LOW POWER ELECTROSTATIC ENERGY HARVESTING SYSTEM IC

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Abstract: This paper presents the design of a novel low power electrostatic energy harvesting integrated circuit in AMI 0.7µm high voltage CMOS process. To increase the output power extracted from a variable capacitor acting as a mechanical to electrical energy converter, a novel controller unit is proposed to synchronize the operation of the energy harvesting circuit (EHC) with the motion of the capacitor's plates. The converter consists of parallel steel plates, with a variable capacitance between 250pF-850pF and resonance frequency of 27Hz. Simulation results show a net harvested power of 332.7nW at resonance. The energy harvested and losses of the combined EHC and controller IC cores attribute to about 54% and 30% of the system power budget respectively.

Keywords: energy harvesting, electrostatic converters, integrated microscale power generators, flyback architecture.

INTRODUCTION

Micro-power generators using piezoelectric, electromagnetic, and electrostatic energy conversion have numerous applications in wireless sensor networks and biomedical implants [1-5]. Electrostatic micro-generators consisting of variable capacitors can be readily implemented using existing micro-electro-mechanical systems (MEMS) fabrication techniques which enable integration with power processing and communication circuitry [6].

Electrostatic energy harvesting circuits (EHC) can either be synchronized or unsynchronized with the mechanical cycles. Asynchronous electrostatic converters, shown in Fig. 1 [7], alleviate the gate clocking requirements of traditional synchronous energy harvesters. Energy is harvested by first storing it on an intermediate storage capacitor C_S, and then transferring it to a reservoir capacitor C_{RES} after a fixed number of mechanical cycles *n,* through the inductor *L*. The energy transfer from the intermediate to reservoir capacitor is often referred to as energy flyback. Unlike synchronous architectures, successful EHC operation is guaranteed provided that the frequency of gate drive of MOSFET switch SW accommodates several mechanical cycles of the electrostatic generator. While asynchronous architectures are simpler to implement than their synchronous counterpart, their net energy harvested is typically much lower due to the capacitive loading of the intermediate storage capacitor. To overcome this shortcoming, a new circuit architecture is presented here that combines the advantages of both architectures for efficient energy conversion.

PROPOSED ARCHITECTURE

One of the fundamental issues affecting the net energy gain of asynchronously controlled electrostatic converters is the need for the intermediate storage capacitor C_S. The capacitor C_S essentially acts as a parasitic capacitance to the energy converter, reducing the net power harvested. On the other hand, the power stored is proportional to the value of C_s. For a fixed cycle number, there is an optimum storage capacitance value at which the harvested power is maximized. Vice-versa, for a fixed C_S, the cycle number after which flyback is to be performed to get the maximum energy also has an optimum. Ideally, the system approaches its peak output power for n=1 and C_S=0 (analogous to synchronous energy harvesting with zero parasitic capacitive loading) as shown by the contour plot in Fig. 2

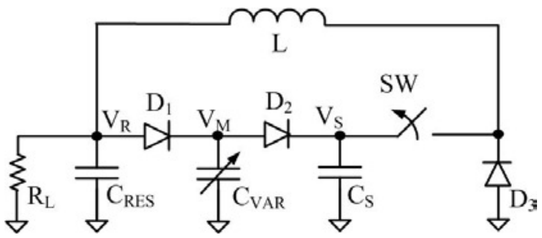

Fig. 1: Asynchronous energy harvesting circuit.

To eliminate the effect of C_S, while still avoiding sophisticated gate synchronization intelligence as in [8], [9], the architecture proposed here uses a controller unit that interfaces with the asynchronous EHC core. As shown in Fig. 3 (the red box), the controller senses the voltage difference across the diodes in the EHC and uses this information to initiate the process of energy transfer from variable and storage capacitors to the reservoir capacitor. Thus, the EHC will operate at its optimum region of operation, synchronizing the dynamics of the variable capacitor with the EHC and producing peak output power. The controller unit uses simple circuitry with ultra low power consumption.

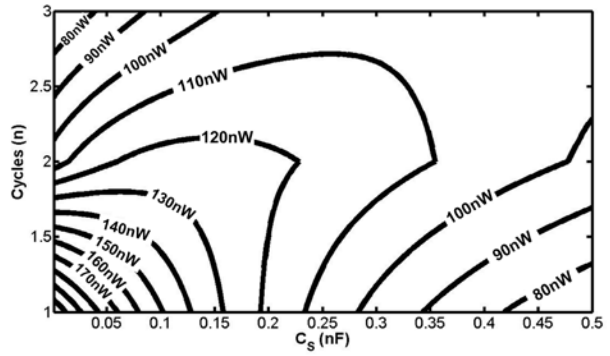

Fig. 2: Power harvested as function of cycle and storage capacitor value for traditional asynchronous architectures.

The operation of the proposed circuit can be explained as follows. Energy conversion begins when the variable capacitor is at its maximum value C_{VAR}=C_{MAX} and the capacitors C_{VAR} and C_S are initialized to $V_{M\text{-initial}}$=V_{RES}-V_{D1} and $V_{S\text{-initial}}$=V_{RES}-V_{D1}-V_{D2} respectively, where V_{D1} and V_{D2} are the voltage drops across diodes D_1 and D_2. As the mechanical excitation signal pulls the variable capacitor plates apart, C_{VAR} supplies charge to C_S forward biasing D_2 and gradually increasing V_M and V_S until a maximum is reached at C_{VAR}=C_{MIN}. Comparator A in the controller unit continuously monitors V_M and V_S and initiates the ON switching of the MOSFET switch SW1 once the differential voltage across D_2 becomes negative (reverse biased), signaling that C_{VAR} has reached C_{MIN}. As C_{VAR} and C_S discharge into C_{RES}, V_L rises above V_{RES} signaling the beginning of the discharge sequence while V_L, dropping below $V_{RES,}$ signals the completion of the discharge sequence. Since voltage V_L is also continuously monitored by comparator B of the controller unit, the completion of the discharge sequence is detected initiating the OFF switching of SW1 before ON and OFF switching of SW2. SW2 free-wheels the energy stored in L into C_{RES} as energy harvesting sequence reaches its completion. As C_{VAR} returns to its initial position, C_{RES} begins its initialization process while the whole sequence repeats itself once C_{VAR}=C_{MAX}.

To reduce power consumption in the IC, comparator A and B are designed to operate in sub-threshold regime while all decision logic is operated at a low voltage power supply (VDD=2V). Efficient level shifters and MOSFET gate drivers further minimize power consumption.

CHARACTERIZATION OF PROPOSED EHC

The EHC and the controller IC cores are designed in AMI 0.7µm high voltage CMOS process to handle the high voltage excursions across diodes D_1, D_2 and MOSFET switches SW_1, SW_2. The EHC core (Fig. 3 in blue) consists of integrated high voltage diodes, MOSFETs and capacitor C_S. C_S is selected to be 10pF

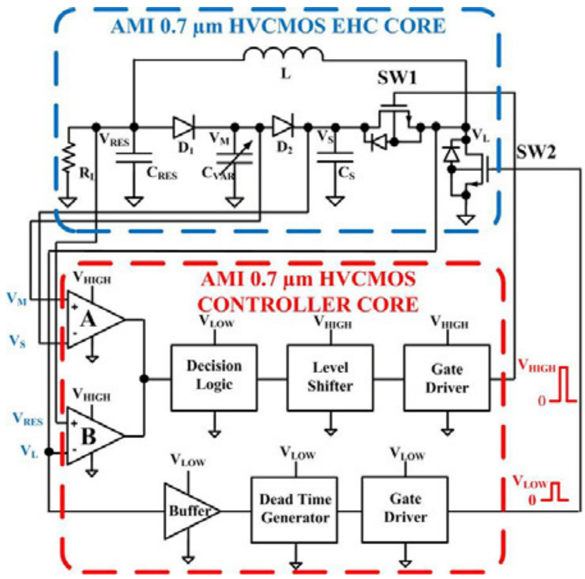

Fig. 3: AMI 0.7µm EHC Core (blue) and Controller IC Core (red).

for minimal parasitic loading of EHC. Due to practical limitation of implementing large value passives on chip, C_{RES}, R_L and L are implemented off-chip using discrete components.

As shown in Fig. 4, a macro electrostatic generator with capacitor variation of 250pF-850pF resonating at 27Hz is fabricated using 12``x6``x0.005`` top spring steel cantilever and bottom rigid stainless steel plate. The system is actuated emulating ambient environment vibration by a Labworks Inc. ET-132-2 Electrodynamic Shaker driven by a high power piezo amplifier. Its parameters are used in the characterization of the designed controller IC.

The designed EHC system IC is simulated using a behavioral model for the variable capacitor with the specifications of the fabricated macro electrostatic generator. The reservoir is initialized to 4V with C_{RES}=10µF, R_L=200MΩ and L=25mH respectively. Simulation results using AMI 0.7um technology parameters show a net harvested power of 332.7nW from the controlled electrostatic converter with a capacitor ratio of approximately 3.2, for a vibration signal of frequency= 27Hz. The same variable capacitor would deliver a net power of 180nW when using the same EHC core without the controller unit, while having a storage capacitor of C_S=1nF with energy flyback every three cycles. The cycle number of flyback is chosen based on the maximum harvestable power for a storage capacitance of C_S=1nF as shown in Fig. 2. Thus the controller unit can increase the net harvested power by 84.3%.

Fig. 5 compares the voltages on variable (V_M), storage (V_S) and reservoir (V_r) capacitors for the proposed EHC IC and the original EHC without the controller unit during steady state operation. Due to the power delivered from flyback, the reservoir capacitor exhibits a higher increase in stored energy for the

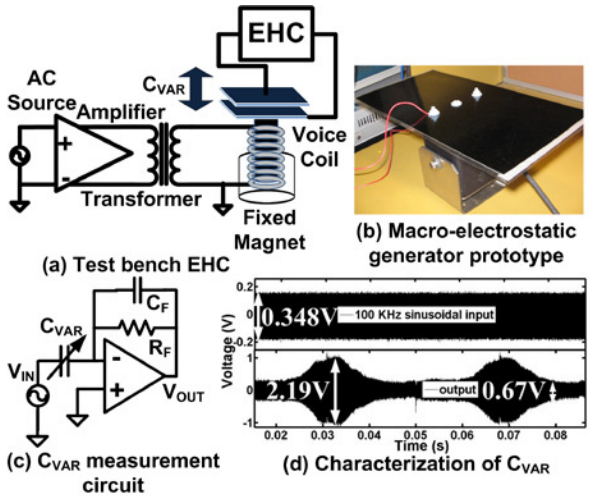

Fig. 4: (a) Experimental setup for testing the energy harvesting circuit with macro variable capacitor prototype, (b) Macro generator prototype (c) Circuit for direct measurement of variable capacitance, (d) Measured capacitance variation of electrostatic generator.

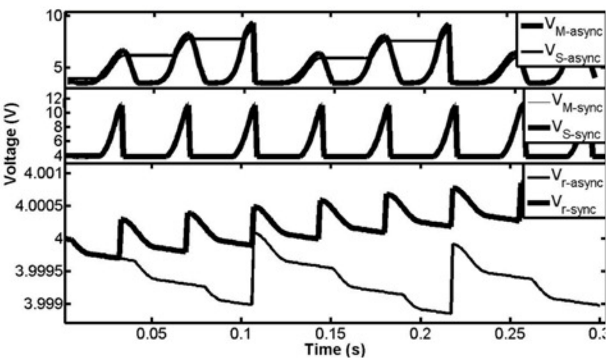

Fig. 5: Comparison between proposed and asynchronous architectures during steady state operation.

proposed topology where energy is delivered every cycle in comparison to the asynchronous case where energy is delivered every three cycles. This is illustrated with the transient voltage signal $V_{r\text{-sync}}$ of the reservoir capacitor steadily increasing in value for the proposed structure. Fig. 6 depicts the signals generated by the controller core as flyback of energy is performed in the EHC core. Due to the larger capacitive loading of the original EHC, the voltages on the variable and storage capacitors behave differently acquiring a lower final voltage at the end of each cycle. The residual charge of the variable capacitor causes voltages $V_{M\text{-async}}$ and $V_{S\text{-async}}$ to steadily rise every consecutive cycle until saturation or discharge.

Fig. 7 examines the power budget for the low power EHC IC. For a 332.2nW of harvested power delivered to the reservoir capacitor every cycle, 177nW of power is consumed by the controller core. The conduction losses of the diodes D_1 and D_2 are 26.94nW and 1.56nW respectively, while that for MOSFETs SW1 and SW2 are approximately 32.51nW and 31.44nW. The replacement of the flyback diode of

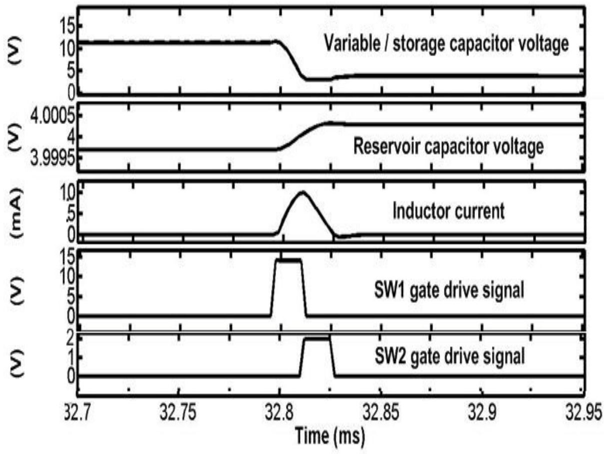

Fig. 6: Voltage and current waveforms for proposed structure during flyback of energy.

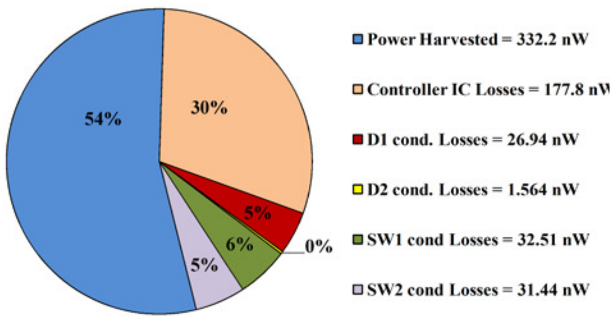

Fig. 7: Power budget for synchronous electrostatic energy harvesting IC

the original EHC with MOSFET SW2 reduces conduction losses by approximately 10nW. Compared to other sensing mechanisms using complex active circuitry [8], [9], D_2 which is the primary position sensing mechanism for the proposed electrostatic generator has minimal power consumption and enable efficient ambient energy harvesting. The power harvested by the proposed EHC and the control circuitry attribute to about 54% and 30% of the total power budget respectively. The MOSFET and diode conduction losses attribute to about 16 % of the overall power.

CONCLUSION

This paper proposes a low power energy harvesting IC that synchronizes the operation of the harvesting circuit with the motion of the variable capacitor plates. The building blocks of the controller unit utilize a combination of operation in sub threshold regime, low voltage scaling on comparator driver stages and efficient level shifters for gate drivers. Simulation results show that the proposed IC harvests a power of 332.7nW from a 27Hz vibration signal compared to 180nW of harvested power from an asynchronously-controlled converter under the same operating conditions.

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