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, witch 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

1. 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.

2. 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}>>C_{store}, during pumping V_{res} remains nearly constant, and only the V_{store} evolution represents the accumulation of energy.

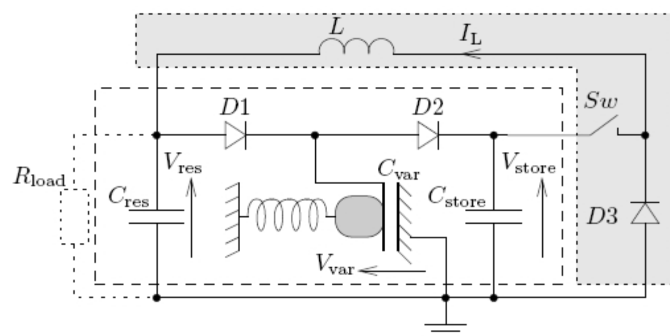

Fig. 1: Conditioning circuit of vibration energy harvester.

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.

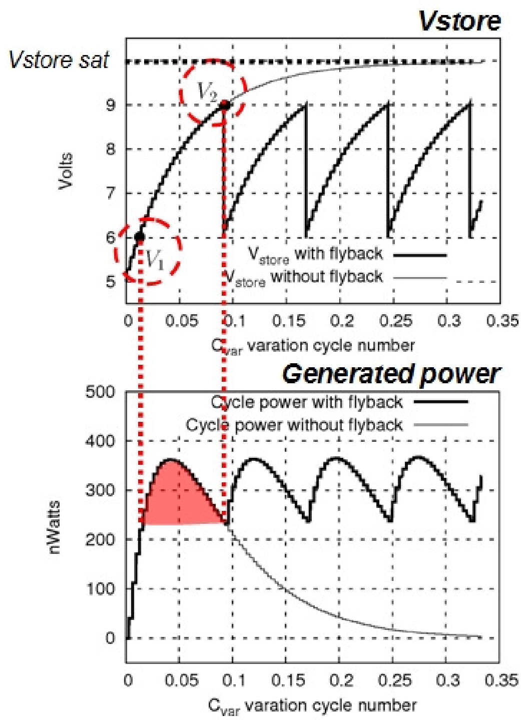

Fig. 2: Operation of the harvester with basic conditioning circuit architecture.

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]:

$$V_1=V_{res}+0.1\cdot (V_{store\ max} - V_{res})$$
$$V_2=V_{res}+0.6\cdot(V_{store\ max} - V_{res}), \qquad (1)$$

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

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

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 priory 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.

3. 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 (ΔV_{store}) between two neighboring measured values of V_{store} becomes lower than a predefined value ΔV_{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.

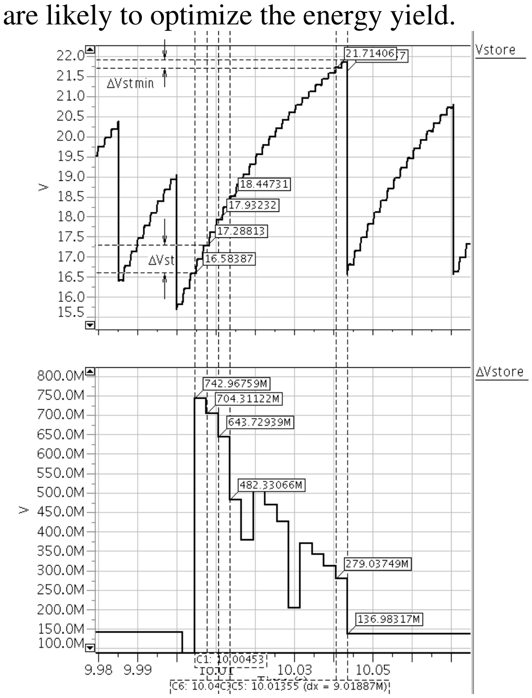

Fig.3: Calibration phase operation

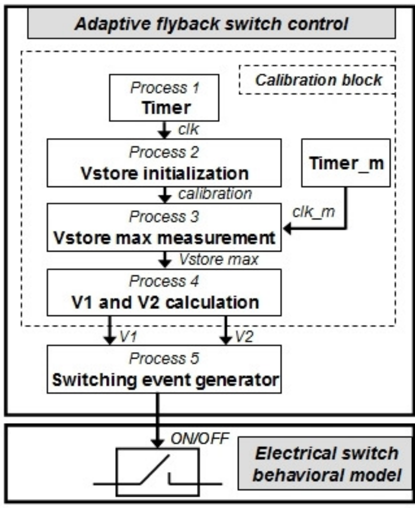

Fig. 4: Structure of adaptive flyback switch model

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].

4. 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.

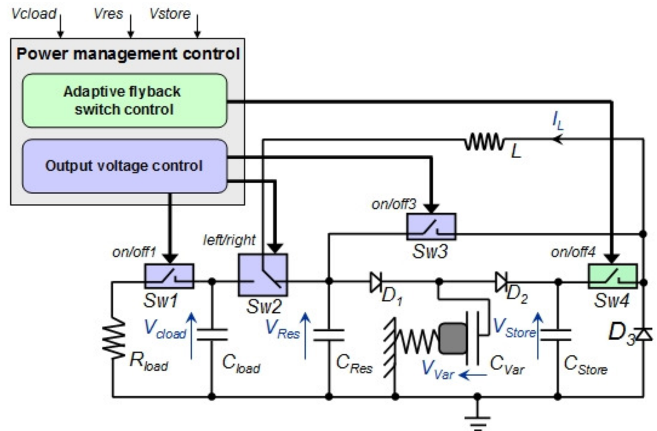

Fig. 5: Conditioning circuit of energy harvester with power management blocks

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).

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.

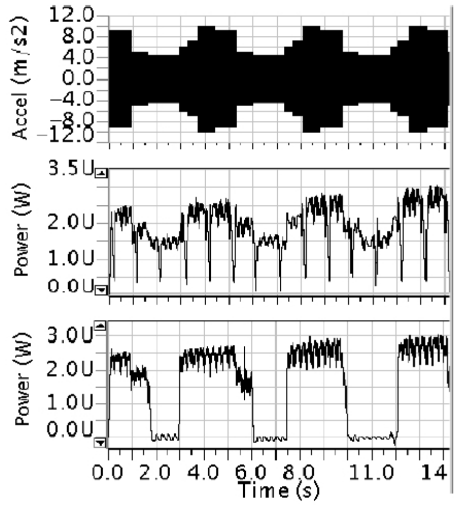

Fig. 6: Comparison of the simulation results of two identical models of harvester with and without auto-calibration

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.

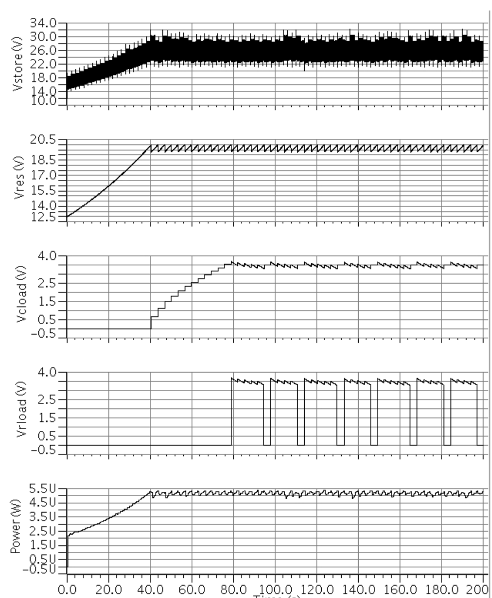

Fig. 7: Simulation results of harvester model with output voltage control

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.

6. 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 ΔV_{store} value.

ACKNOWLEDGEMENTS

This work is funded by the French National Research Agency.

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