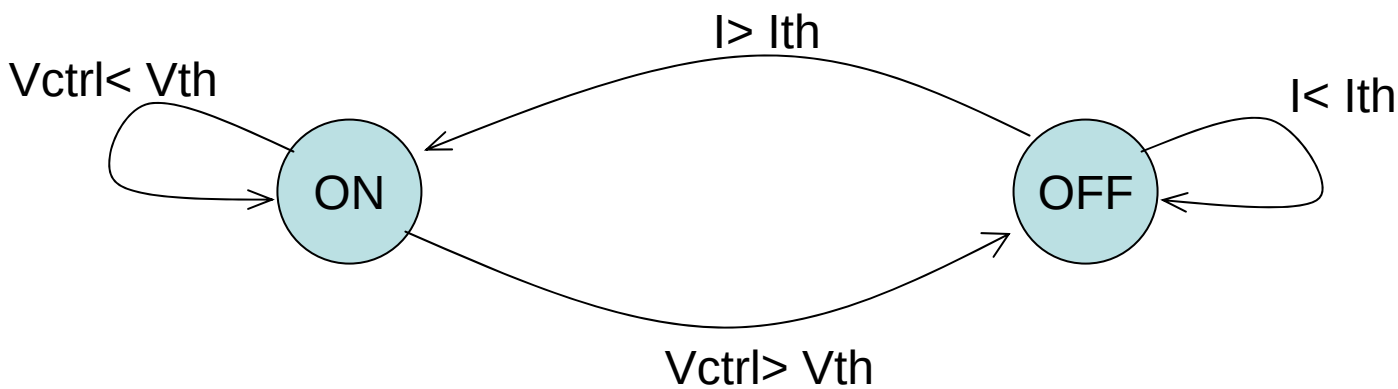
Modeling
Switch functional model

The switch has two states : ON and OFF, behaving like a resistance :

U=Ron I and U=Roff I

The transition between states is controlled by the switch current and by a control voltage (Vstore)

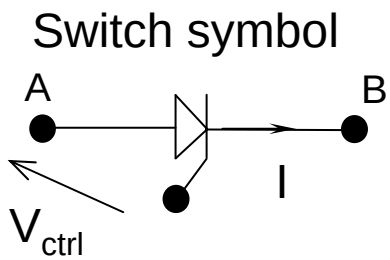
Two states imply a one-bit memory cell (variable) in the model

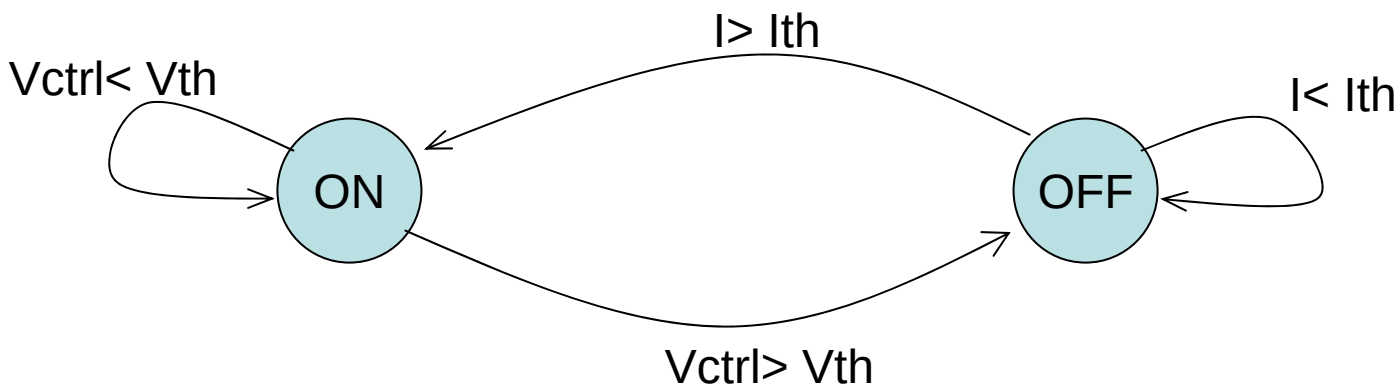


Modeling
Switch functional model

U = Ron I , if ON="1" and I < Ith
ON = "0", if ON="0" and I > Ith
U = Roff I , if ON="0" and Vctrl < Vth
ON = "1", if ON="0" and Vctrl > Vth

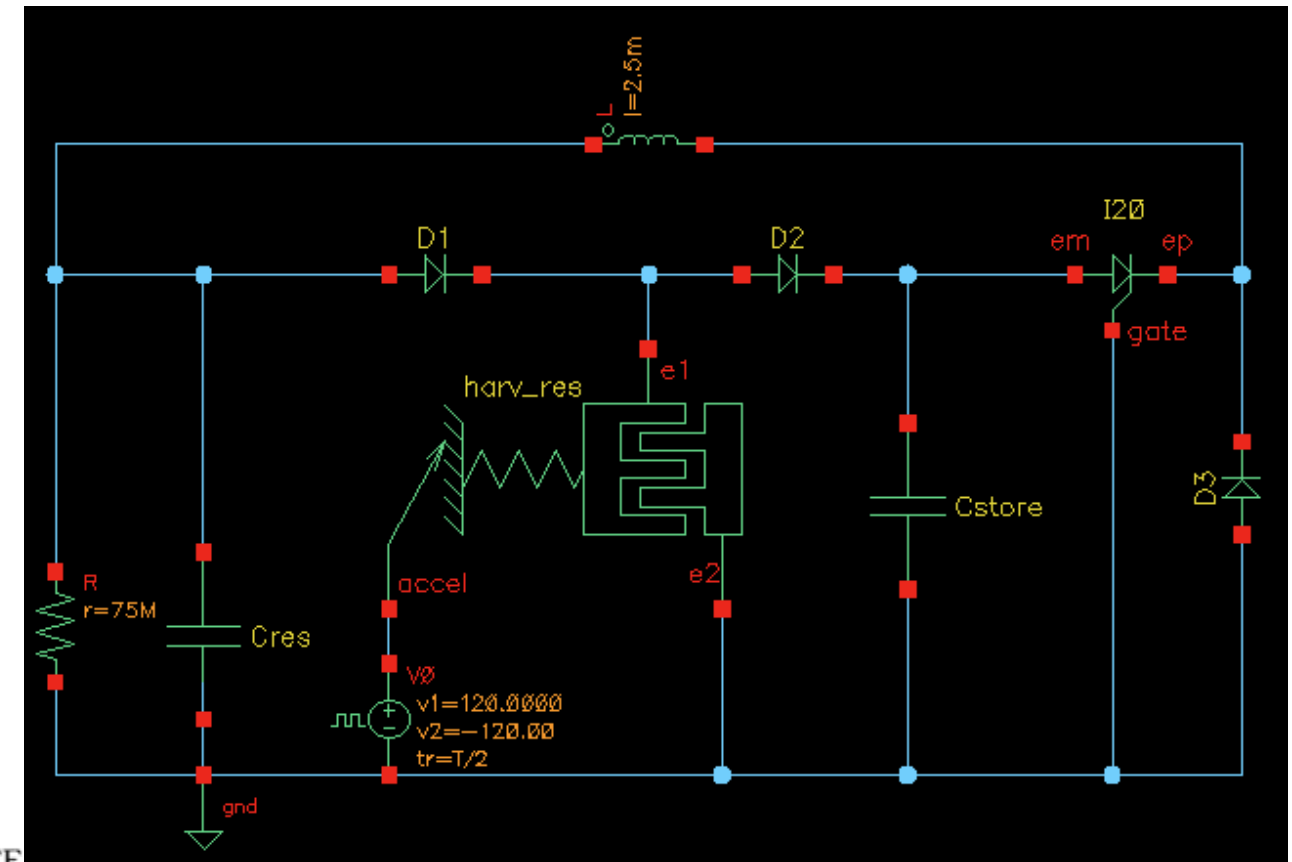
Implementation : VHDL





Modeling
Global system

Modeled in CADENCE Analog Artist Environment
Was used AdvanceMS simulator (mixed Eldo-VHDL AMS)

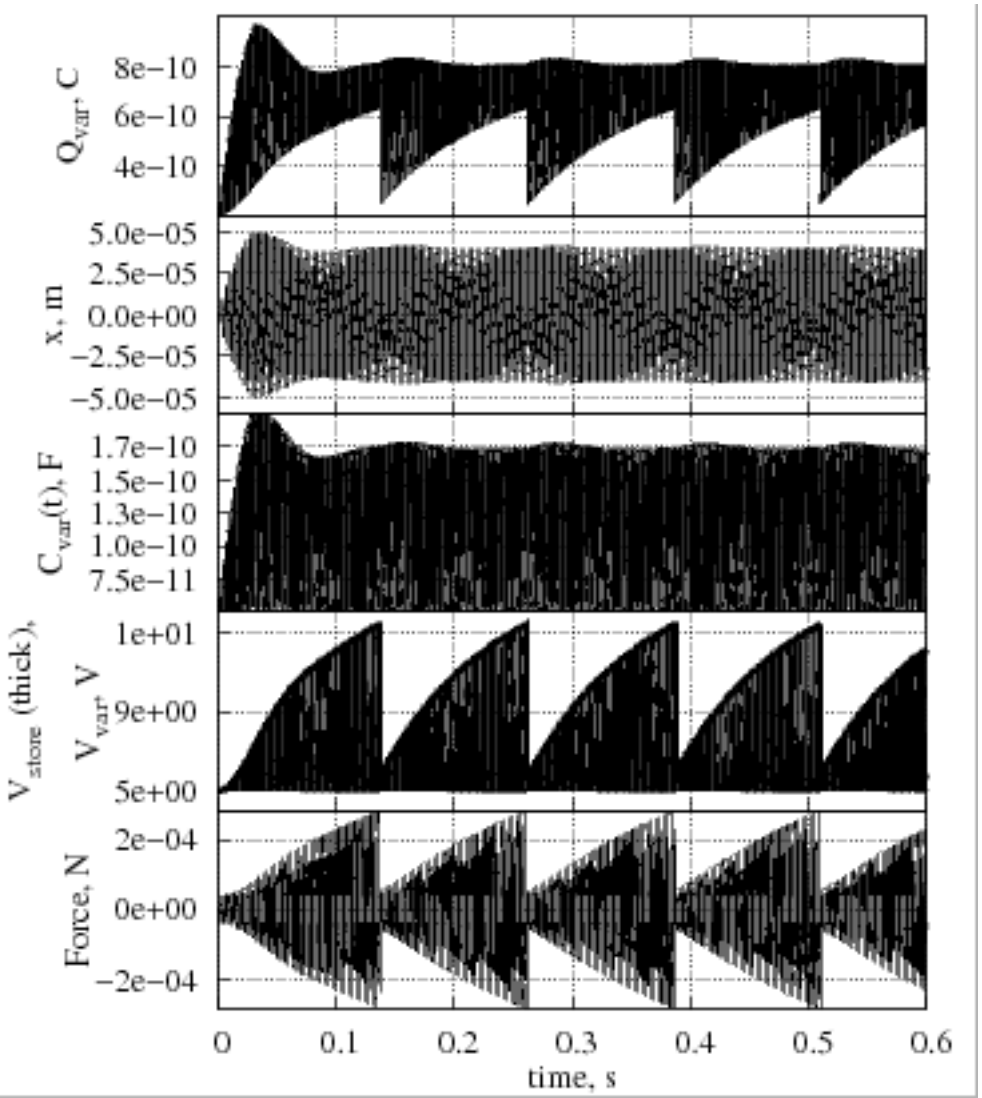


Simulation results

- Switch timing : the choice of V_1 and V_2 has been achieved using numeric/analytic optimization
- The threshold cut-off current of the switch was derived
- With Cres=1 μF, Cstore=3.3 nF, Cvar max=174 pF; Cvar min=51 pF, external acceleration frequency = 300 Hz,

A charge of 26 MΩ could be driven by this harvester

Simulation results



Transducer charge

Resonator displacement

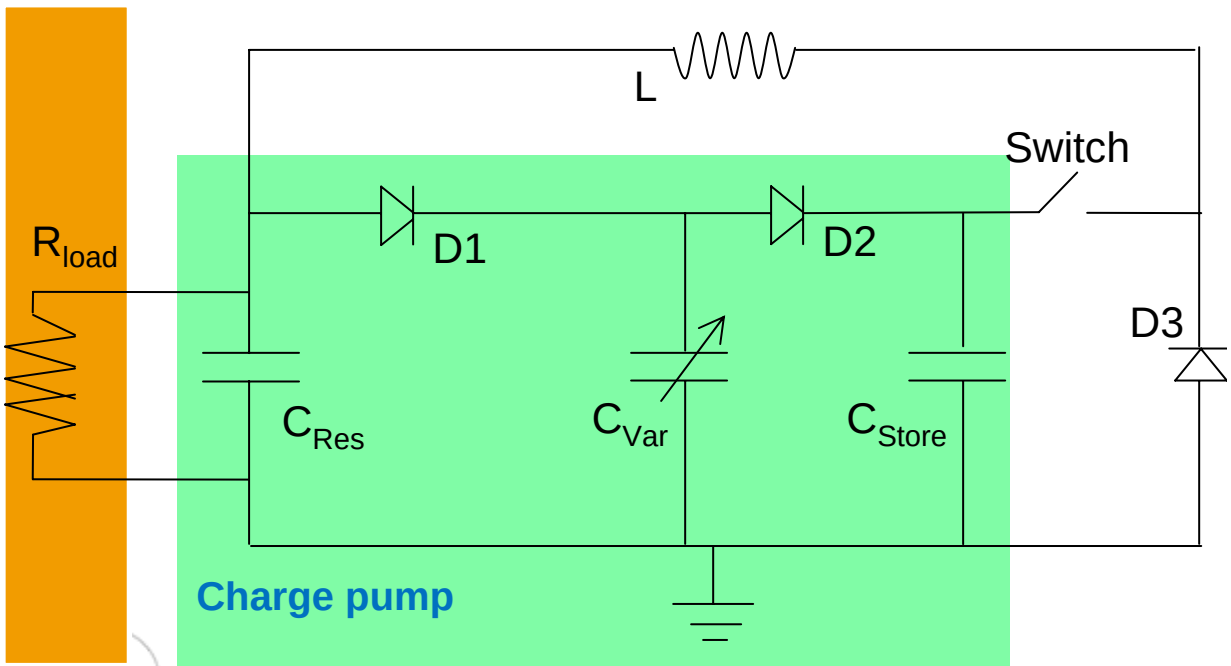
Capacity of transducer

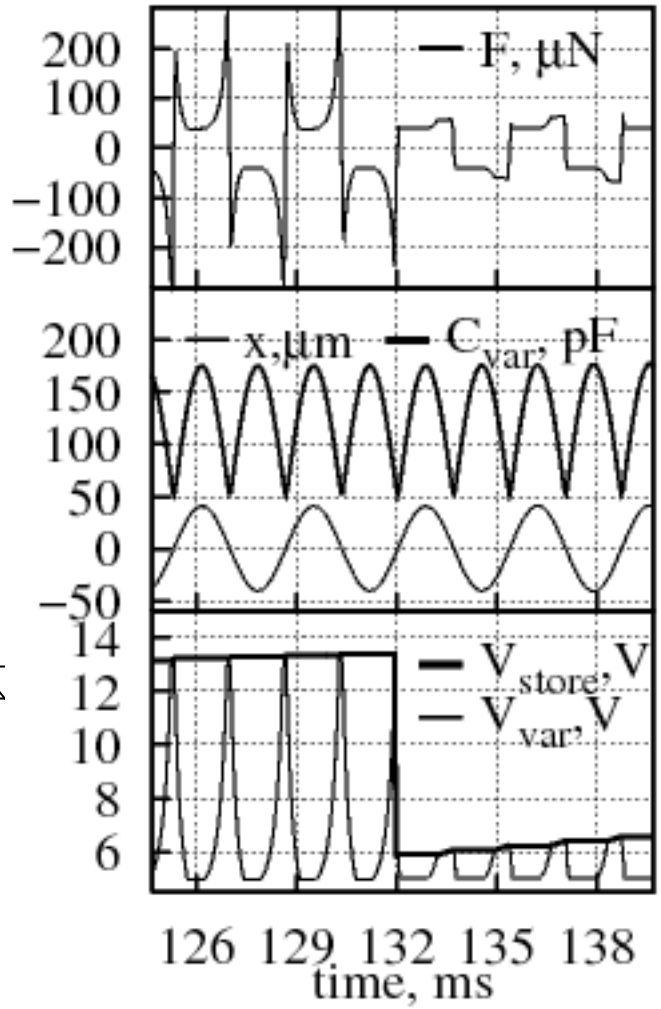
V_{store}

Electrical force generated by the transducer

Simulation results

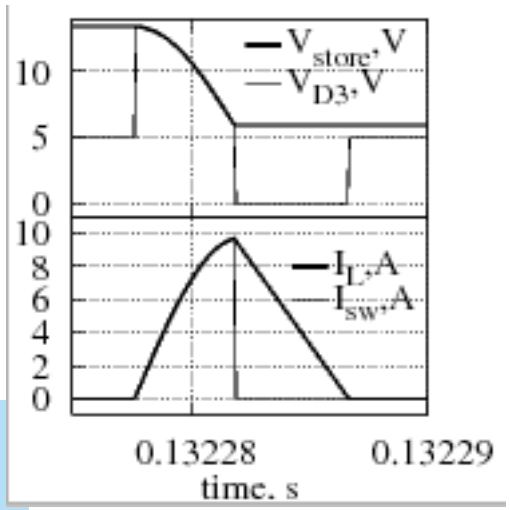
Zoom on charge pump operation

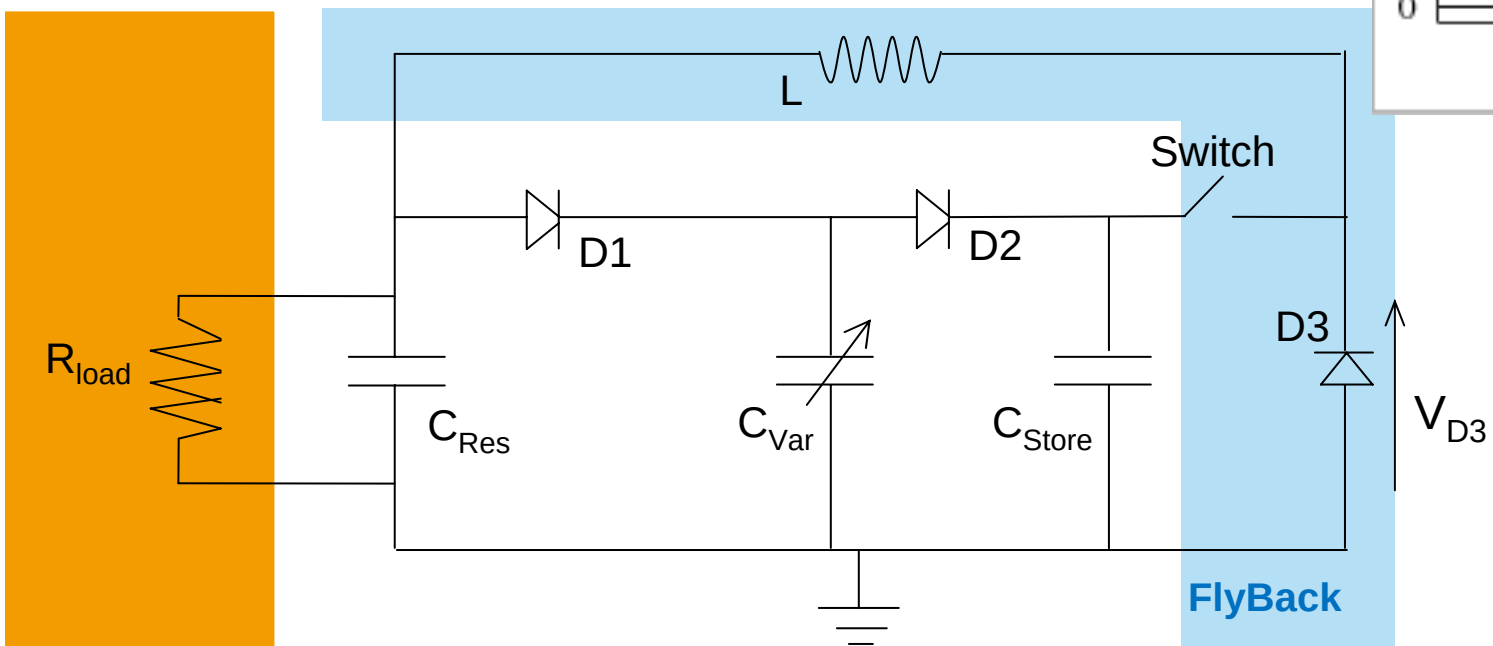




Simulation results

Zoom on flyback circuit operation





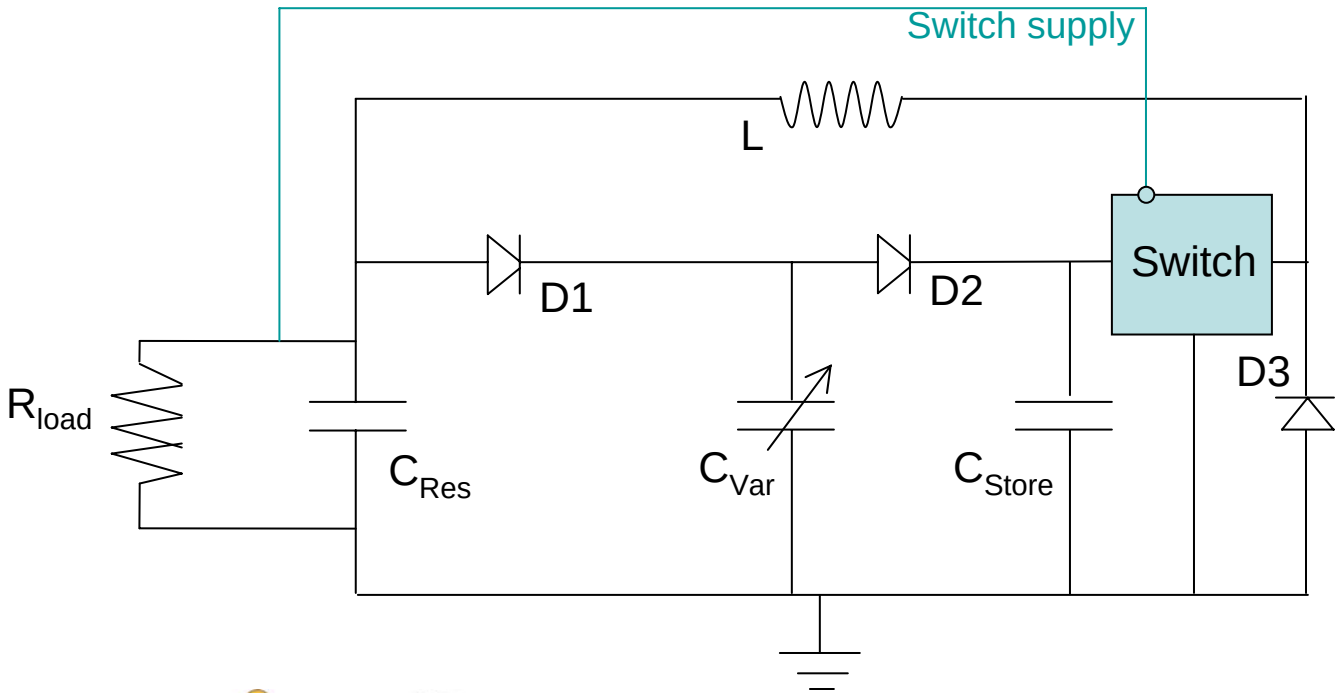
Conclusions

- The proposed VHDL-AMS model of the resonator highlighted an electromechanical coupling
- The model embedes the internal structure of the resonator : at input, the external acceleration, at output, the variable capacitor as electrical component

- The functional model of the switch : allows to find functional specifications of the real switch block
- « Top-down » design approach

Conclusions

- The switch: circuit state driven, no predefined time cadence
- Possible realization: an active and « intelligent » circuitery
- Supplied by the harvested energy



Conclusions

- Ongoing work : Integration of the parasitics in the definition of the optimum commutation scenario ;
- Electrical design of the « intelligent » switch

Acknowledgement

This work is partially funded by the French Research Agency
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