

# SMART ADAPTIVE POWER MANAGEMENT IN ELECTROSTATIC HARVESTER OF VIBRATION ENERGY

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**Abstract:** This paper reports a new functional design and modeling of a vibration energy harvester composed from a mechanical resonator (MEMS), capacitive transducer and a conditioning circuit based on the BUCK DC-DC converter architecture. The basic configuration of conditioning circuit from [1][2] is enhanced with two major features for the power management allowing, firstly, to adapt dynamically to the variation of external vibration parameters and, secondly, a smart interface with the load, which allows the system to manage a possibly variable load and to adapt to different situations (e.g. insufficient generated power level, load too large, etc.). The study is validated by behavioral VHDL-AMS/ELDO modeling.

**Keywords:** energy harvesting, MEMS, adaptive switch, DC-DC converter, power management, VHDL-AMS

## INTRODUCTION

This study is focused on conversion of the energy of mechanical vibrations into electricity with a use of electrostatic transducer, which is represented by a variable capacitor of MEMS technology. Harvesting the vibration energy with capacitive transducer requires complex conditioning electronics for managing the transducer operation. This study aims, firstly, to adapt the conditioning circuit to the variation of environment parameters, which requires an adaptive control of the system operation. Secondly, we provide a “smart” power management control, which allows interface the load with the transducer and adapt to different situations. Here we present original architecture and algorithm of smart energy harvesting system based on capacitive transducer and present simulation results.

## BASIC ARCHITECTURE OF CONDITIONING CIRCUIT

The basic architecture of the conditioning circuit is composed of a charge pump and a flyback circuit controlling by a switch (fig.1).

All the three capacitors of charge pump are initially pre-charged with some external energy source. The role of the charge pump is to generate a voltage difference between a large capacitor  $C_{res}$  and a small  $C_{store}$ . This is done by transferring electrical charges from  $C_{res}$  to  $C_{store}$  making use of variation of the variable capacitor  $C_{var}$ . The energy for this charge pumping comes from the mechanical domain through the variations of the transducer capacitor, and during pumping, the converted energy is stored in the capacitive network composed of  $C_{res}$  and  $C_{store}$  connected in series. Quantitatively, the energy is

represented by  $V_{res}$  and  $V_{store}$  difference, but since  $C_{res} \gg C_{store}$ , during pumping  $V_{res}$  remains nearly constant, and only the  $V_{store}$  evolution represents the accumulation of energy.

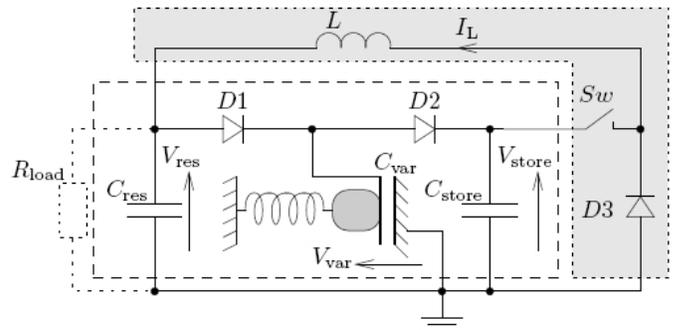


Fig. 1: Conditioning circuit of vibration energy harvester.

Thin lines in fig.2 demonstrate the evolution of  $V_{store}$  and of generated power during only the charge pump operation. In the beginning,  $V_{store}$  grows quickly and the corresponding power during harvester operation goes up to some maximal value. Then,  $V_{store}$  starts to saturate and power decreases dropping to zero. One can observe that there is some  $V_{store}$  range where the generated power is maximal. Such the range corresponds to  $V_1$  and  $V_2$  limit values of  $V_{store}$ . Hence, to continuously harvest the energy generating the maximal power,  $V_{store}$  should remain in this range, varying periodically (bold line plots in fig.2). For this, when  $V_{store}$  reaches  $V_2$ , it should be quickly reduced to  $V_1$  without energy losses. It is performed by a flyback circuit, which is activated by a switch when  $V_{store}$  crosses  $V_2$ .

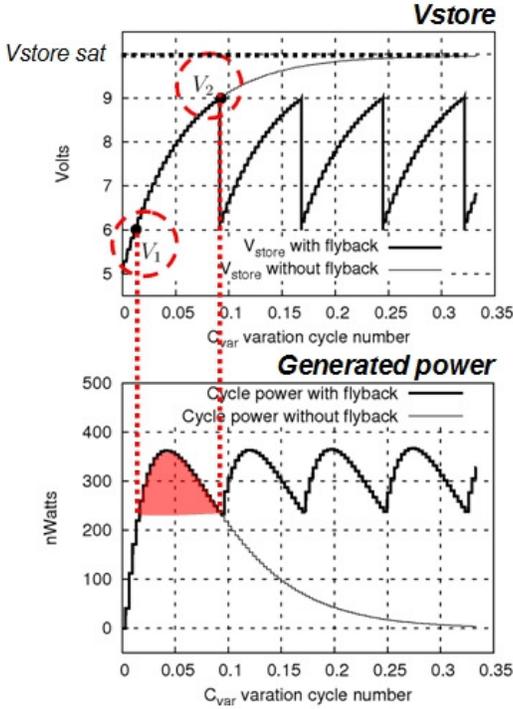


Fig. 2: Operation of the harvester with basic conditioning circuit architecture.

Flyback operates as a Buck DC-DC converter, transferring the charges and the energy from  $C_{store}$  to  $C_{res}$  using an inductor as an energy buffer. When  $V_{store}$  drops to  $V_1$ , switch turns off, and the charge pump cycle starts. Theoretical investigation provides us with following semi-empirical formula for  $V_1$  and  $V_2$  threshold voltages calculation [4]:

$$\begin{aligned} V_1 &= V_{res} + 0.1 \cdot (V_{store\ max} - V_{res}) \\ V_2 &= V_{res} + 0.6 \cdot (V_{store\ max} - V_{res}), \end{aligned} \quad (1)$$

where  $V_{store\ max}$  is the saturation voltage of the charge pump (fig.2) given by [3]:

$$V_{store\ max} = V_{res} \cdot C_{max} / C_{min} \quad (2)$$

where  $C_{max}$  and  $C_{min}$  are the maximal and minimal values of the transducer capacitance respectively. Here,  $V_1$  and  $V_2$  are optimized for particular parameters of external vibrations. However, in reality, parameters of vibrations are variable. For example, if vibrations amplitude varies, the displacement low of the mobile mass of resonator changes, causing the variation of the range of the transducer capacity ( $C_{max}$  and  $C_{min}$ ). From (2), as  $V_{store\ max}$  is the function of  $C_{max}$  and  $C_{min}$ , change of  $V_{store\ max}$  causes  $V_1$  and  $V_2$  variation (1). Hence, to adapt the system to the variation of the external vibration parameters,  $V_1$  and  $V_2$  should be updated periodically. As we said,  $V_1$  and

$V_2$  are the functions of maximal value of  $V_{store}$ . But  $V_{store\ max}$  is unknown a priori and it can not be measured directly, since during the energy harvesting cycle  $V_{store}$  never reaches the saturation (fig.2). However, we propose to measure it in an ad-hoc auto-calibration phase, which should be repeated periodically. During this cycle, the charge pump would run freely from the initial state up to the saturation at which  $V_{store}$  is maximal. This saturation value would be measured and used for  $V_1$  and  $V_2$  calculation. To allow a free run of the charge pump, the flyback is deactivated.

## AUTO-CALIBRATION OF THE SYSTEM

The proposed technique of auto-calibration can be summarized as follows. In the beginning of each calibration cycle,  $V_{store}$  value is reset to  $V_{res}$ , to place the charge pump in the initial state (fig.2). Then the flyback circuit is deactivated: for this  $V_2$  voltage is temporarily set to a high unreachable value during the whole calibration cycle. To detect the  $V_{store}$  saturation, periodic measurements of  $V_{store}$  value are done during the calibration cycle. At each measurement,  $V_{store}$  is compared with the previously measured value (fig.3). When the difference ( $\Delta V_{store}$ ) between two neighboring measured values of  $V_{store}$  becomes lower than a predefined value  $\Delta V_{min}$ , it is concluded that  $V_{store}$  is saturated and the last measured value is considered as  $V_{store\ max}$ . After the  $V_{store\ max}$  measurement,  $V_1$  and  $V_2$  are calculated and the calibration cycle ends. Between two calibration cycles, the system operates with updated  $V_1$  and  $V_2$  which are likely to optimize the energy yield.

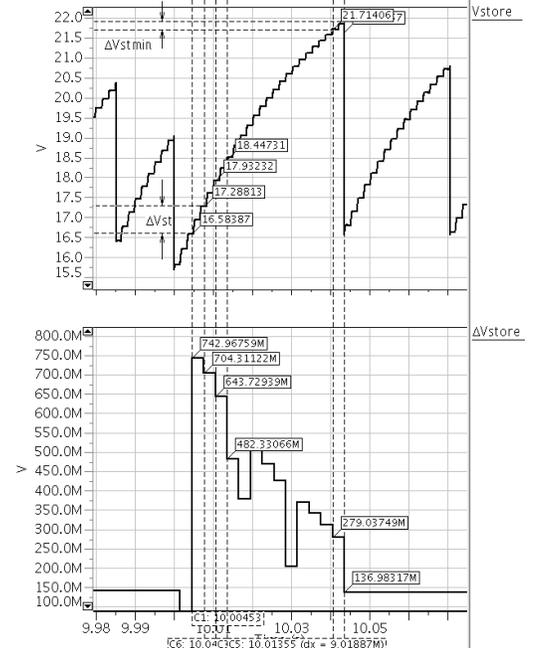


Fig.3: Calibration phase operation.

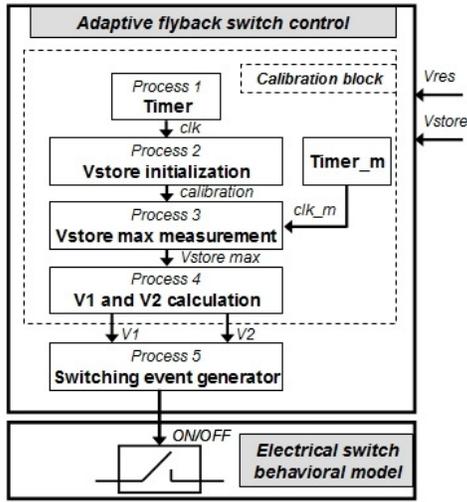


Fig. 4: Structure of adaptive flyback switch model.

Auto-calibration algorithm is implemented in a block, which is integrated into the existing VHDL-AMS model of the flyback switch. This new model implements the flyback adaptive switch as two terminal electrical component, which can be integrated in an ELDO electrical model of the conditioning circuit, which have been presented in [2].

## POWER MANAGEMENT OF THE HARVESTED ENERGY

Theoretical investigations presented in [4] highlight that optimal power yield of harvester operation requires high voltage level on  $C_{res}$  (tens of volts), whereas usually, the load is supplied by low voltages. Hence, an interface with the load is required.

For this, we propose to add a large capacitor  $C_{load}$  (fig.5). This capacitor must be charged to a low voltage and is intended for storing the energy immediately available for the load. To charge this capacitor with the energy available in the high voltage capacitor  $C_{res}$ , a DC-DC converter is needed. However, the basic architecture already contains a BUCK DC-DC converter implemented by the inductor and the diode  $D_3$ . This DC-DC converter can be directly used to charge  $C_{load}$ . This is done by introducing a switch  $SW_2$ , which allows the inductor to discharge on one of two capacitors. The idea is to allow the flyback circuit to return the energy on  $C_{res}$  or, alternatively, on  $C_{load}$ .

The theory [4] shows that for each external vibration parameters, there exists an optimal value of  $V_{res}$ . If, for example,  $V_{res}$  is higher than this optimal voltage, it should be quickly reduced. This is done by adding an additional switch  $SW_3$ , which allows  $C_{res}$  to discharge directly on  $C_{load}$ . The switch  $SW_1$  is added to interface the load with the harvester. It allows

disconnect the load from the generator, if the harvested power is low, hence, avoiding discharge of the capacitors  $C_{load}$  and  $C_{res}$ . The switches  $SW_1$ - $SW_3$  are supposed to be controlled by some smart electronics, which senses the voltages  $V_{load}$  and  $V_{res}$ , and which, depending on the application and the nature of the load, implements some optimal power measurement strategy.

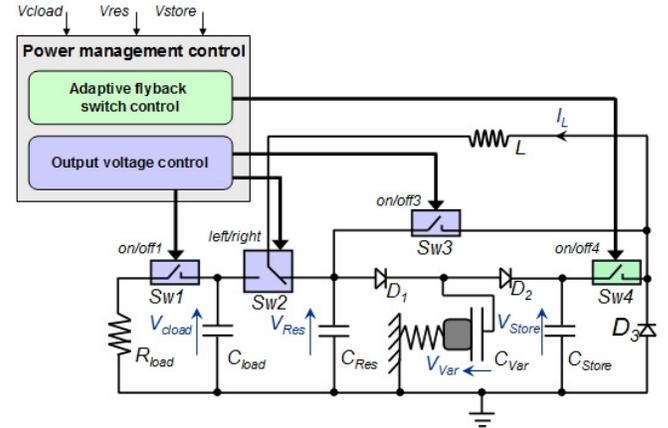


Fig. 5: Conditioning circuit of energy harvester with power management blocks.

The model of the improved configuration of conditioning circuit with power management interface is implemented in the same way as the basic model [2]. Switches models are implemented as instances of the block “electrical switch behavioral model” in fig.3. The states of the switches are ordered by the corresponding  $on/off_i$  and left/right (for  $SW_2$ ) signals generated by their control blocks (fig.5).

## MODELING RESULTS

To validate our study, two modeling experiments were done.

The first one aims to compare the operation of harvester with auto-calibration strategy and without ( $V_{store\ max}$  is pre-calculated under hypothesis of constant vibration parameters) under conditions of variable amplitude of the external vibrations. Both models are simulated in the same context of variable acceleration amplitude of vibrations (fig.6) and they don't include nor output voltage control, neither load resistor. The upper plot a) shows the acceleration of the external vibrations with the amplitude varying over time from 4.5 to 10  $m/s^2$ . Plots b) and c) represent the average powers on every 100 ms generating by the harvester with and without auto-calibration periodic phases respectively. Comparing results, we can observe that auto-calibration technique allows the system continuously harvest energy from

the external vibrations with variable parameters, whereas the system without auto-calibration doesn't provide the system with energy when, for example, the amplitude of vibrations decreases substantially.

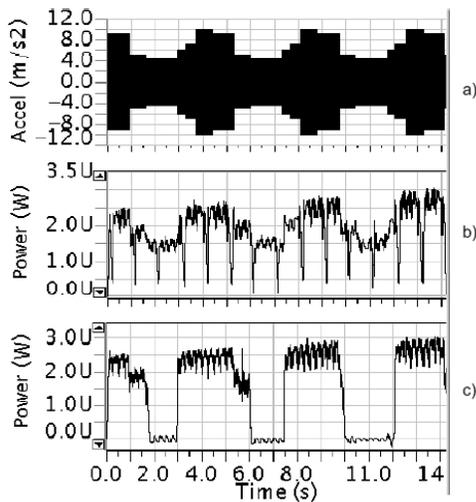


Fig. 6: Comparison of the simulation results of two identical models of harvester with and without auto-calibration.

The second experiment demonstrates the modeling results of the circuit presented in fig.5. The plots in fig.7 highlight 3 phases of operation. The first phase corresponds to the accumulation of internal energy of the harvester in  $C_{res}$ . During this phase  $V_{res}$  increases from 13V (initial value) up to 20.5V (wanted optimal voltage level). The second phase starts when  $V_{res}$  reaches 20.5V.  $C_{res}$  starts to discharge on  $C_{load}$ , accumulating the energy buffer for the load supply.

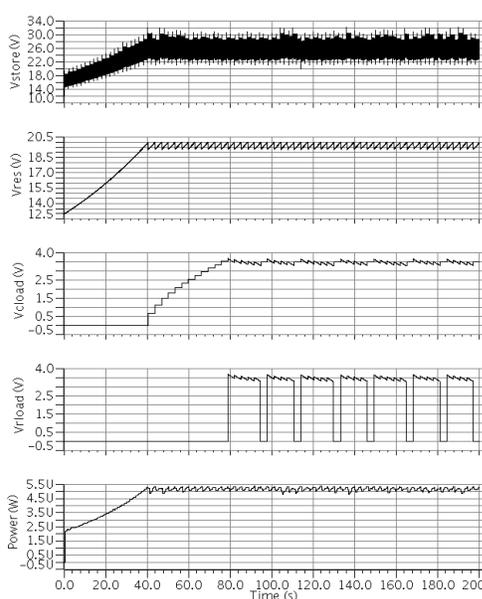


Fig. 7: Simulation results of harvester model with output voltage control.

During this phase  $V_{res}$  remains in the optimal range between 20.5V and 19.5V. When  $V_{load}$  is charged to 3.6V (wanted voltage for the load supply),  $R_{load}$  is connected. This is the start of the third phase corresponding to sustainable energy generation. During this phase,  $V_{load}$  remains in the range between 3.6V and 3.2V.

## CONCLUSION

This study provides the basic architecture of vibration energy harvester with two new features: the possibility to adapt to the environmental conditions and a smart power interface with the load. The complete improved architecture is implemented as VHDL-AMS/ELDO model. The proposed model includes hardware blocks such as switches, resonator and conditioning electronics, and the control blocks which can operate following different algorithms. Hence, this model can be used as the basis for research of the optimal strategy of power management inside the harvester and on the interface between the harvester and the load. Several improvements can be made to the proposed model. Firstly, the switches should be implemented by high-voltage transistors, to adequately model losses and transient phenomena. Secondly, the algorithm of the calibration should take into account the possible measurement losses when detecting the minimal  $\Delta V_{store}$  value.

## ACKNOWLEDGEMENTS

This work is funded by the French National Research Agency.

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