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
- Industrial tools
- Vibrating structures
- Environment surveillance
- Trains
- Aircrafts
- Human body

Ambient mechanical vibrations
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Vibration energy harvester

- Mechanical resonator
- Electrostatic transducer
- Variable capacitor
- Conditioning circuit
- Accumulator capacitor of harvested energy
- Electrical circuit managing transducer operation
- Circuit to be supplied

Circuit

C = f(x)
Vibration energy harvesting with a capacitive transducer

- When $C = C_{\text{max}}$, capacitance is charged; spent energy is:
  \[ W_1 = \frac{Q^2}{2C_{\text{max}}} \]

- When $C = C_{\text{min}}$, capacitance is discharged; returned energy is:
  \[ W_2 = \frac{Q^2}{2C_{\text{min}}} \]

- Since $C_{\text{min}} < C_{\text{max}}$:
  \[ W_2 > W_1 \]

Converted energy is:
\[ \Delta W = W_2 - W_1 \]
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Advantages:
- Only one inductor and only one switch
- Switch doesn’t need to be synchronized with Cvar variation
- Switch commutates rarely relatively to the Cvar variation frequency

[Yen et al., 2006]
Consists of:
- a charge pump;
- a flyback circuit (Buck DC-DC converter).
Charge pump operation

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

$C_{\text{res}} >> C_{\text{store}} > C_{\text{var}}$
Charge pump operation

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

$C_{res} \gg C_{store} > C_{var}$
Charge pump operation

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

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

$V_{store max} = V_0 C_{max} / C_{min}$
Charge pump operation

Charge pump

\[ C_{res} \gg C_{store} > C_{var} \]

- \( V_{store} \) increases quickly – average power increases and becomes maximal;
- \( V_{store} \) saturates – average power decreases and drops to zero.
Charge pump operation

\[ C_{\text{res}} \gg C_{\text{store}} > C_{\text{var}} \]
Charge pump operation

C_{\text{res}} \gg C_{\text{store}} > C_{\text{var}}

V_{\text{store}}

Generated power

C_{\text{var}} \text{ variation cycle number}

nWatts

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35

Cycle power with flyback
Cycle power without flyback

0 100 200 300 400 500

Charge pump

L

I_L

\text{Sw}

D_1 \quad D_2

D_3

\text{Q}

\text{Q}

C_{\text{Res}} \quad C_{\text{Var}} \quad V_{\text{Store}} \quad \text{Q}

R_{\text{load}}

\text{V}

\text{V_{store max}}

0 5 10 15 20 25 30 35

V_{\text{V1}} \quad V_{\text{V2}} \quad V_{\text{store with flyback}} \quad V_{\text{store without flyback}}

0 0.05 0.1 0.15 0.2 0.25 0.3 0.35
Flyback circuit operation

Composed of a BUCK DC-DC Converter

Flyback circuit operation

Generated power

Vstore

Voltage vs. Cycle power with flyback
Voltage vs. Cycle power without flyback

Generated power

Vstore max

Voltage vs. Cycle power with flyback
Voltage vs. Cycle power without flyback

Generated power

Vstore max

Voltage vs. Cycle power with flyback
Voltage vs. Cycle power without flyback

Generated power
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 ($V_{store} = V_1$)
Commutation parameters $V_1$ and $V_2$ are calculated with empirical formula:

$$V_1 = V_{res} + 0.1(V_{store\ max} - V_{res});$$
$$V_2 = V_{res} + 0.6(V_{store\ max} - V_{res}),$$

where $V_{store\ max} = V_{res} \frac{C_{max}}{C_{min}}$. 
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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?

\[ V_1, V_2 \leftrightarrow V_{\text{store max}} \leftrightarrow \frac{C_{\text{max}}}{C_{\text{min}}} \leftrightarrow X_{\text{max}} \leftrightarrow A_{\text{ext}} \]

\[ V_{\text{store max}} = V_{\text{res}} \frac{C_{\text{max}}}{C_{\text{min}}} \]

\[ V_1 = V_{\text{res}} + 0.1 \left( V_{\text{store max}} - V_{\text{res}} \right) \]

\[ V_2 = V_{\text{res}} + 0.6 \left( V_{\text{store max}} - V_{\text{res}} \right), \]

Hence, \( V_1 \) and \( V_2 \) should be updated periodically.

How to measure \( V_{\text{store max}} \)?

**Solution:**

Periodic AUTO-CALIBRATION phase.
Modeling blocks of the system

VHDL-AMS/ELDO model [BMAS 2007]

Auto-calibration block

Flyback switch control

R_{load} \quad C_{Res} \quad D_{1} \quad D_{2} \quad D_{3} \quad V_{res} \quad V_{store} \quad I_{L} \quad 1\mu F \quad 3,3nF

FlyBack

Pompe de charge

V_{Res} \quad V_{store}
Modeling blocks of the system

VHDL-AMS/ELDO model [BMAS 2007]

Auto-calibration block

Flyback switch control

VHDL-AMS Model of Flyback Adaptive Switch

V_{res} \rightarrow V_{store}

V_{1} \rightarrow V_{2}

ON/OFF

V_{load}

R_{load}

1uF

C_{Res}

C_{Var}

L

I_{L}

D_{1}

D_{2}

D_{3}

V_{Res}

V_{store}

C_{Store}

Pompe de charge

FlyBack
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 $V_{res}$ corresponds to the energy harvesting
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Motivation for Improved architecture of the condition

\[ V_{\text{res}} \] – needs High Voltages
\[ V_{\text{load}} \] – needs Low Voltages

\{ \text{The load interface is required} \}
Improved architecture of the conditioning circuit

\[ V_{\text{res}} \] – needs High Voltages
\[ V_{\text{load}} \] – needs Low Voltages

\[ V_{\text{load}} = 2 \div 3 \text{V} \]
\[ V_{\text{res}} = 20 \text{V} \]

The load interface is required
Decision: reuse the existing DC-DC converter
Decision: reuse the existing DC-DC converter
Improved architecture of the conditioning circuit
Improved architecture of the conditioning circuit
Improved architecture of the conditioning circuit

Dual-output dual-input Buck DC-DC convertor

- $L$ (inductor)
- $R_{load}$ (load resistance)
- $C_{load}$ (load capacitor)
- $C_{Res}$ (resonant capacitor)
- $C_{Var}$ (variable capacitor)
- $C_{Store}$ (storage capacitor)
- $D_1$, $D_2$, $D_3$ (diodes)
- $Sw1$, $Sw2$, $Sw3$, $Sw4$ (switches)
Improved architecture of the conditioning circuit

Power management control

Adaptive flyback switch control

Output voltage control

Vres

Vstore

Vload

Sw1

Sw2

Sw3

Sw4

$R_{load}$

$C_{load}$

$C_{Res}$

$C_{Var}$

$C_{Store}$

$D_1$

$D_2$

$D_3$

$L$
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Simulation results of model with power management (Example)

3 operation phases:

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

Power generated by harvester
3 operation phases:

- Accumulation of internal energy
- Charging of $C_{\text{load}}$ capacitor aimed for the load supplying
- Load supplying phase
Modeling results – Example

3 operation phases:

- Accumulation of internal energy
- Charging of Cload capacitor aimed for the load supplying
- Load supplying phase
3 operation phases:

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

Modeling results – Example
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.