

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

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Philippe Basset, Ayyaz Mahood
Paracha, Gilles Amendola

Outline

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

Outline

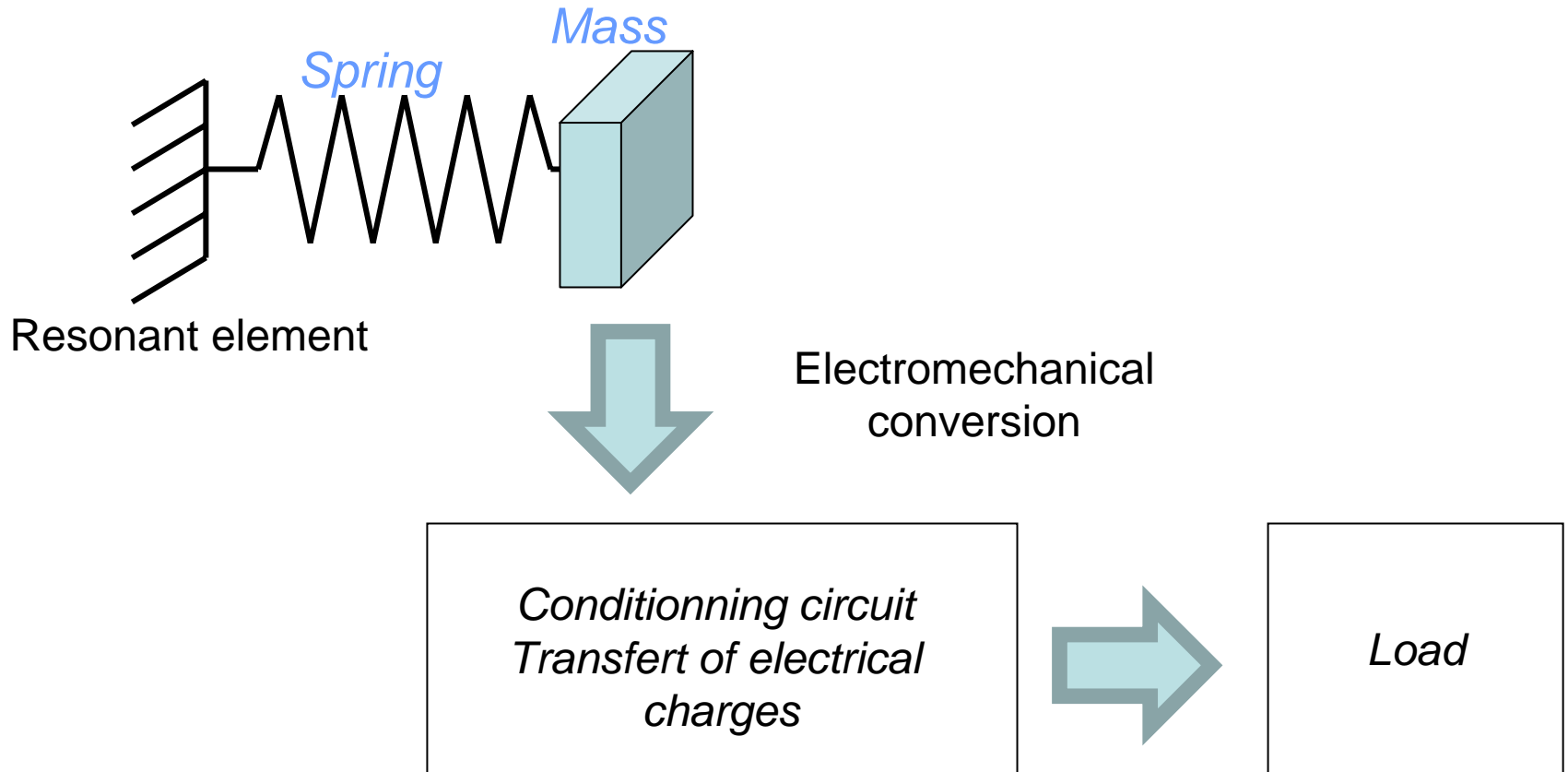
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Introduction

- Motivations
 - Ambient 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...)

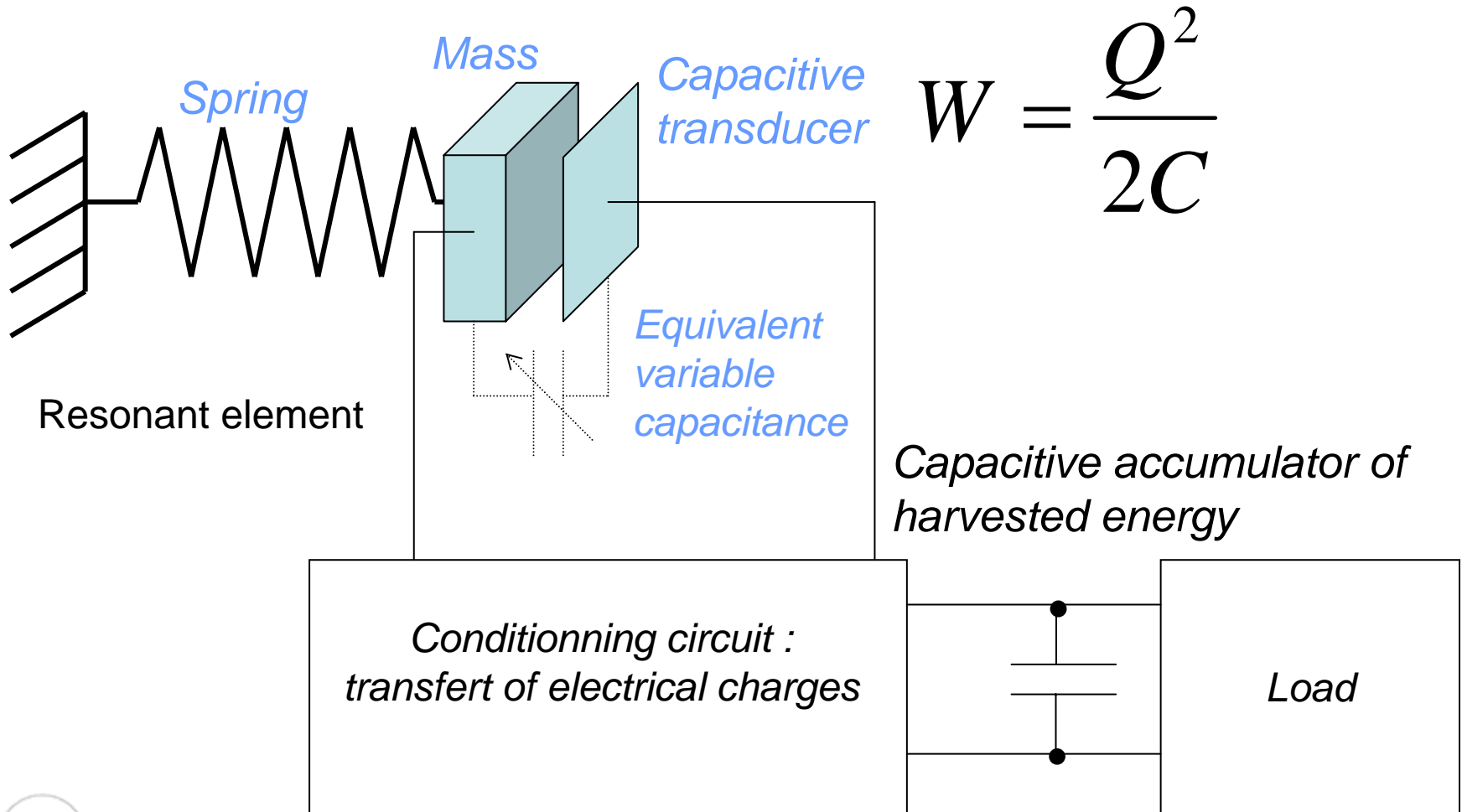
Introduction

Mechanical energy harvesting principle



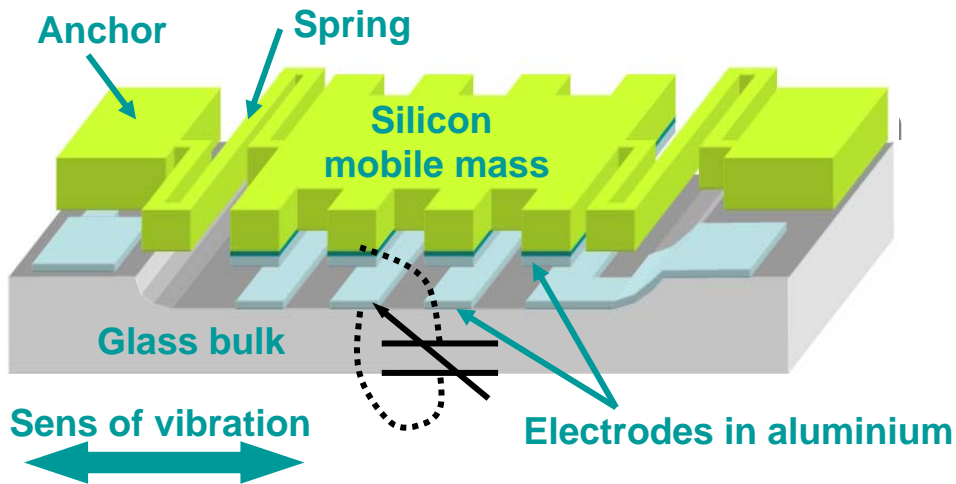
Introduction

Mechanical energy harvesting principle

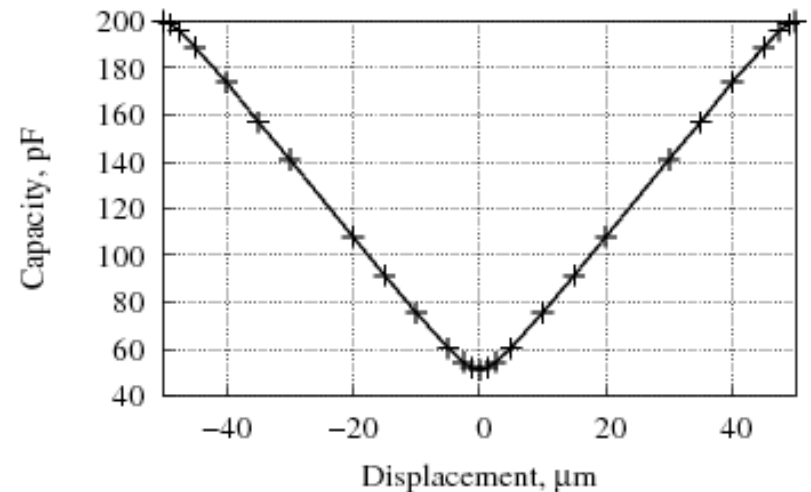
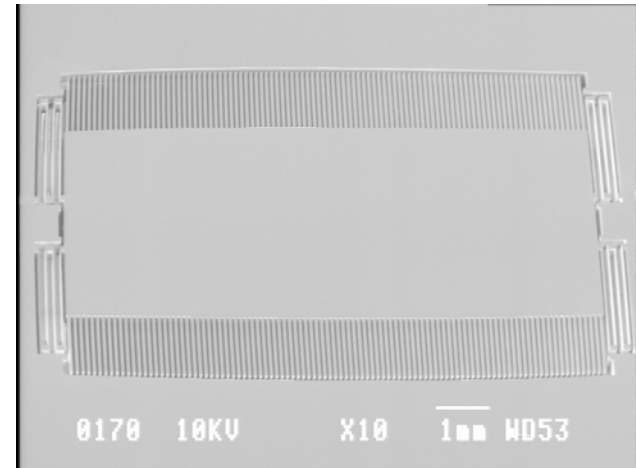


Introduction

Resonator for energy harvesting



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

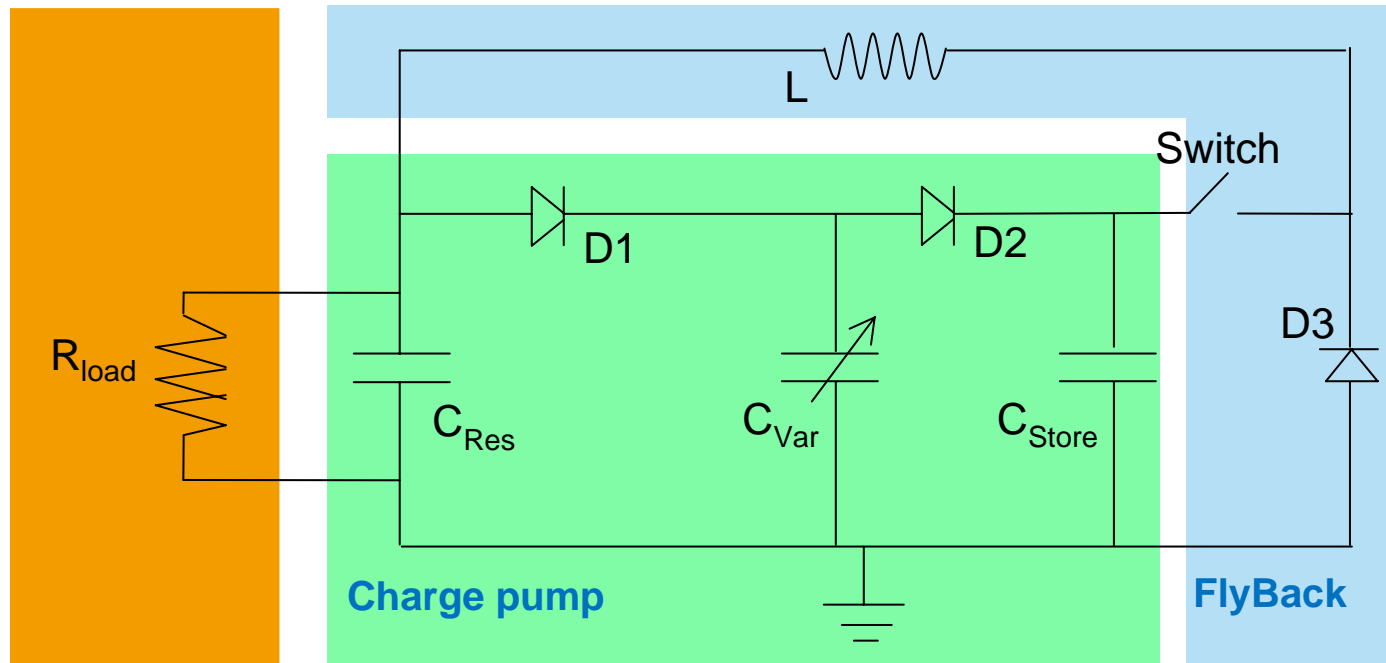


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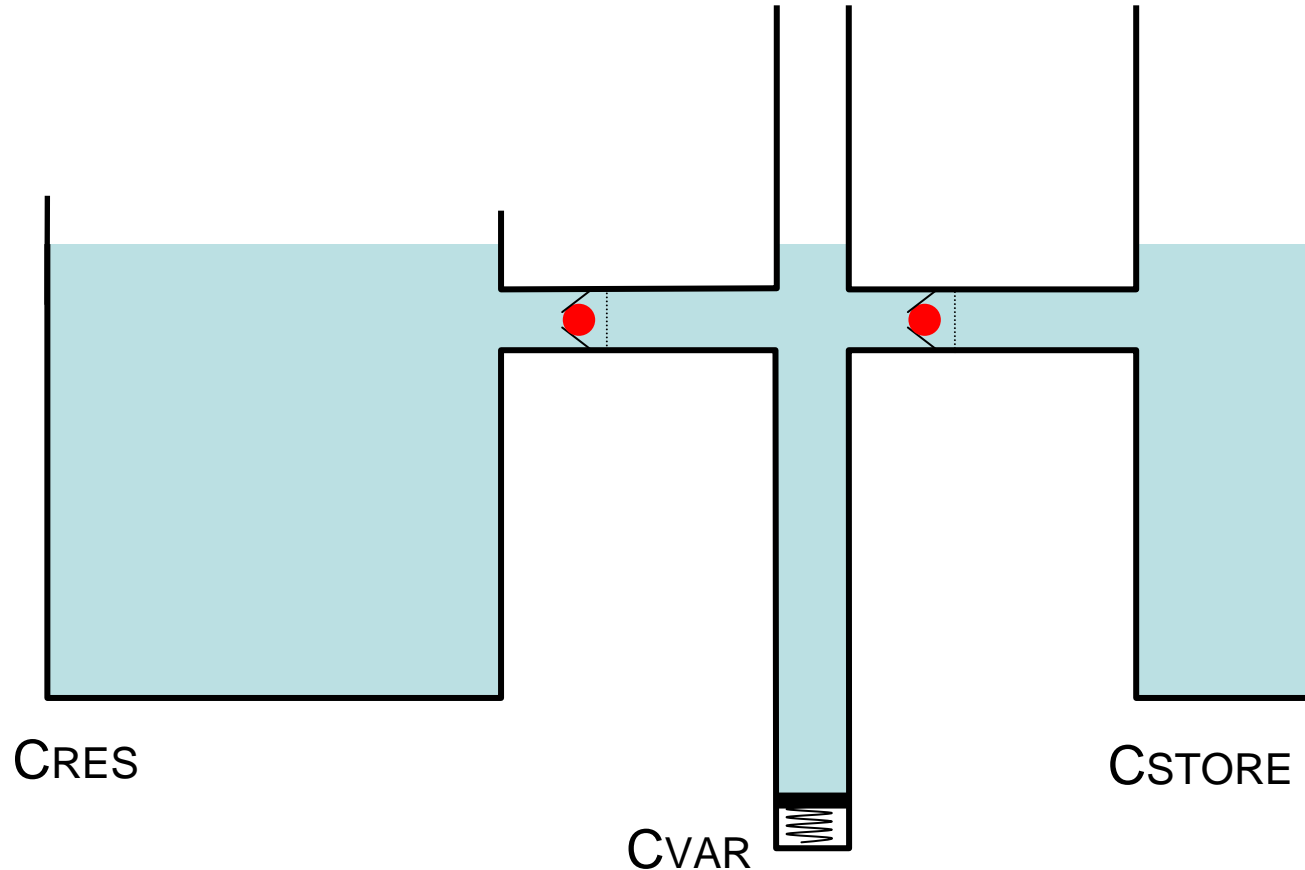
Conditionning circuit

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



Conditionning circuit

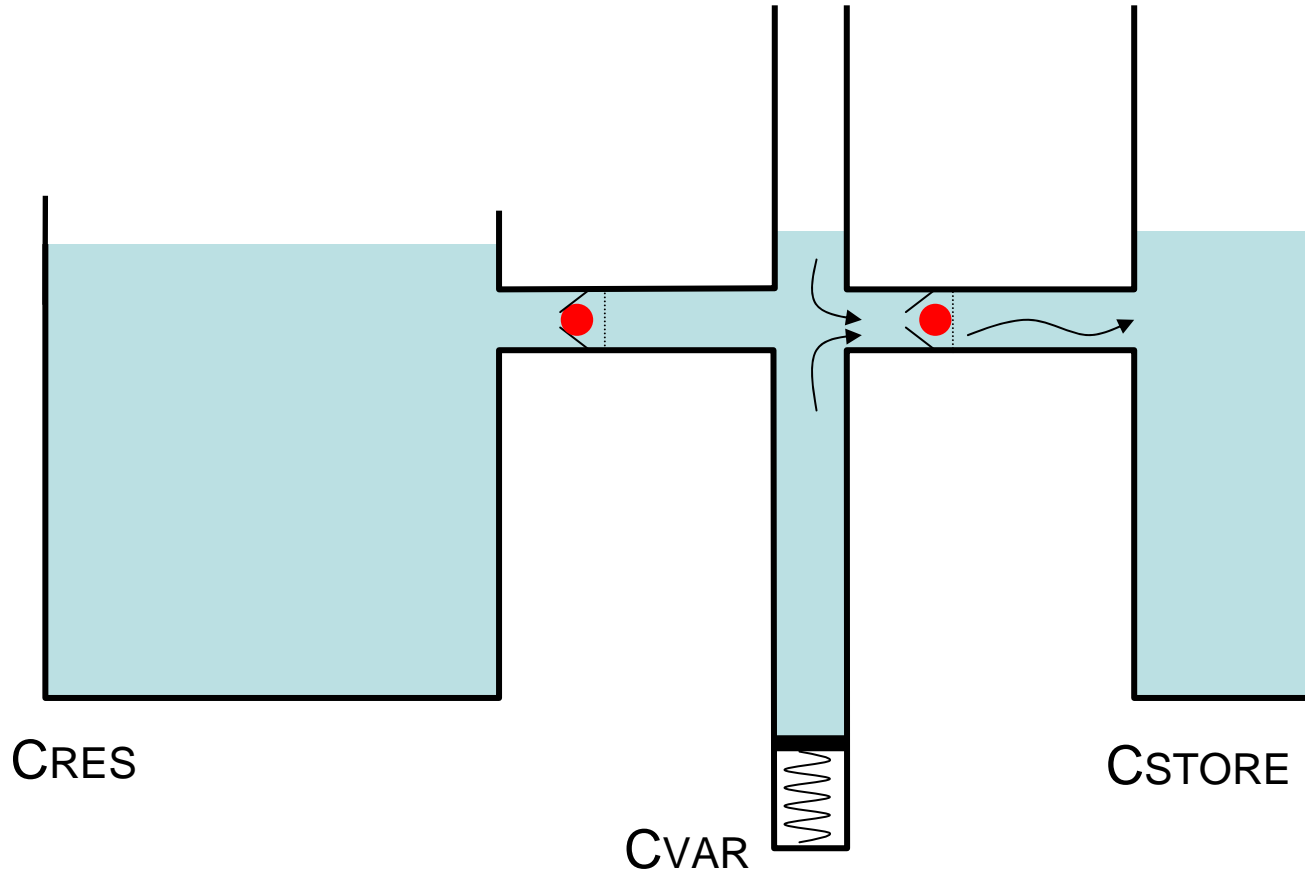
Charge pump operation



$$C_{var} = C_{max}$$

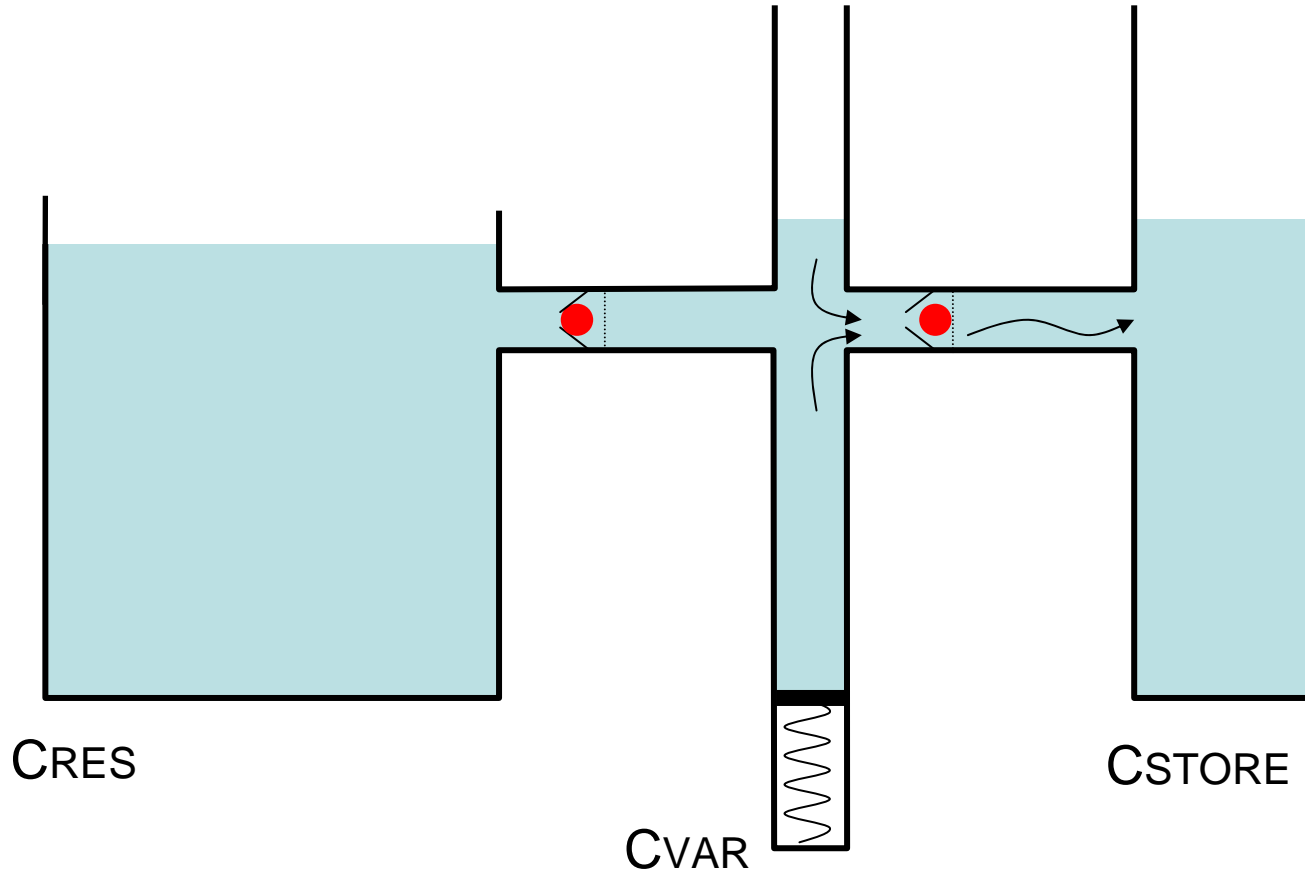
Conditionning circuit

Charge pump operation



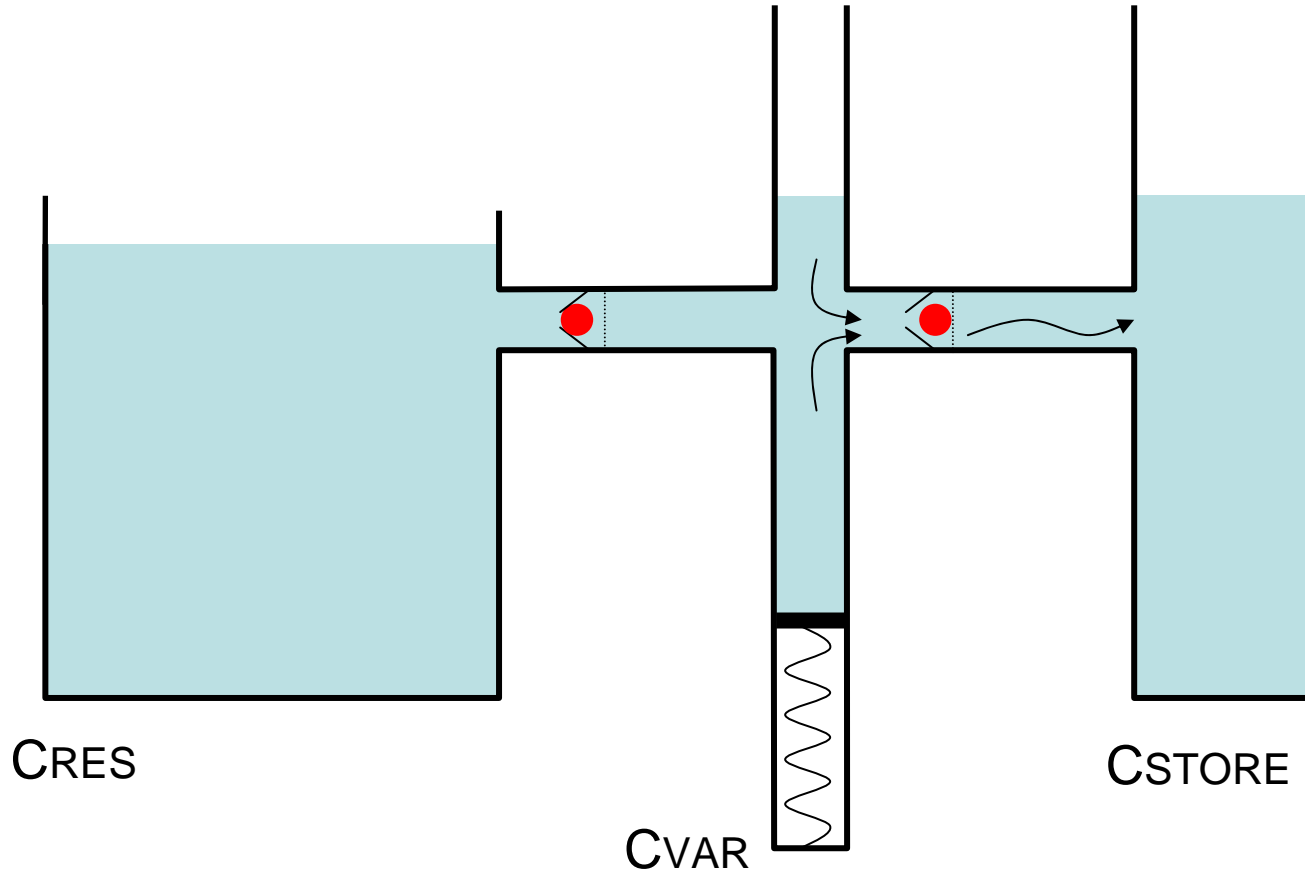
Conditionning circuit

Charge pump operation



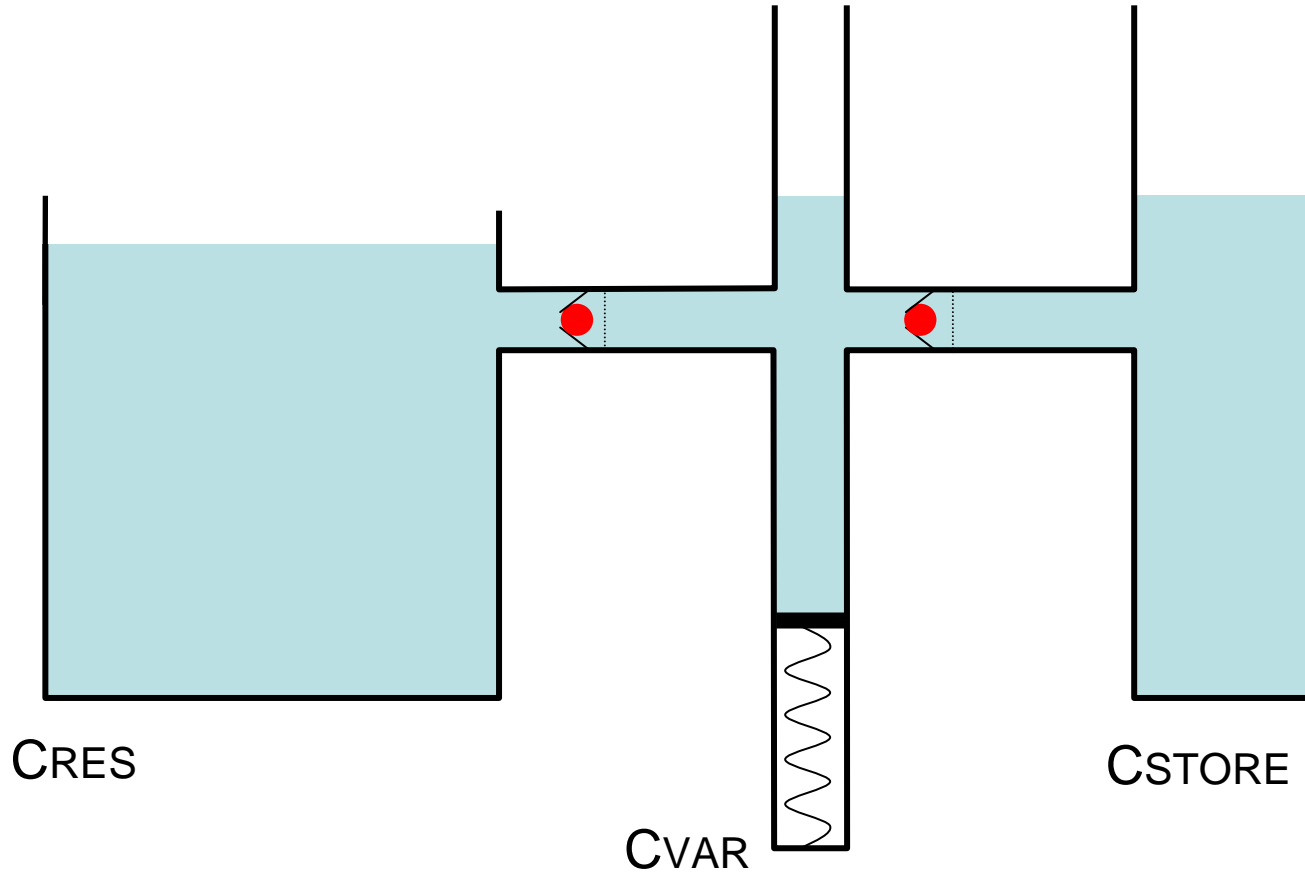
Conditionning circuit

Charge pump operation



Conditionning circuit

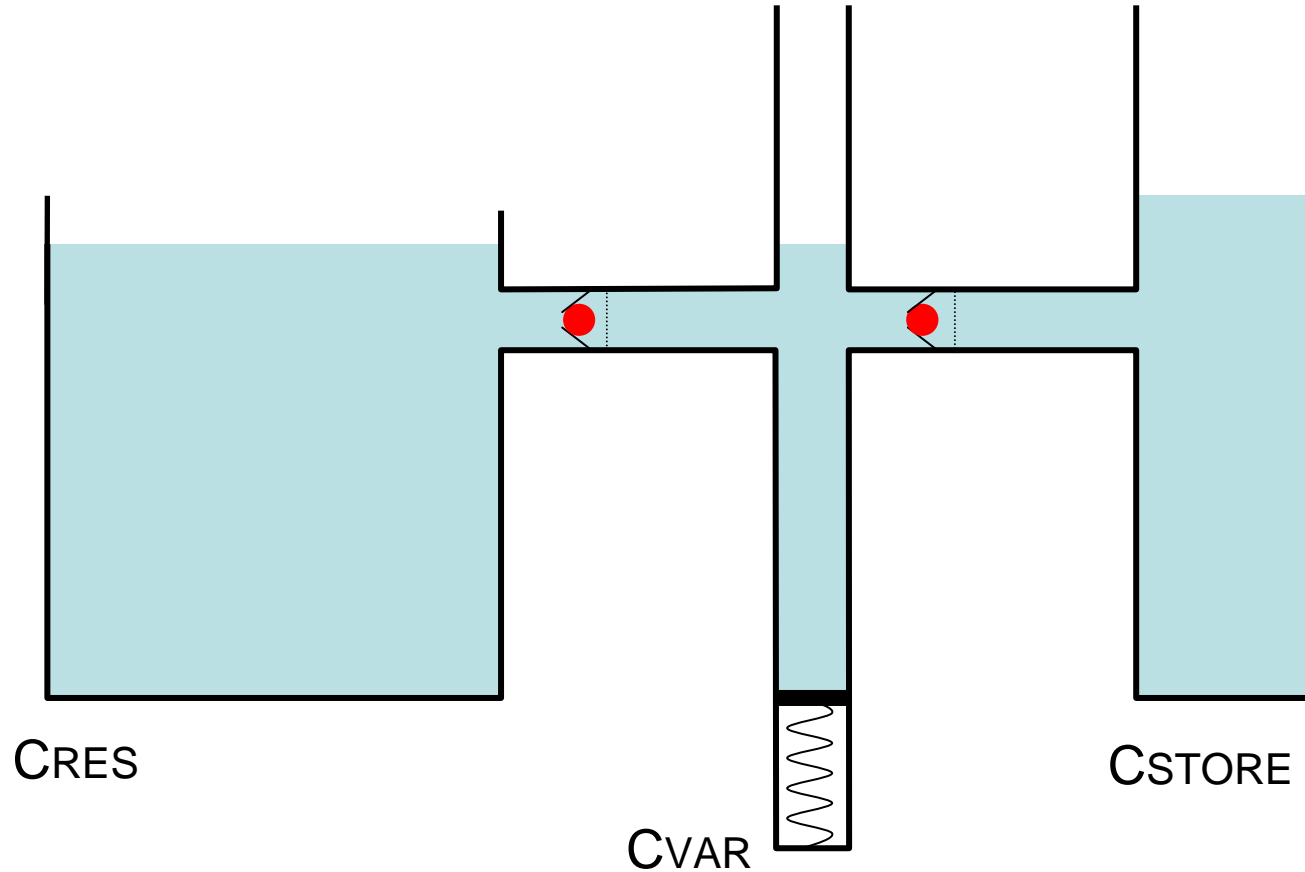
Charge pump operation



$$Cvar = Cmin$$

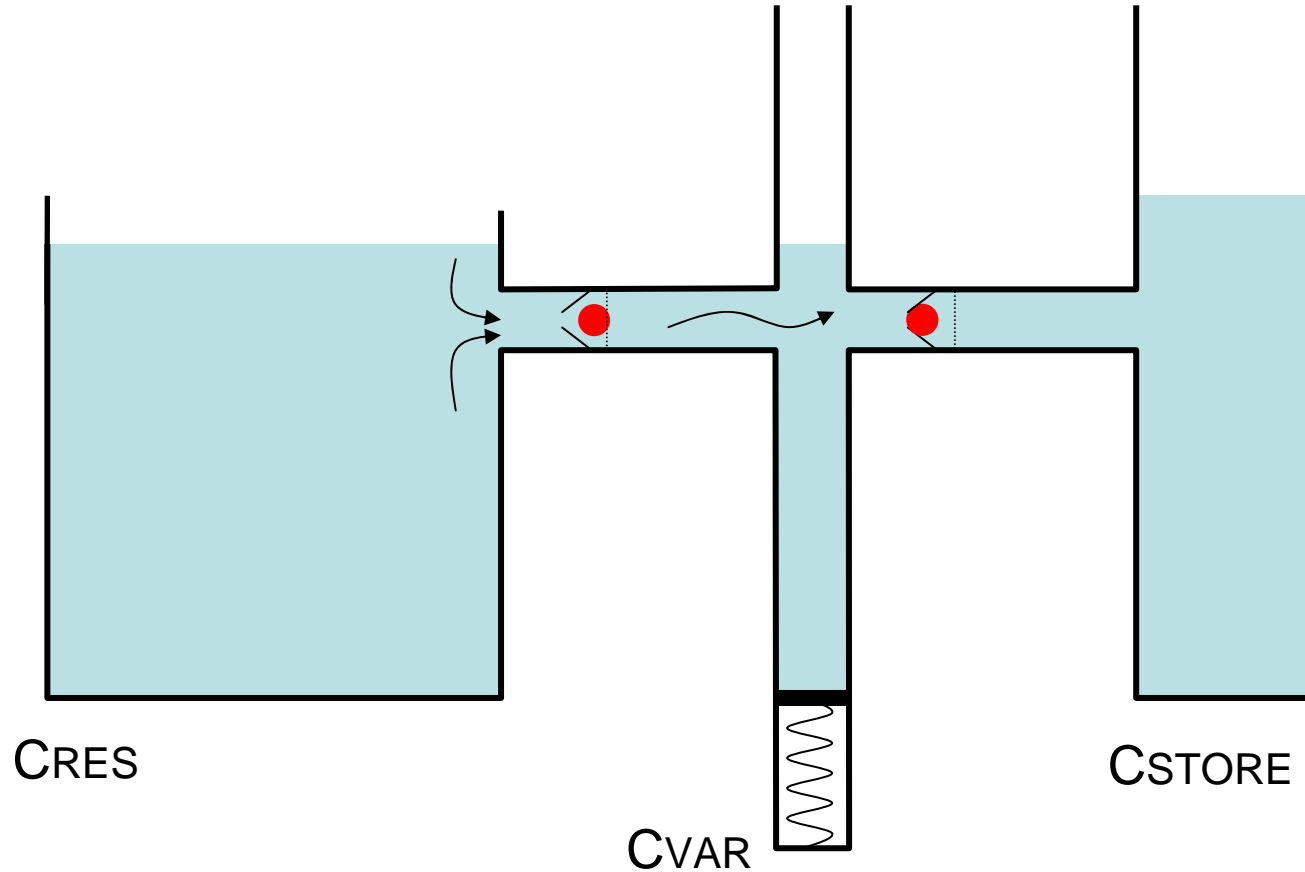
Conditionning circuit

Charge pump operation



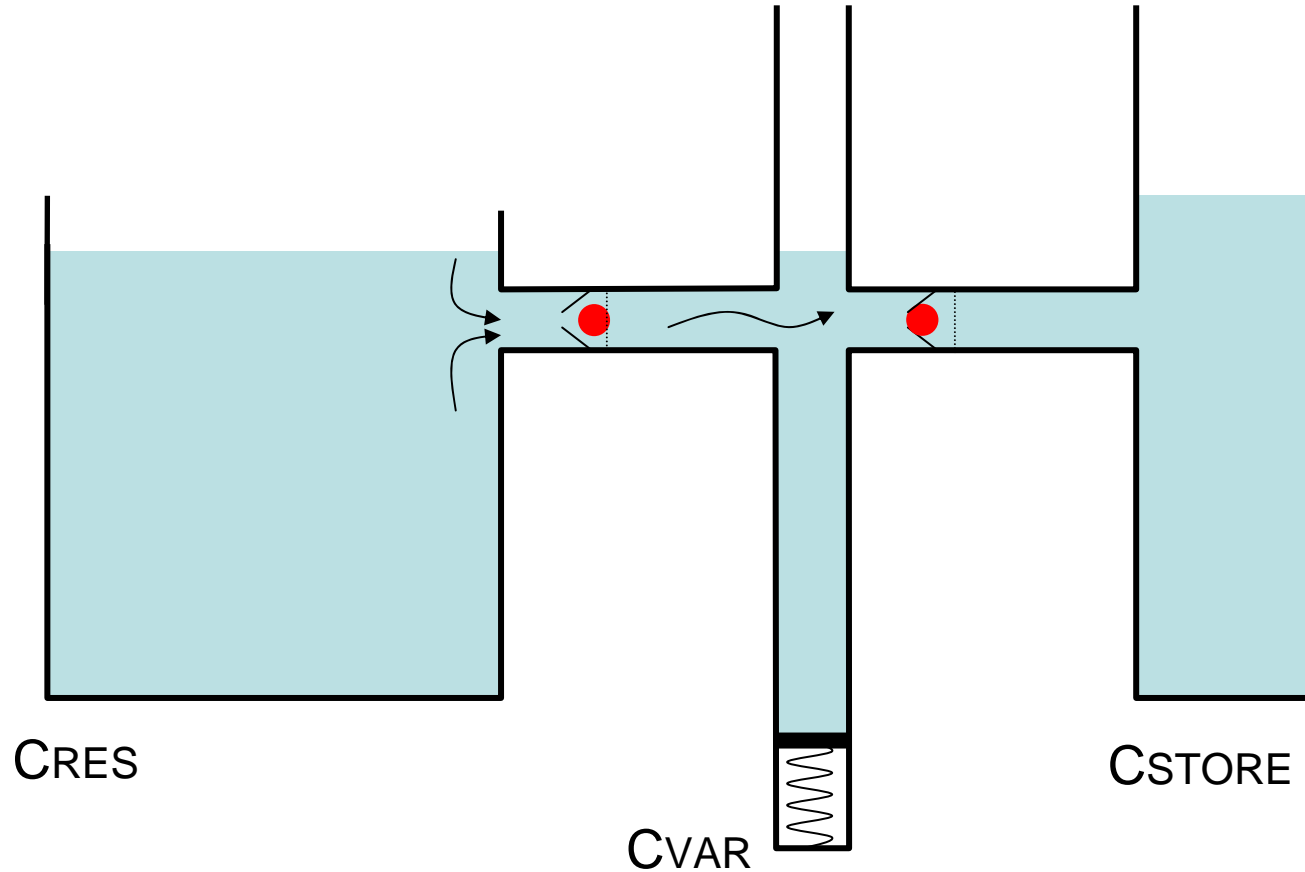
Conditionning circuit

Charge pump operation



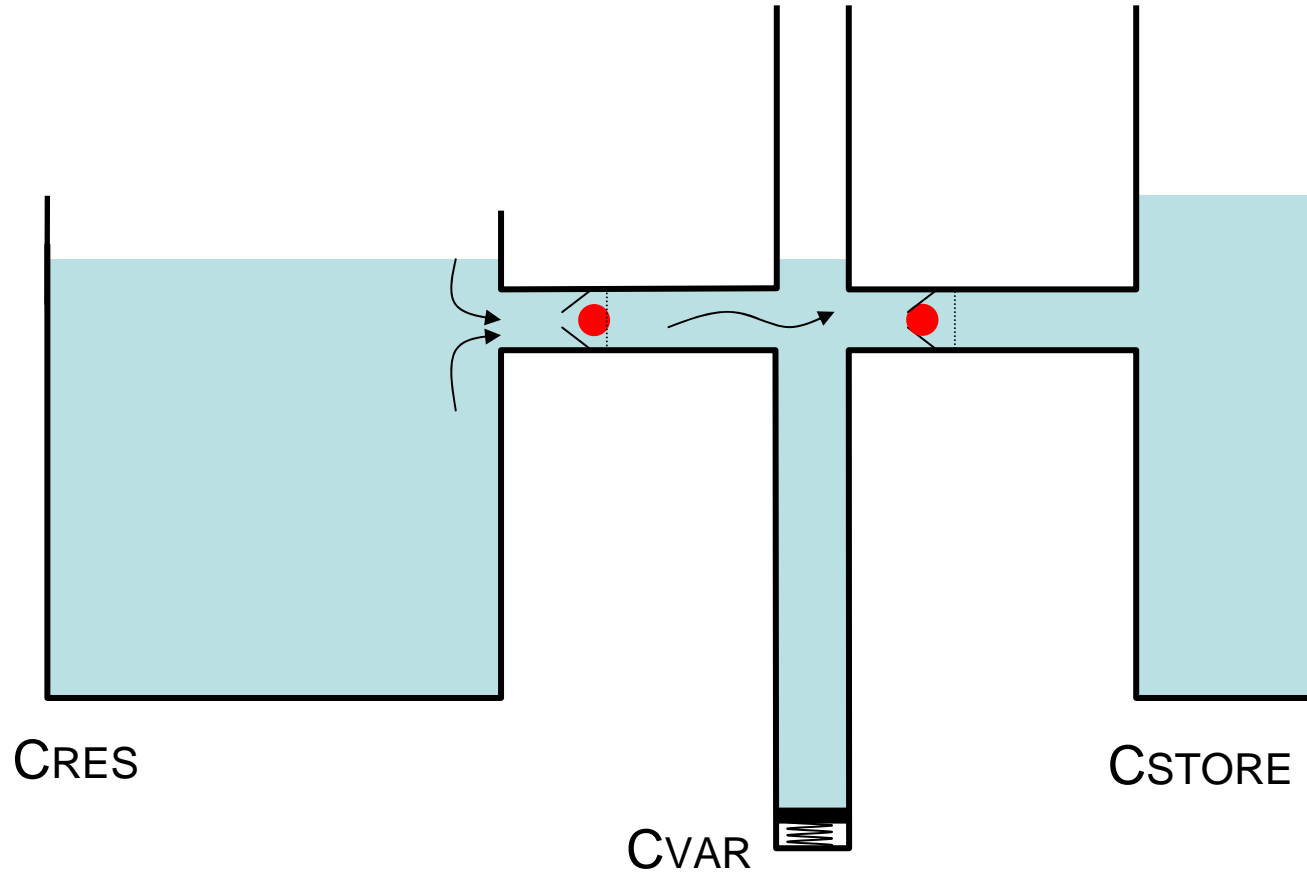
Conditionning circuit

Charge pump operation



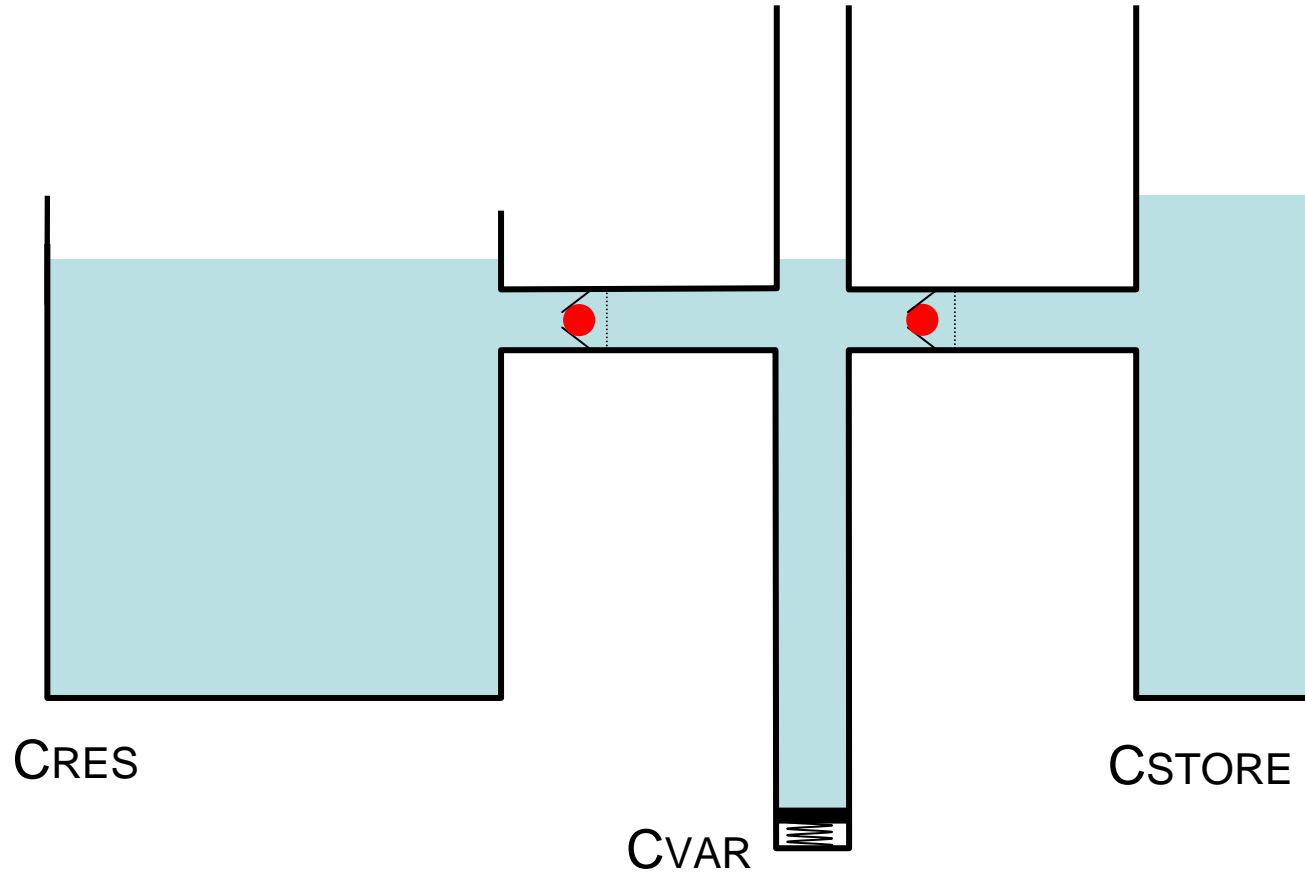
Conditionning circuit

Charge pump operation



Conditionning circuit

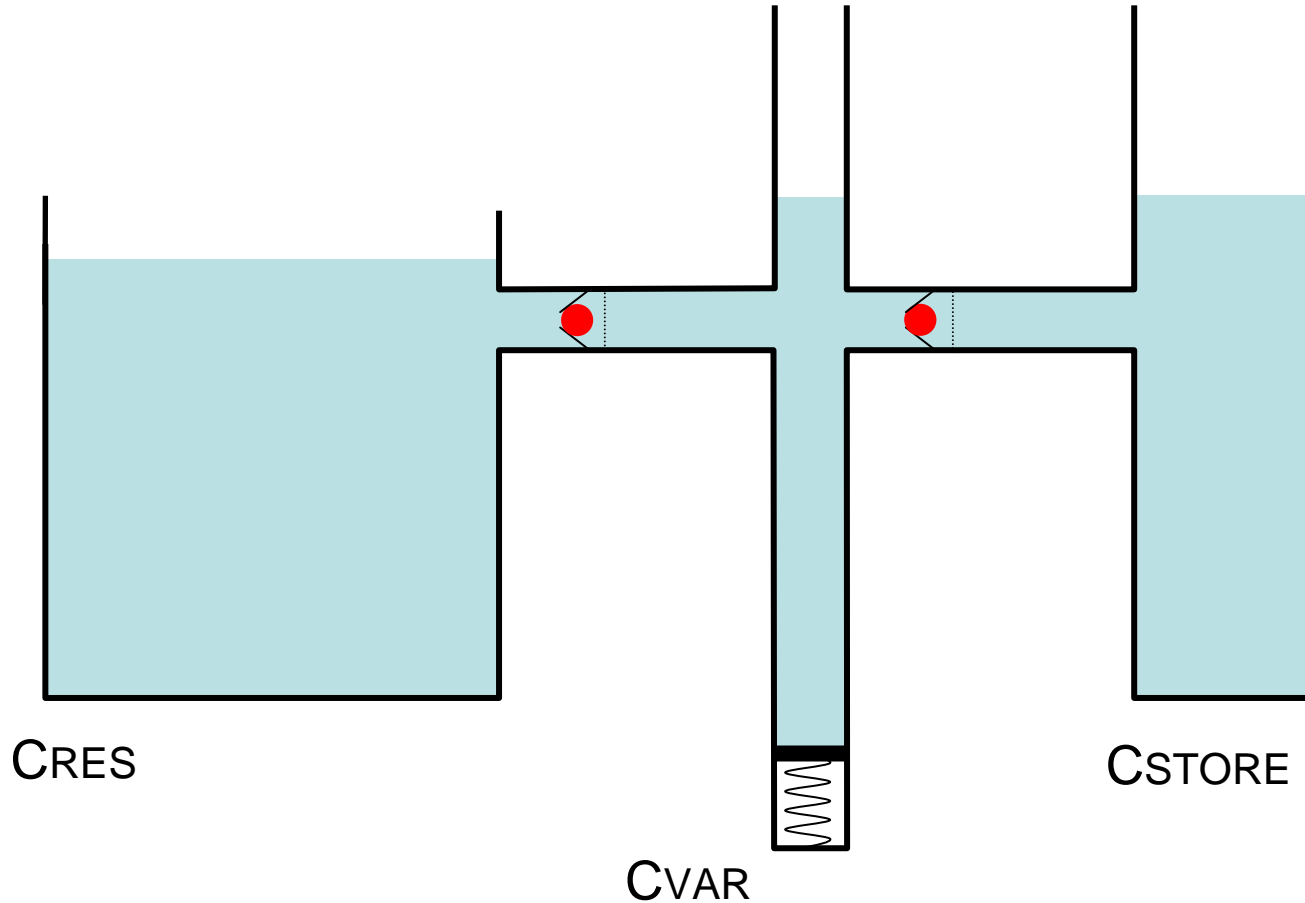
Charge pump operation



$$Cvar = Cmax$$

Conditionning circuit

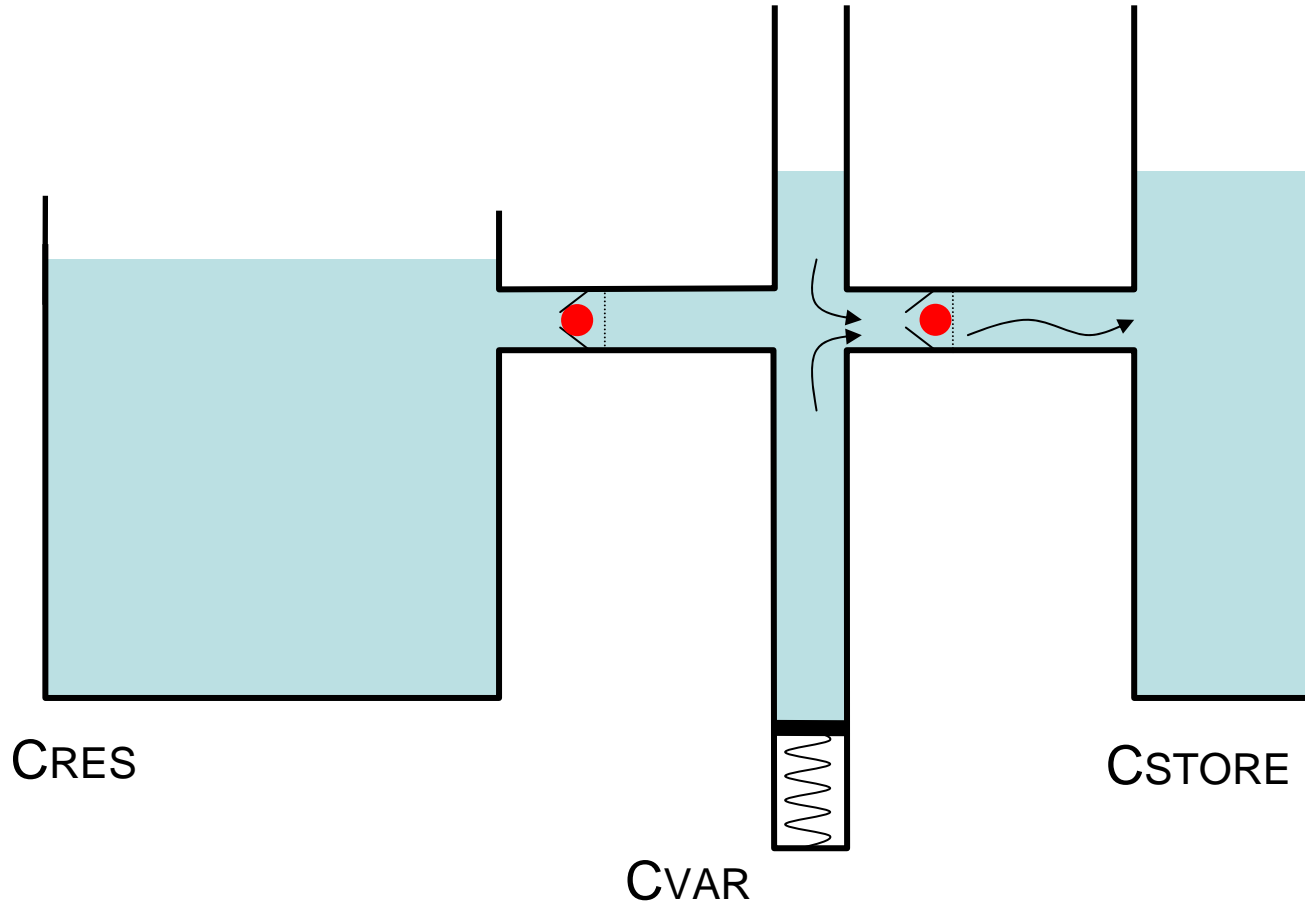
Charge pump operation



$$Cvar = Cmax$$

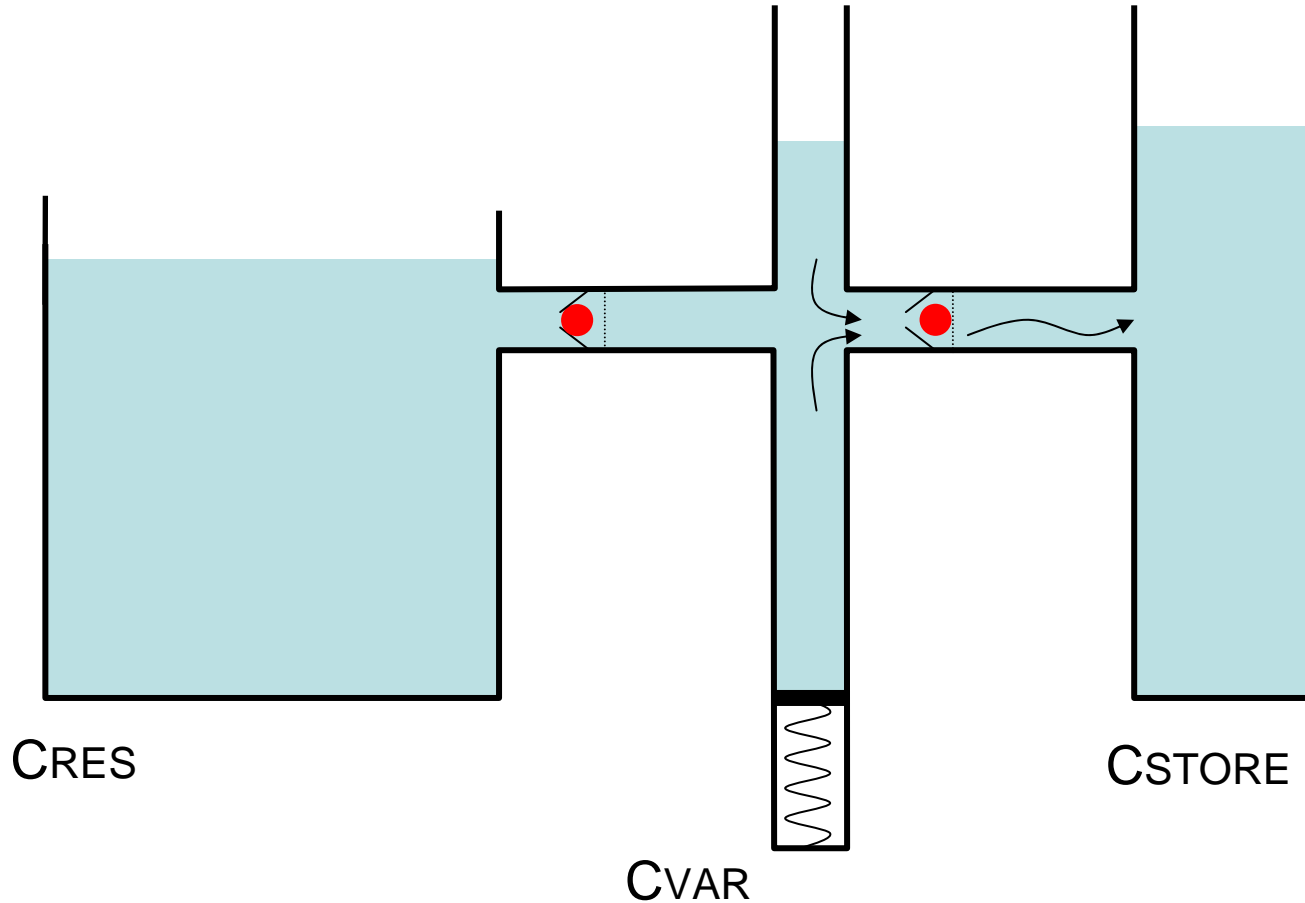
Conditionning circuit

Charge pump operation



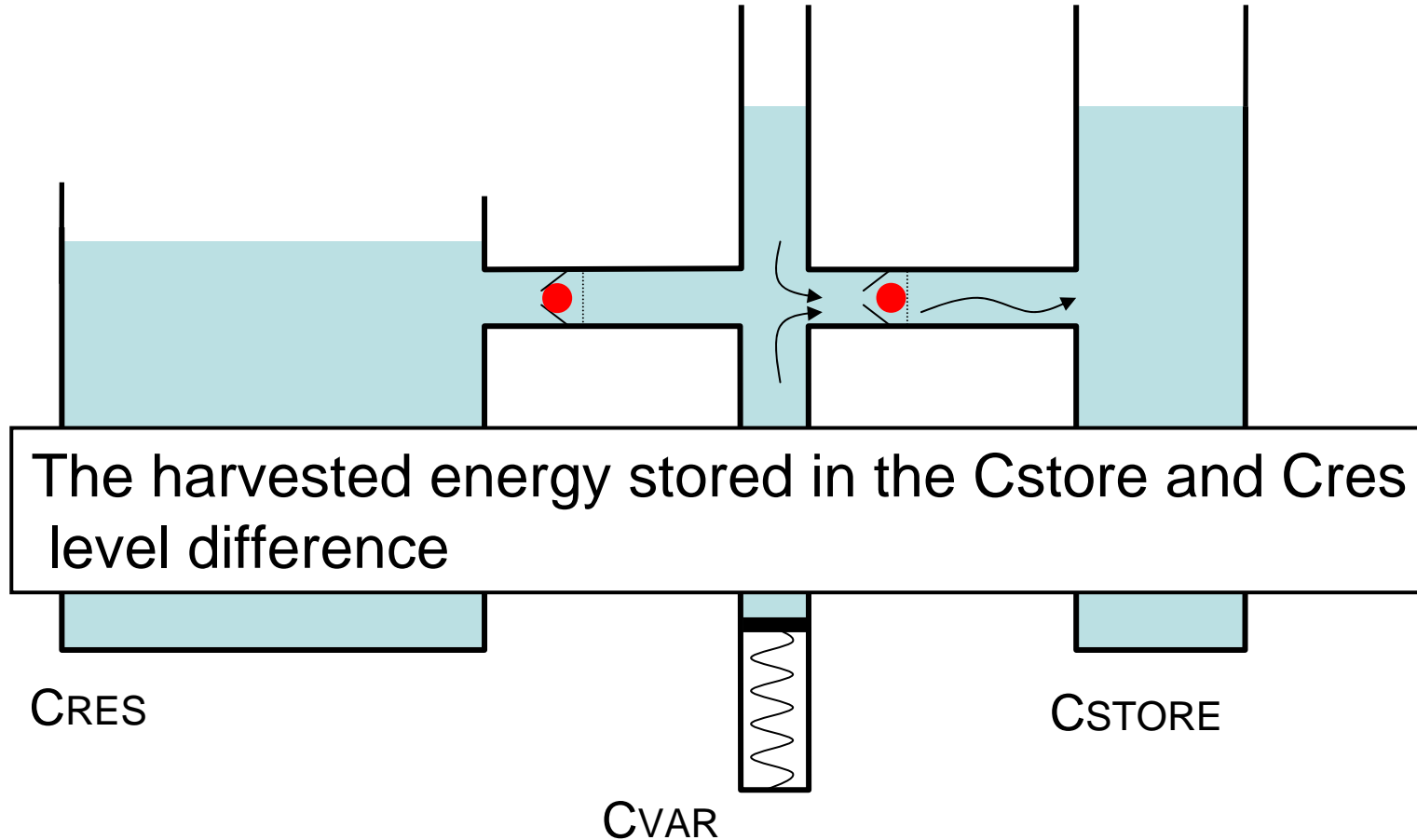
Conditionning circuit

Charge pump operation



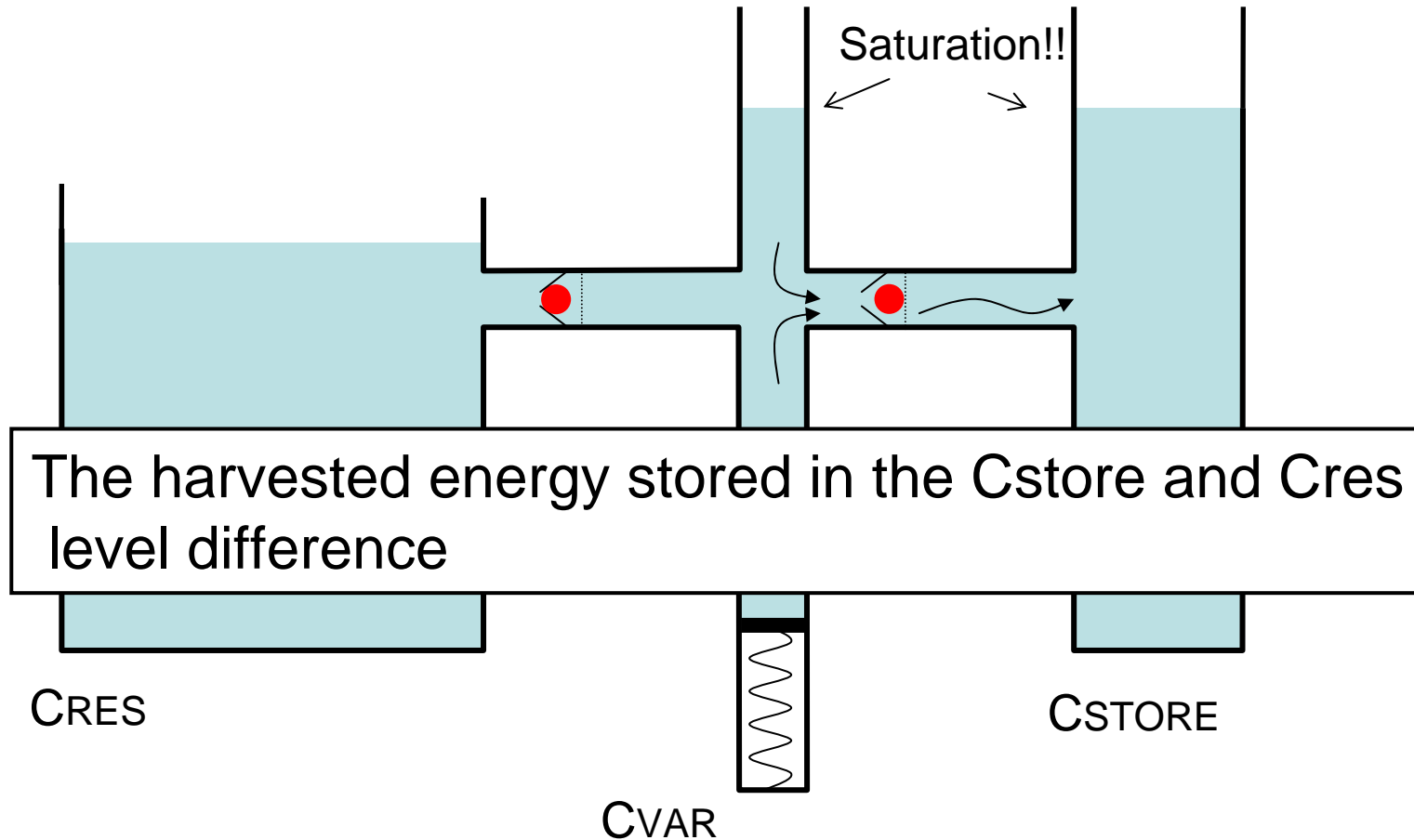
Conditionning circuit

Charge pump operation



Conditionning circuit

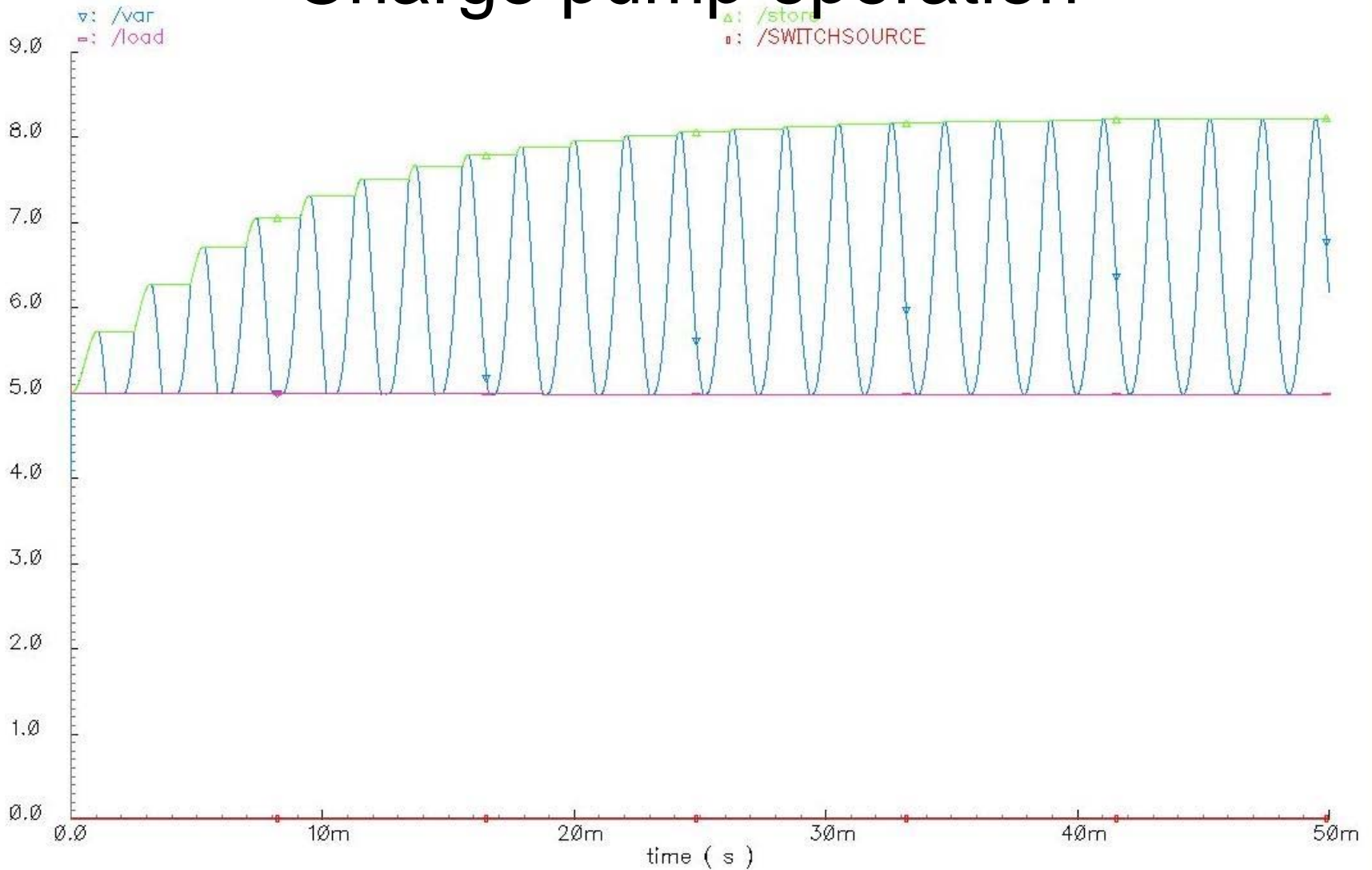
Charge pump operation



$$C_{var} = C_{min}$$

Conditionning circuit

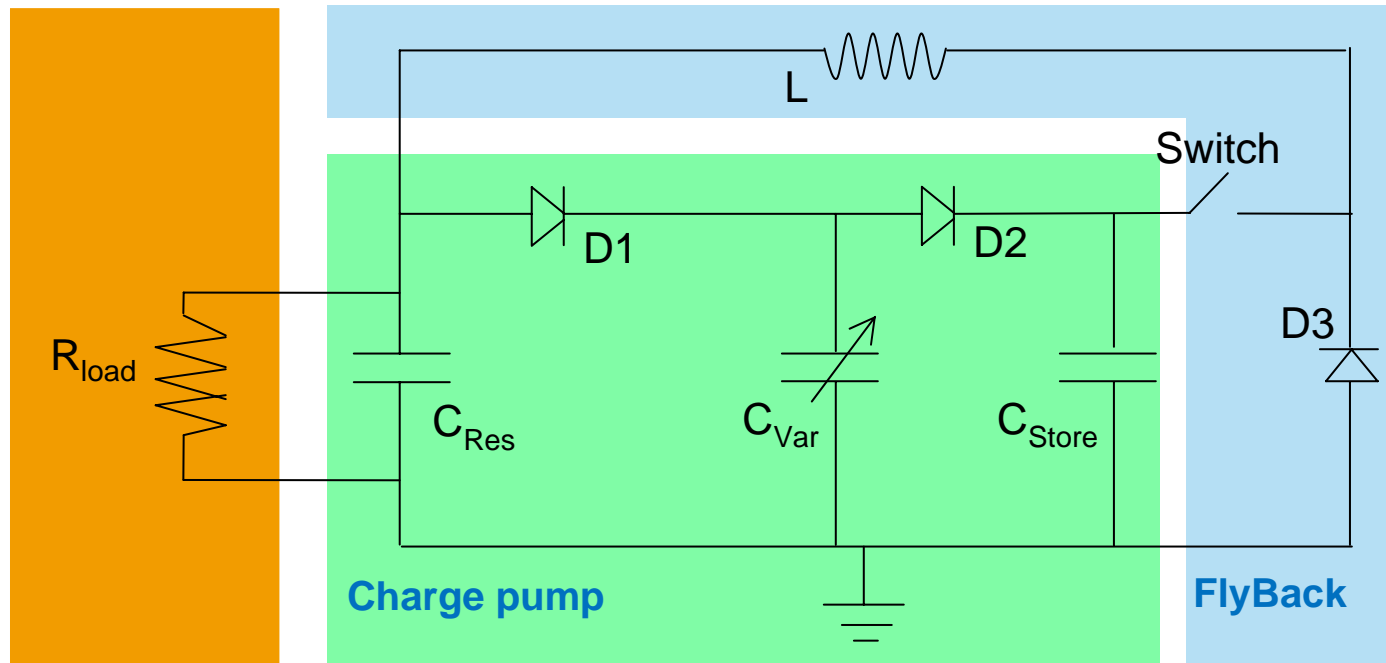
Charge pump operation



Conditionning circuit

Charge pump operation

- Charge return needed (flyback circuit !)

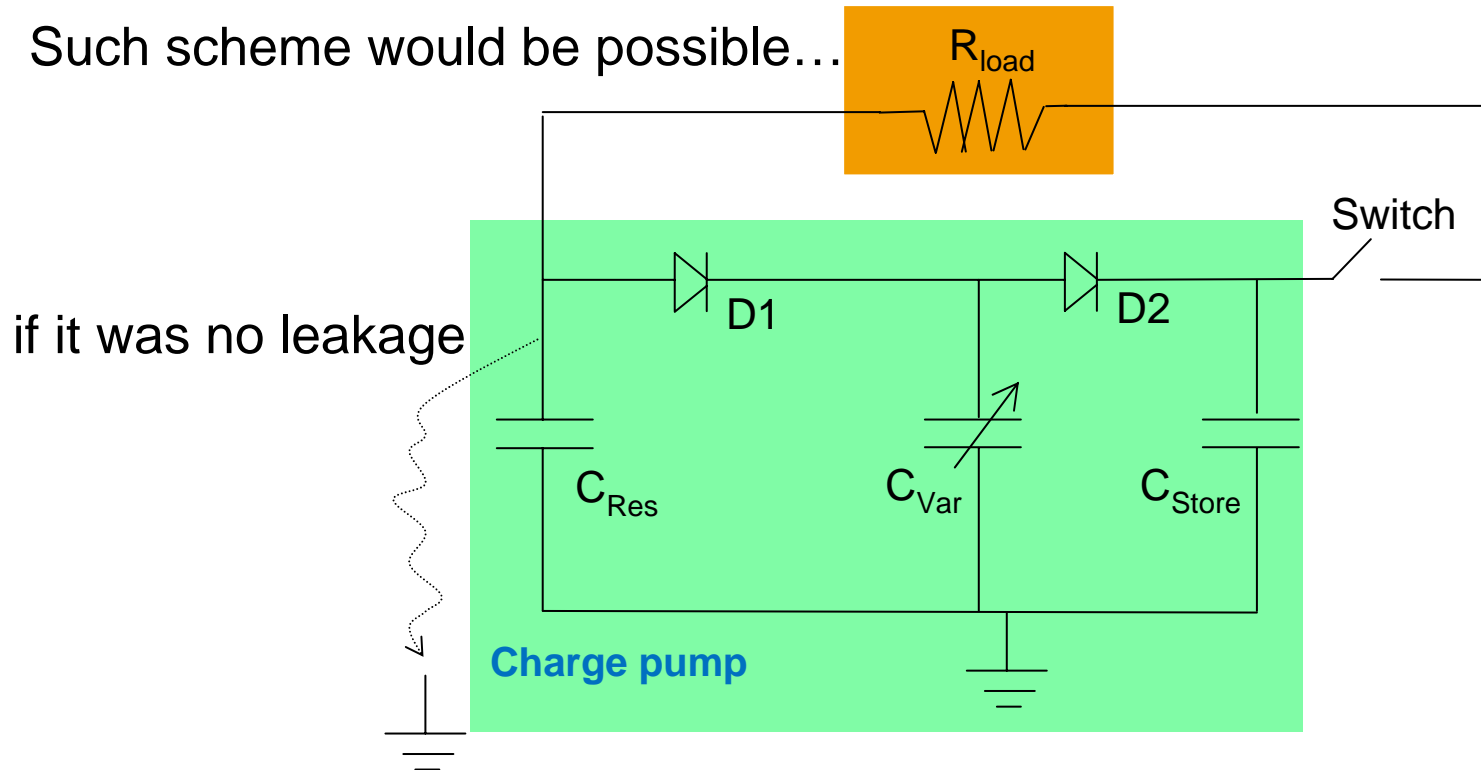


Conditionning circuit

Charge pump operation

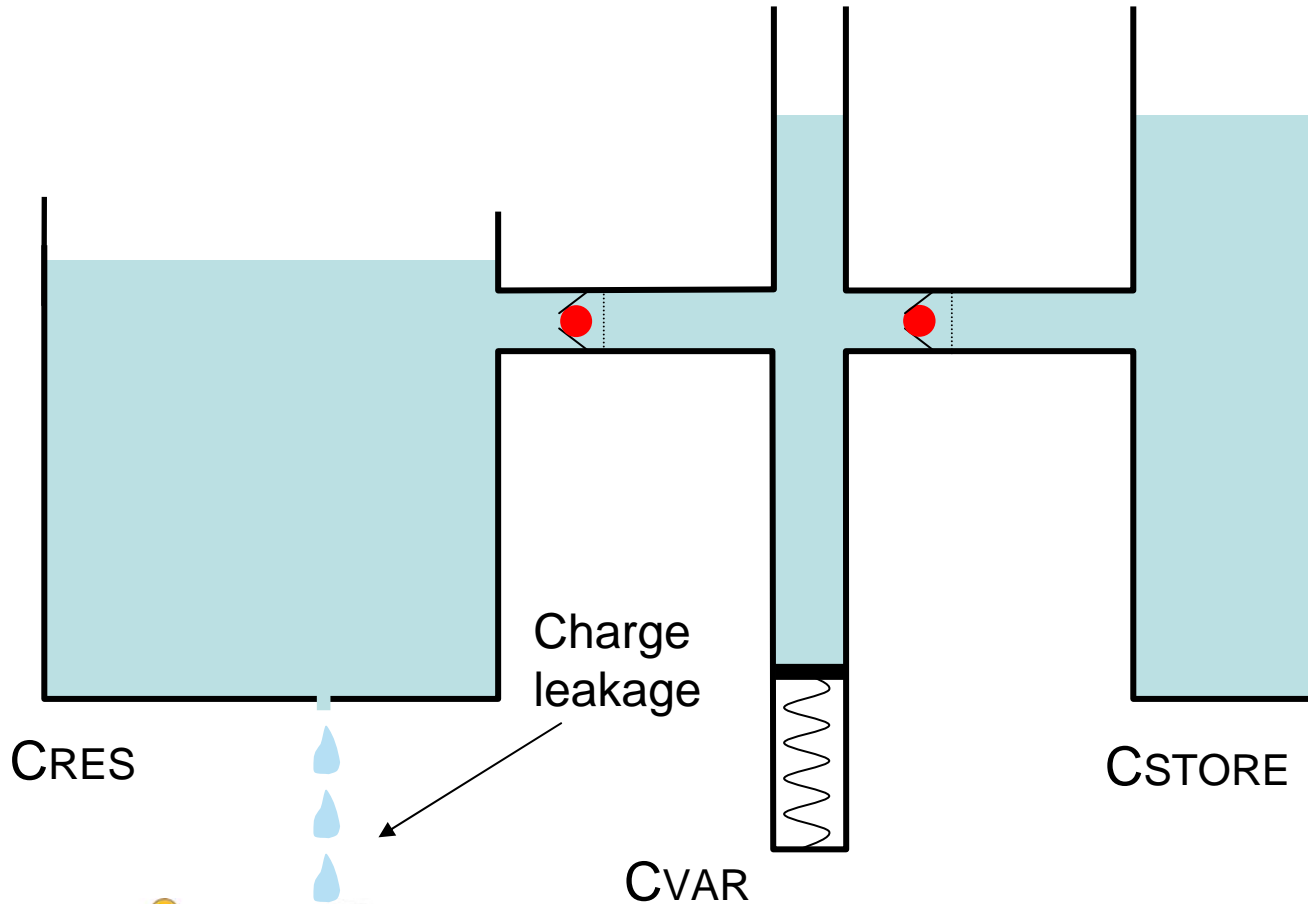
- Charge return needed (flyback circuit !)

Such scheme would be possible...



Conditionning circuit

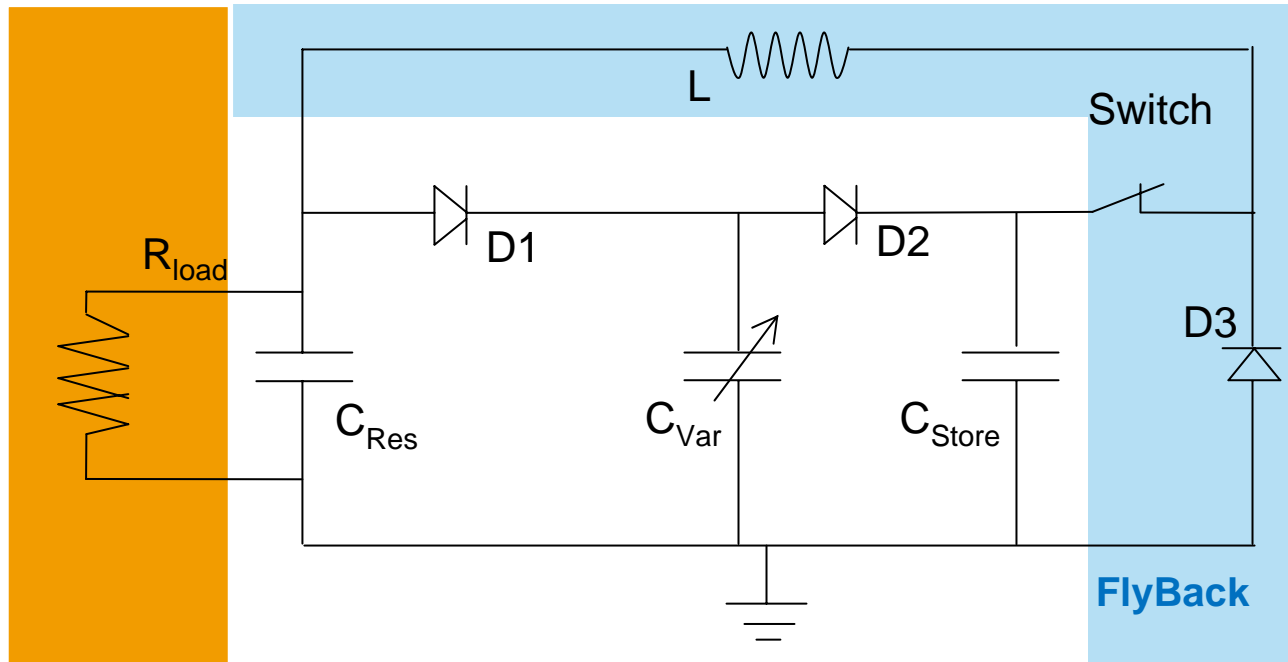
Charge pump operation



Conditionning circuit

Flyback operation

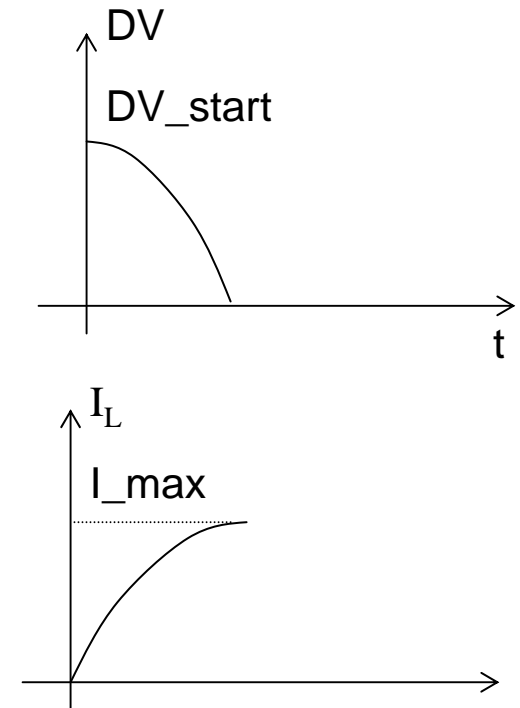
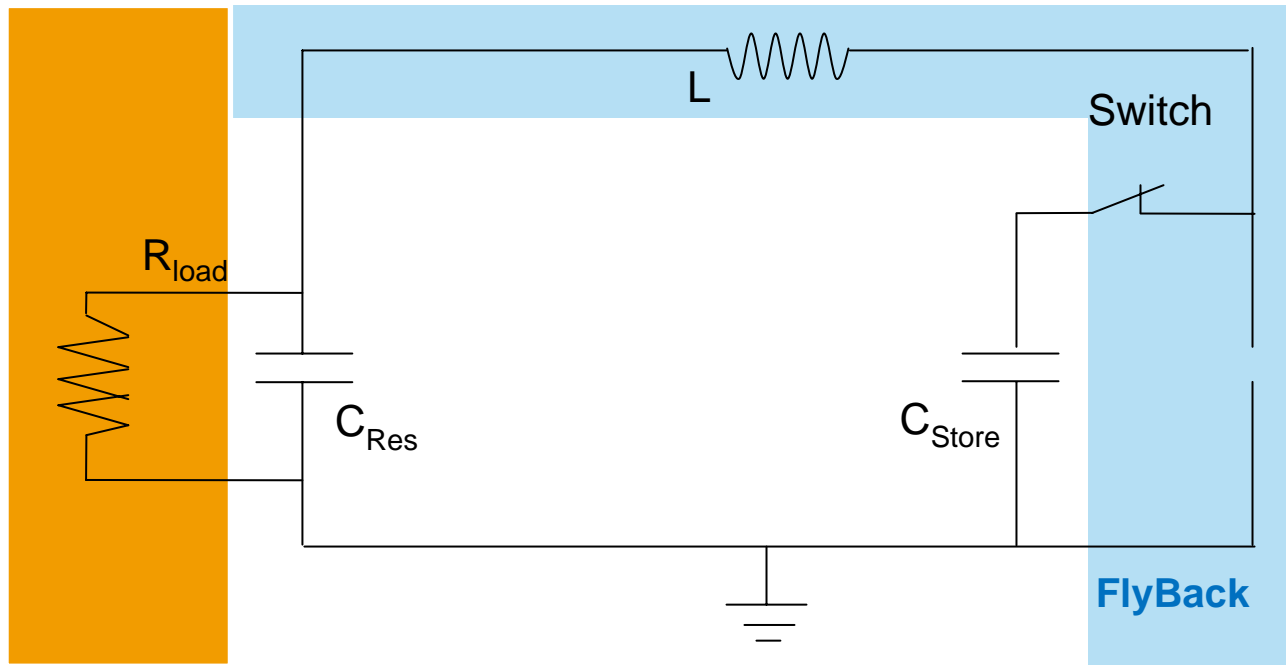
- Stores the harvested energy in the inductor
- This energy is used to recharge C_{res}



Conditionning circuit

Flyback operation

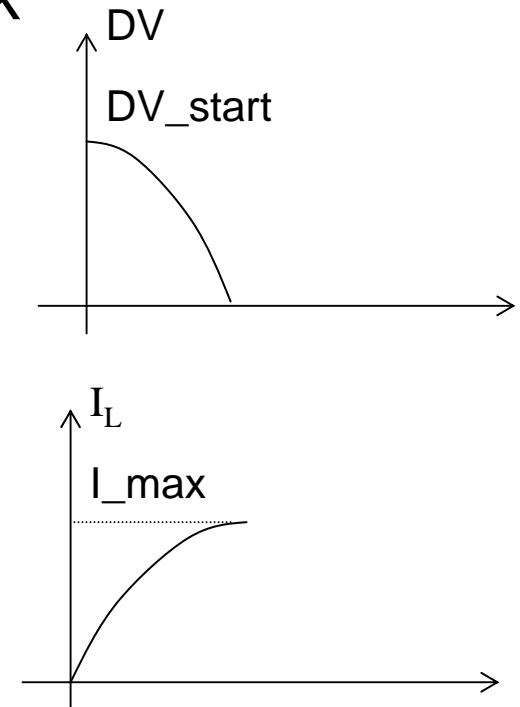
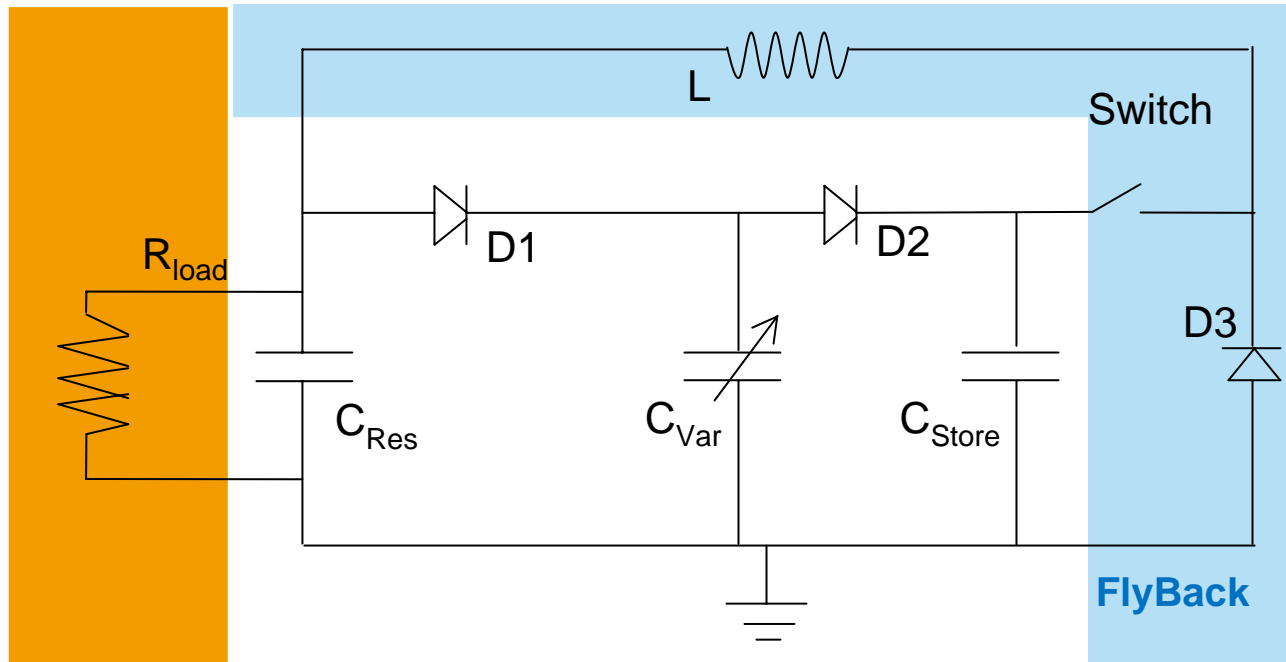
- The switch is on, C_{store} discharge on C_{res} and on L
- L is accumulating the harvested energy



Conditionning circuit

Flyback operation

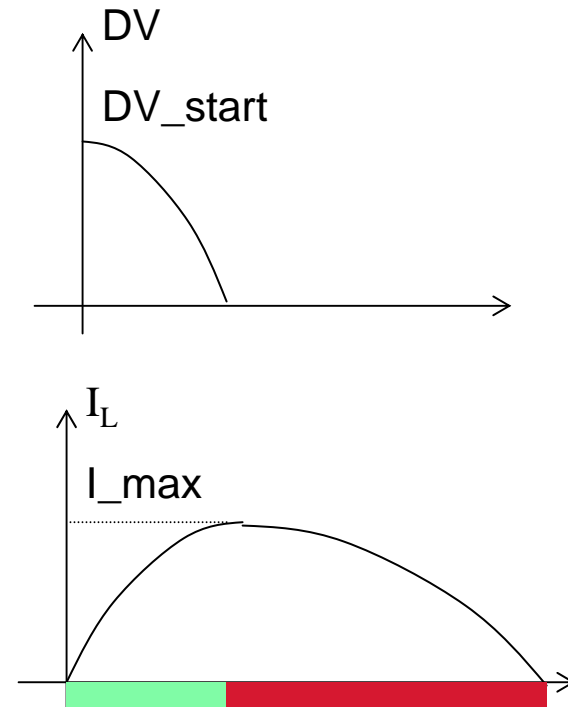
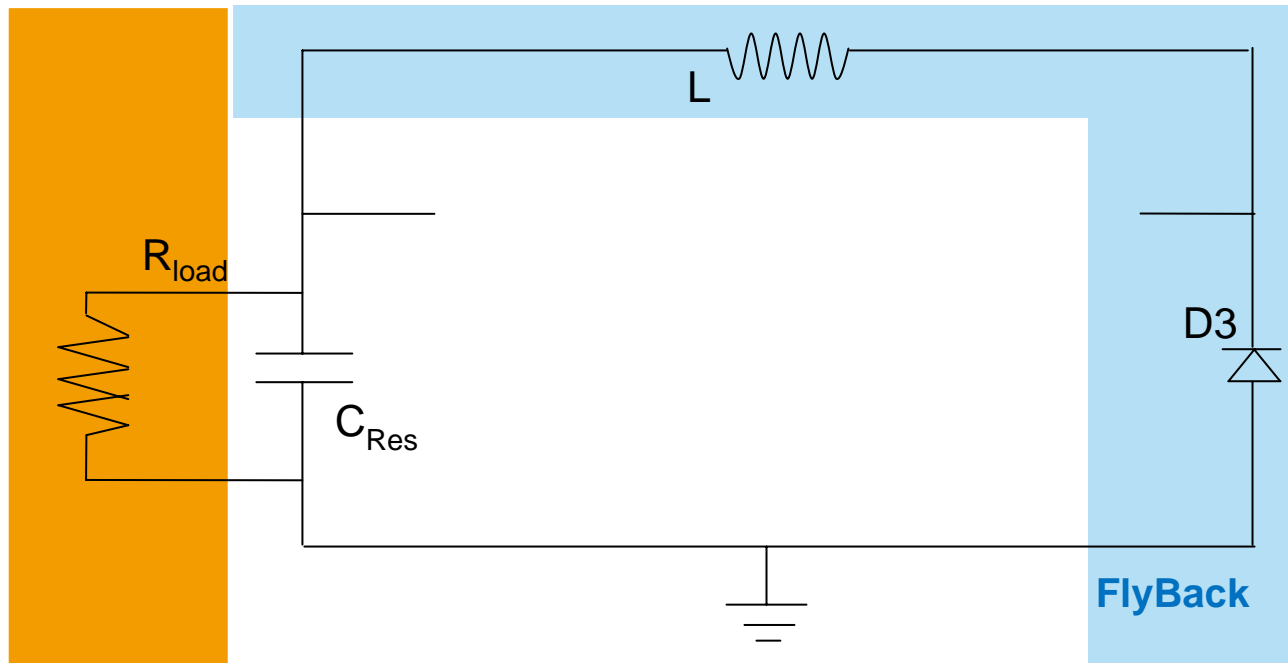
- The switch is off, inductor current continues through D3
- The circuit is equivalent to LCres network



Conditionning circuit

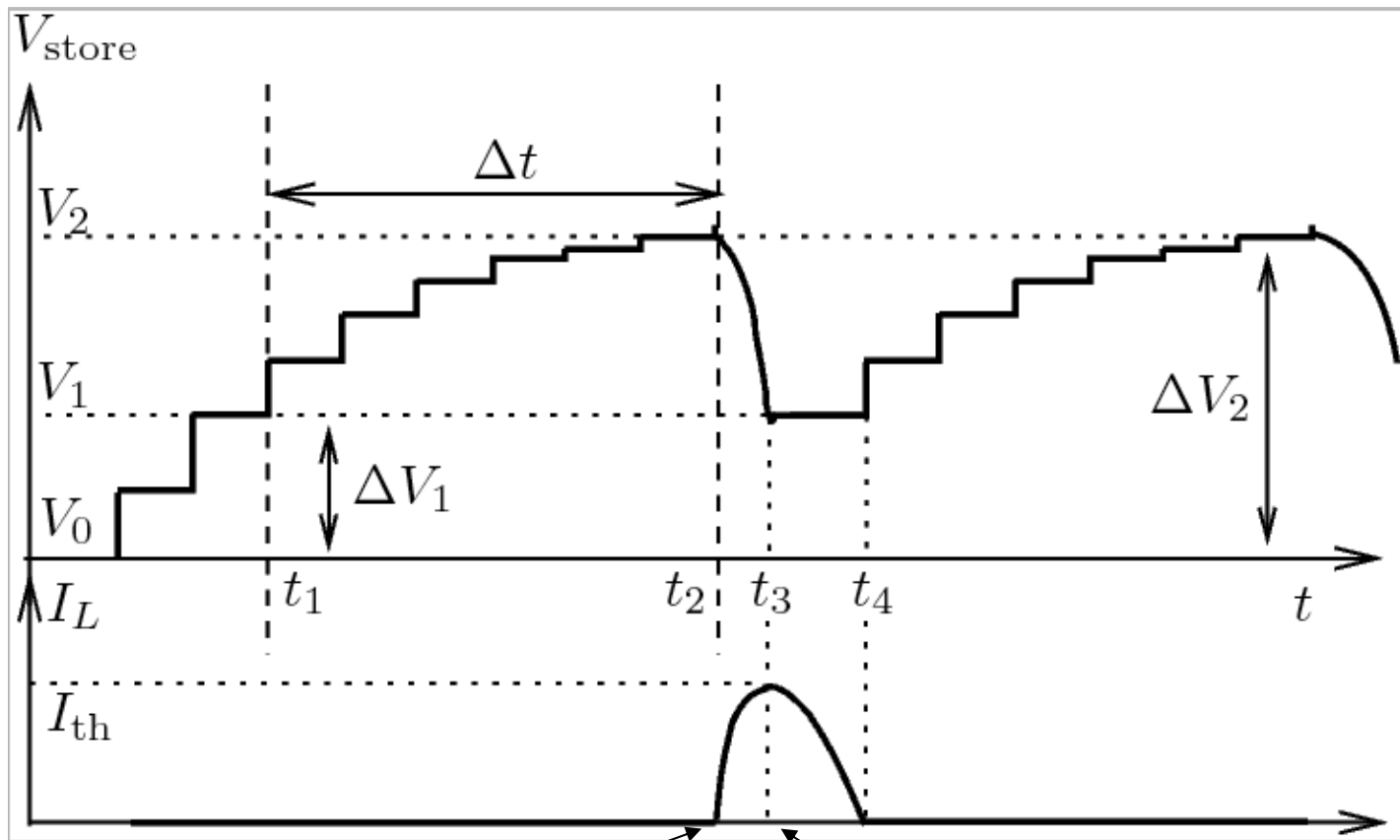
Flyback operation

- 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 C_{Res}



Conditionning circuit

Global operating diagrams

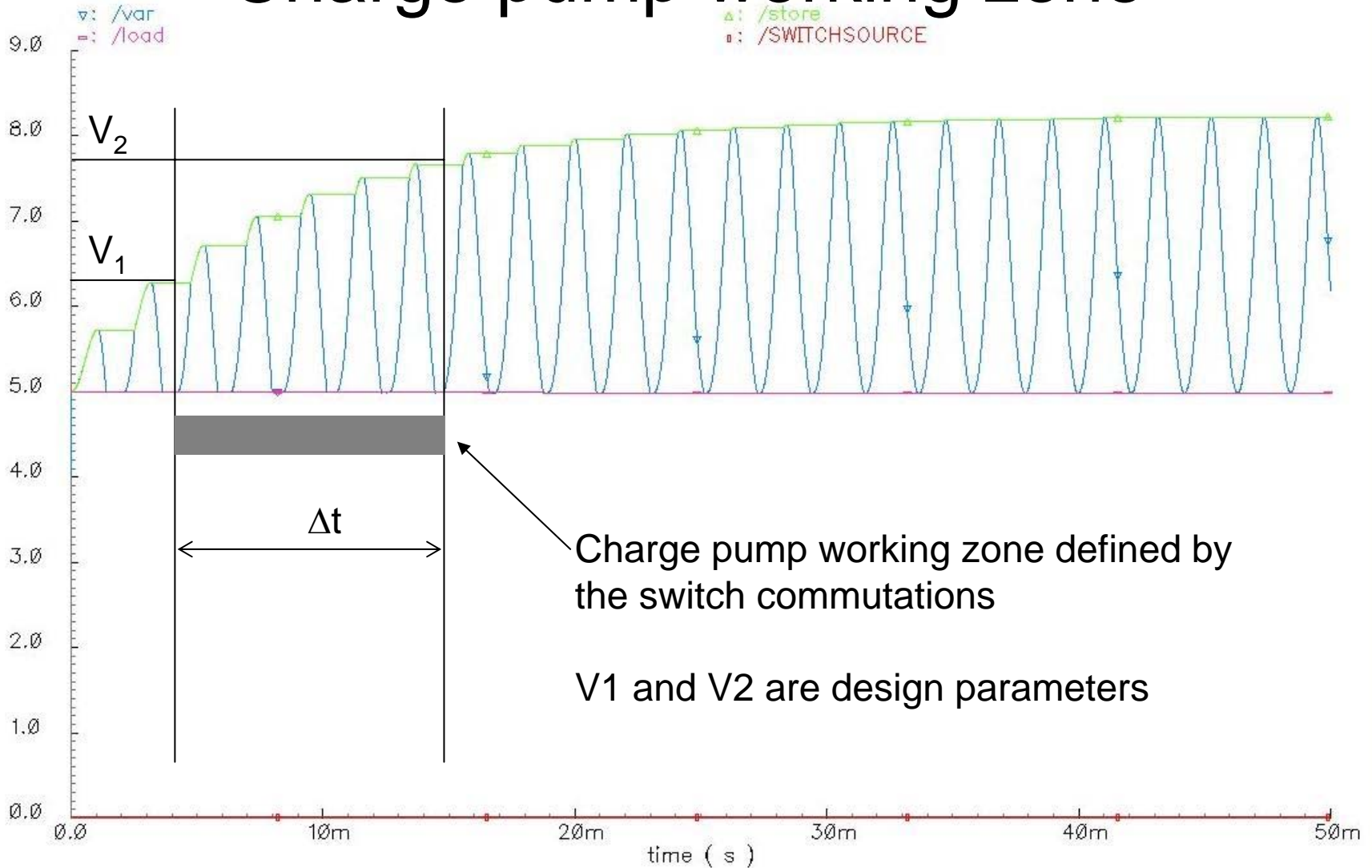


OFF->ON

ON->OFF

Conditionning circuit

Charge pump working zone



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 & transducer

- The force generated by the transducer :

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

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 :

$$Q = C_{var} V_{var} + Q_0$$

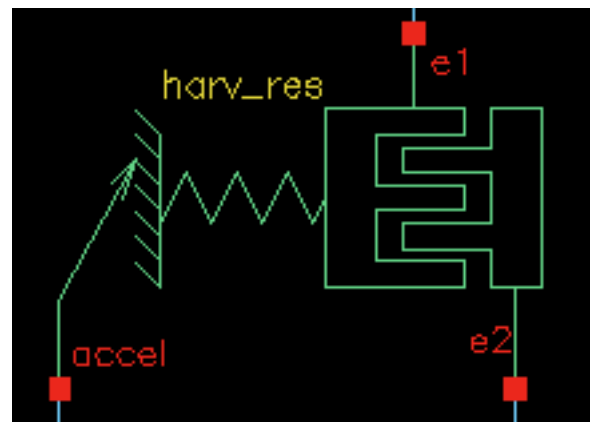
$$I_{var} = \dot{Q}$$

Q: electrical charge of the transducer (C_{var}), 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



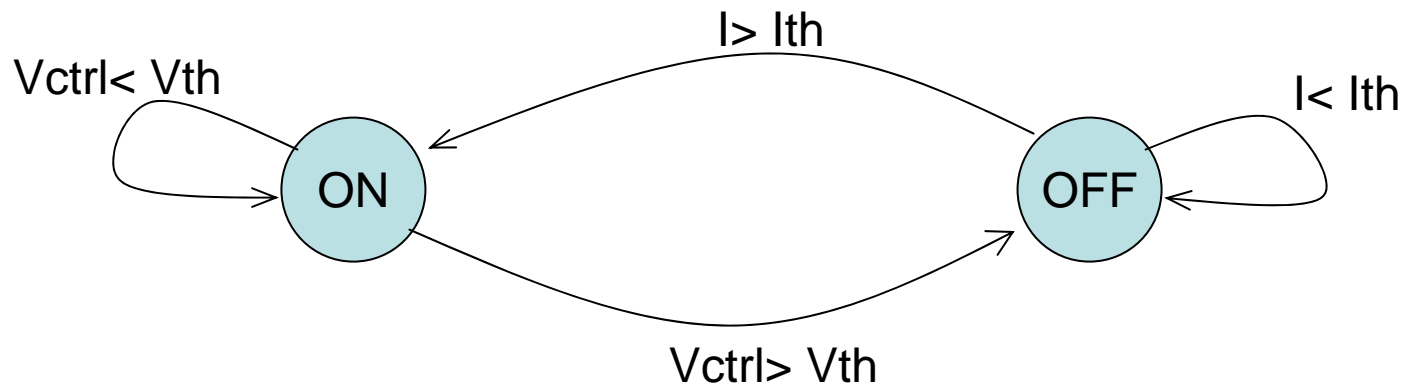
Modeling

Switch functional model

The switch has two states : ON and OFF, behaving like a resistance :
 $U=R_{on} I$ and $U=R_{off} I$

The transition between states is controlled by the switch current and by a control voltage (V_{store})

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

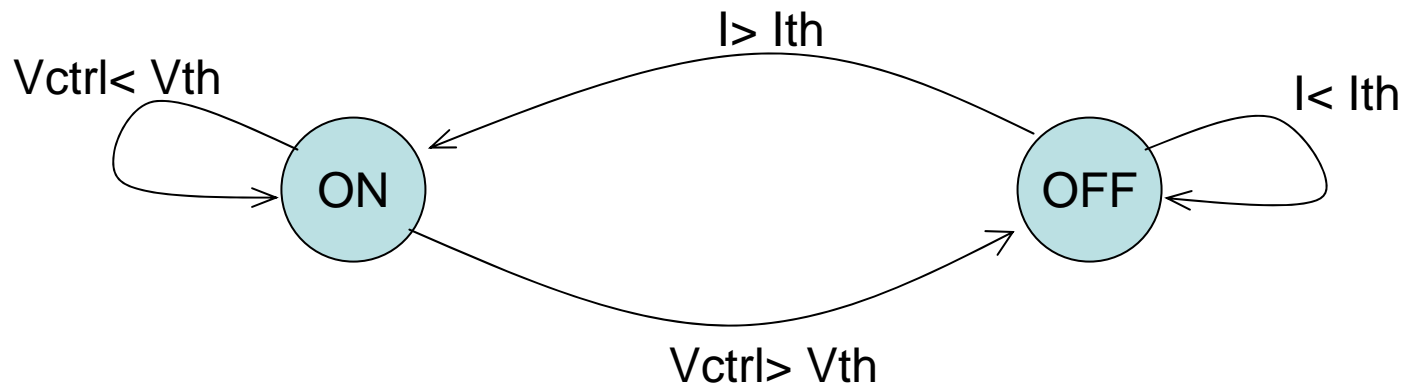
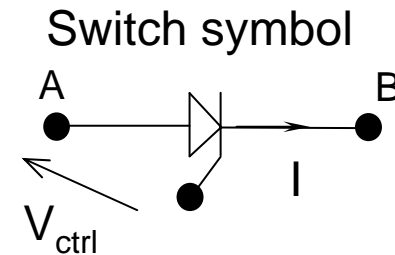


Modeling

Switch functional model

$U = R_{on} I$, if $ON = "1"$ and $I < I_{th}$
 $ON = "0"$, if $ON = "0"$ and $I > I_{th}$
 $U = R_{off} I$, if $ON = "0"$ and $V_{ctrl} < V_{th}$
 $ON = "1"$, if $ON = "0"$ and $V_{ctrl} > V_{th}$

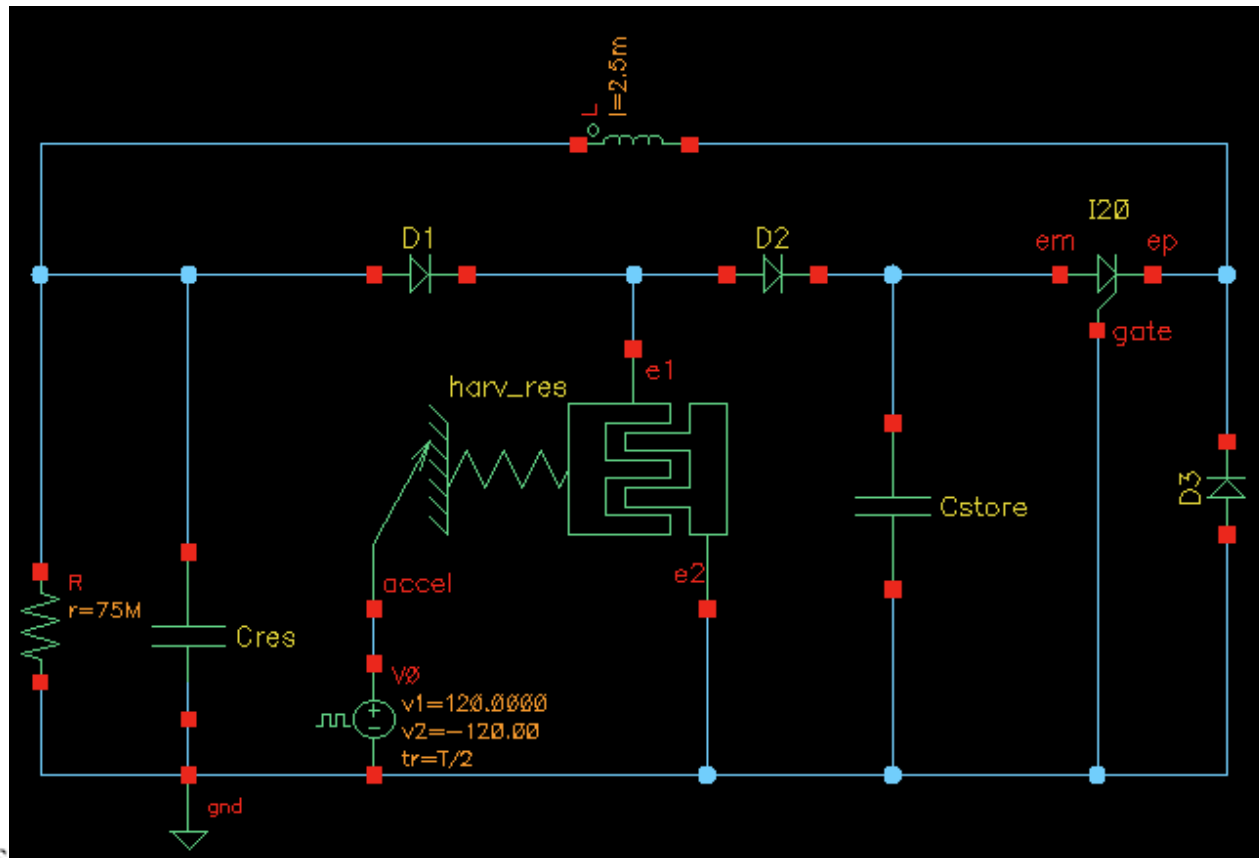
Implementation : VHDL



Modeling Global system

Modeled in CADENCE Analog Artist Environment

Was used AdvanceMS simulator (mixed Eldo-VHDL AMS)

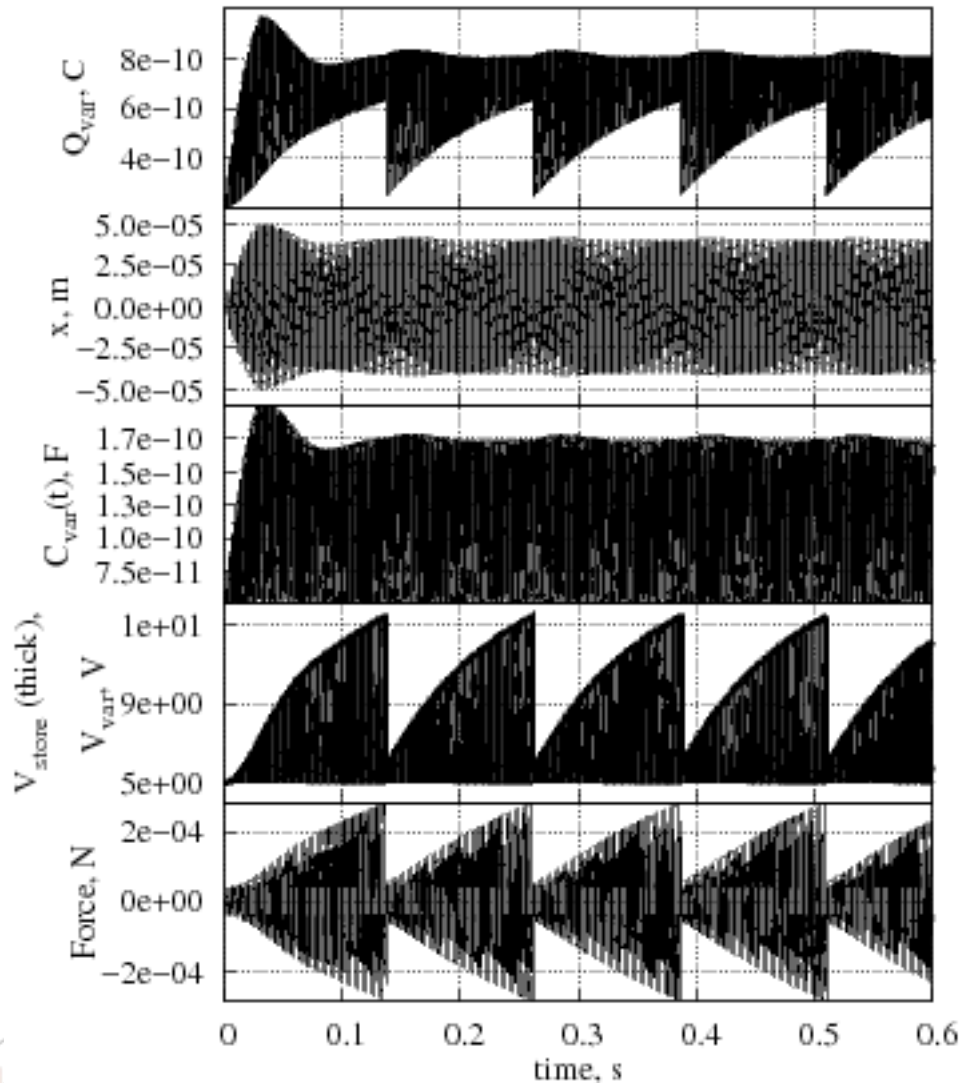


Simulation results

- 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 $C_{res}=1 \mu\text{F}$, $C_{store}=3.3 \text{ nF}$, $C_{var \text{ max}}=174 \text{ pF}$; $C_{var \text{ min}}=51 \text{ pF}$, external acceleration frequency = 300 Hz,

A charge of 26 M Ω could be driven by this harvester

Simulation results



Transducer charge

Resonator displacement

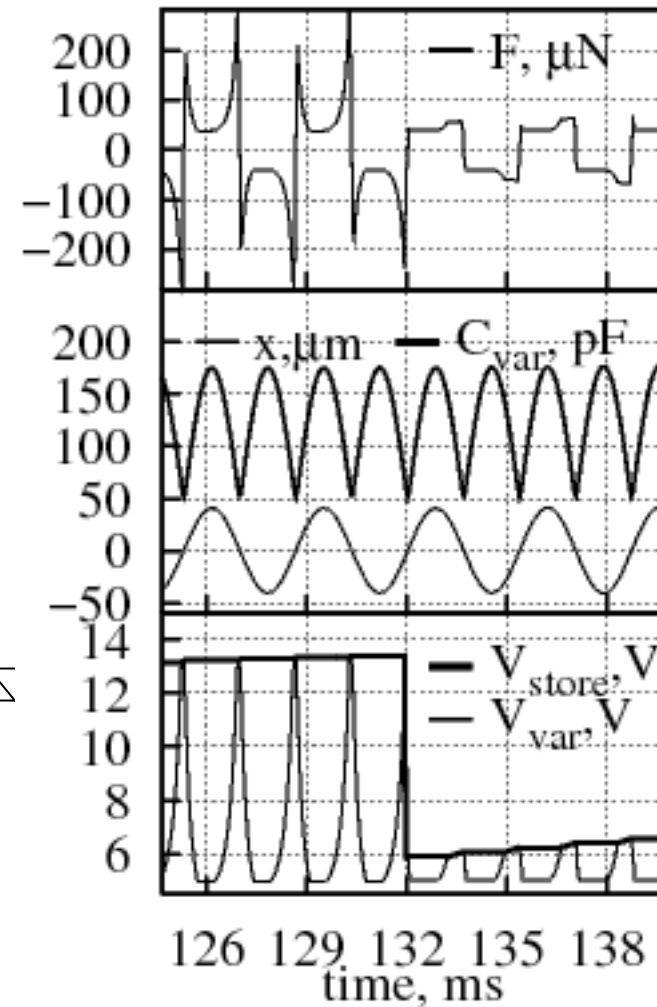
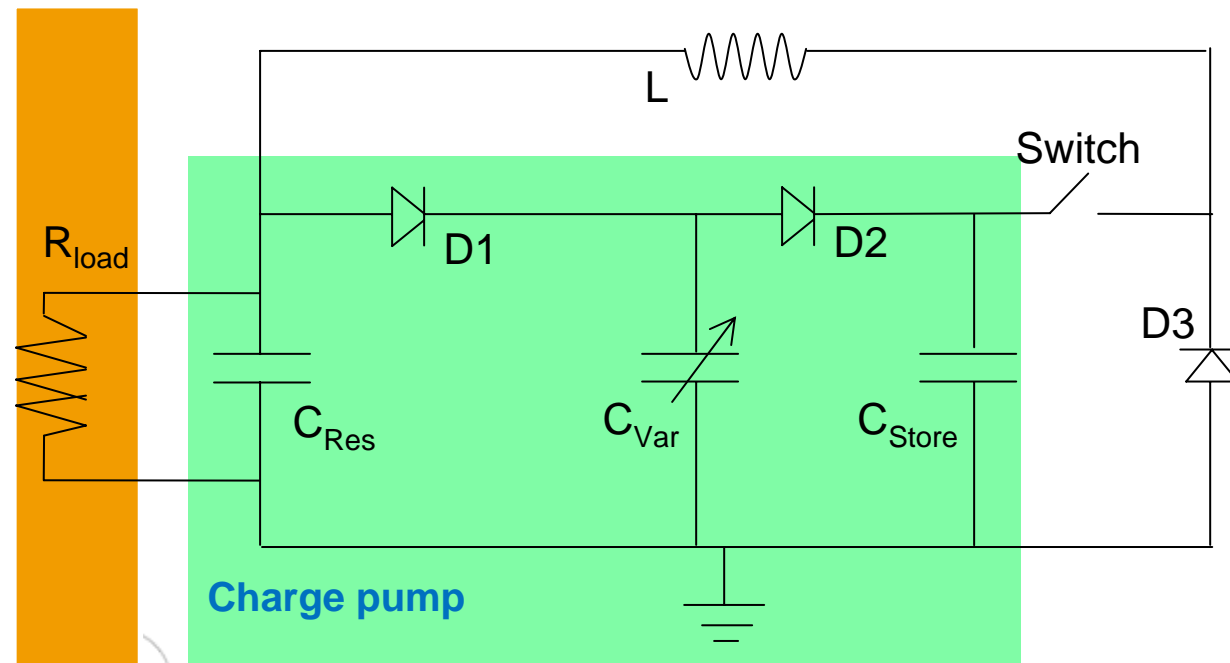
Capacity of transducer

V_{store}

Electrical force generated
by the transducer

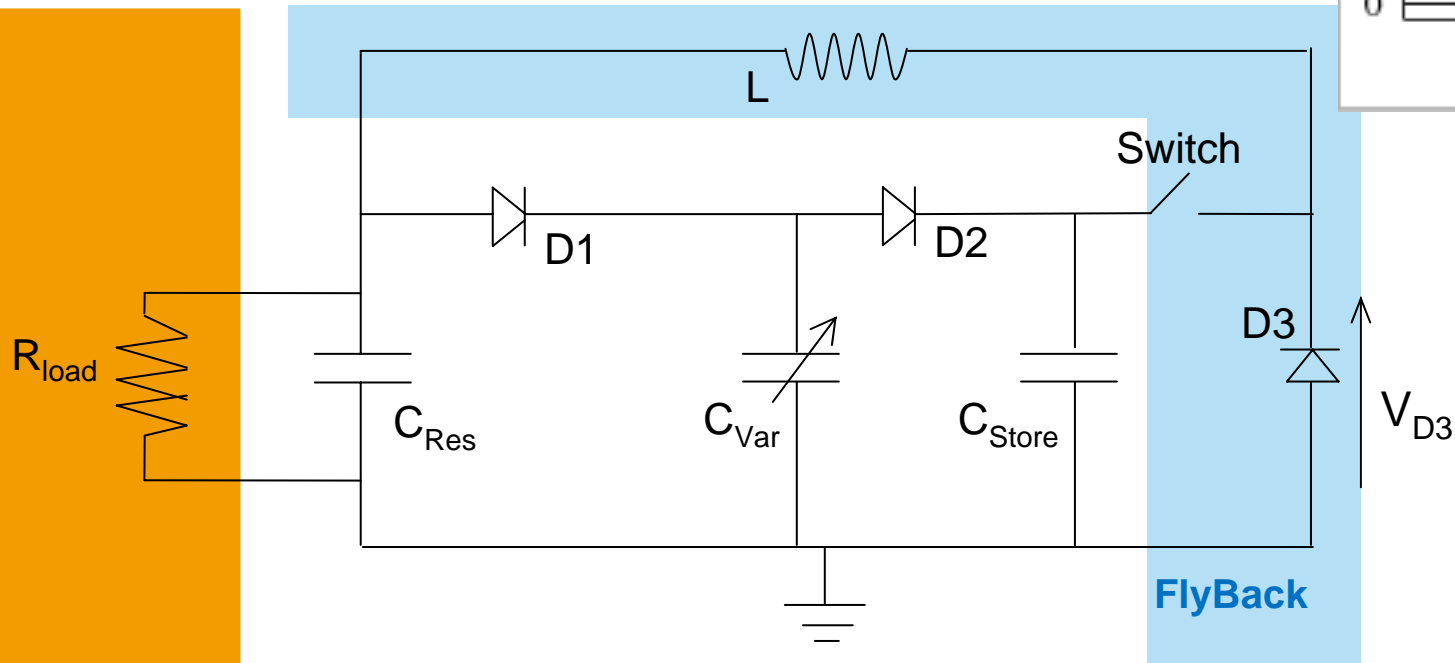
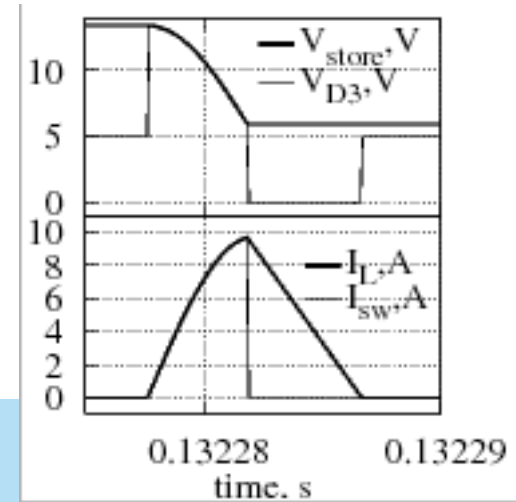
Simulation results

Zoom on charge pump operation



Simulation results

Zoom on flyback circuit operation

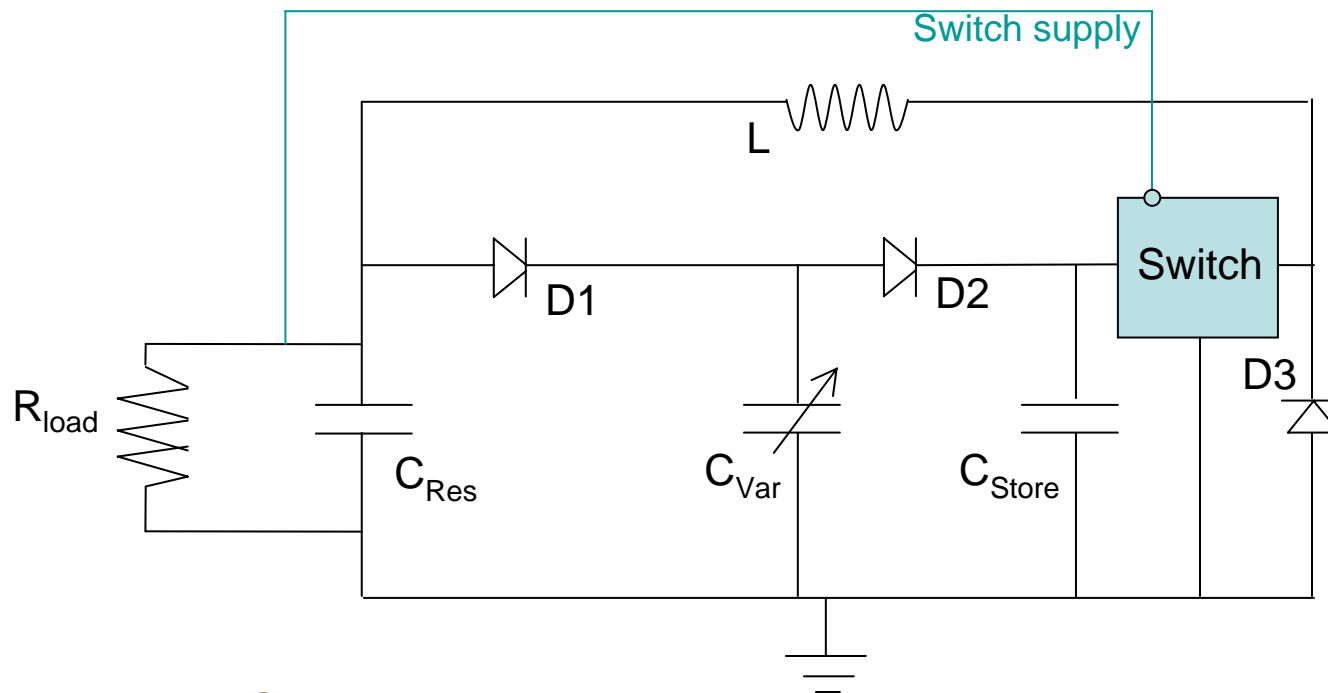


Conclusions

- The proposed VHDL-AMS model of the resonator highlighted an electromechanical coupling
- The model embeds 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 » circuitry
- 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

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