

LOW POWER ENERGY HARVESTING SYSTEM IC FOR TRI-PLATE ELECTROSTATIC CONVERTERS

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Abstract: This paper proposes a low power EHC that performs synchronous energy conversion on a tri-plate variable capacitor to improve the maximum achievable power. A tri-plate macro electrostatic generator with capacitor variation of 405 pF to 1.15 nF and 405 pF to 1.07 nF on two complementary adjacent capacitors operating 180° out of phase at 98 Hz is fabricated and used in the characterization of the designed EHC. The IC is fabricated using the AMI 0.7 μm high voltage CMOS process and tested with the tri-plate capacitor to demonstrate mechanical to electric energy conversion. In steady state operation, the EHC produces a total output power of 1.04 μW to a 10 μF reservoir capacitor from a 98 Hz vibration signal.

Keywords: energy harvesting, electrostatic converters, integrated microscale power generators, tri-plate variable capacitors.

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 converters operating in charge constrain can draw and convert energy from the environment, as vibrations work against the electrostatic force of a mechanical variable capacitor to push its plates apart, the capacitance decreases from maximum (C_{MAX}) to minimum (C_{MIN}) which results in an increase in voltage (to V_{MAX}). By discharging the electrostatic converter at C_{MIN} (V_{MAX}), the converted mechanical energy (E_{HARV}) can be recovered every mechanical cycle ($1/f_{MECH}$). It is apparent that for a traditional dual plate electrostatic variable capacitor, energy is only harvested when the capacitance changes from C_{MAX} to C_{MIN} during a half cycle, providing a maximum harvestable power as shown below in (1).

$$P_{HARV-DUAL\ PLATE} \approx E_{HARV} \cdot f_{MECH} \quad (1)$$

During the second half of the mechanical cycle, as capacitance changes from C_{MIN} to C_{MAX} any mechanical energy the system experiences is wasted.

Furthermore, electrostatic energy harvesting circuits (EHCs) can either be synchronized or unsynchronized with the mechanical cycles. Asynchronous electrostatic converters, shown in Fig. 1 (Power Stage $PS1$) with an additional large storage capacitor C_S , eliminate difficulties associated with precise gate control of transistors employed in synchronous architectures. Energy is harvested by

simply storing the converted mechanical energy on an intermediate storage capacitor C_S , and transferring this energy to a reservoir capacitor C_{RES} after a fixed number of mechanical cycles n through inductor L , in what is known as energy flyback [7]. However, the storage capacitor, C_S acts as a parasitic capacitance to the energy converter by reducing the maximum achievable voltage upon discharge and severely reducing the total harvestable mechanical energy [8]. As a result, synchronous architectures, even at the expense of complex transistor gate control circuitry and associated power dissipation for synchronization [9-10], provide more power to the load. Synchronous electrostatic converters can convert energy in either charge or voltage constrained configurations, with the former producing higher power levels as energy is proportional to voltage.

This paper proposes a low power EHC that performs charge constrained synchronous energy conversion on a *tri-plate* variable capacitor for maximizing energy conversion over the complete mechanical vibration cycle. This enables a new class of tri-plate electrostatic generators combined with low power EHCs with potential for approaching the maximum harvestable power limit which is double that of traditional electrostatic energy harvesters with similar initializing voltage, frequency of operation, capacitor ratio and variation.

PROPOSED ARCHITECTURE

The EHC shown in Fig. 1 consists of four main blocks: power stages $PS1$, $PS2$, and controller units CUI , $CU2$. Energy conversion occurs in the power stages $PS1$ and $PS2$ of the EHC while the controller units CUI and $CU2$ facilitate the synchronous charging and discharging of each electrode pair of capacitors C_{VAR1} and C_{VAR2} that form the external macro tri-plate variable capacitor.

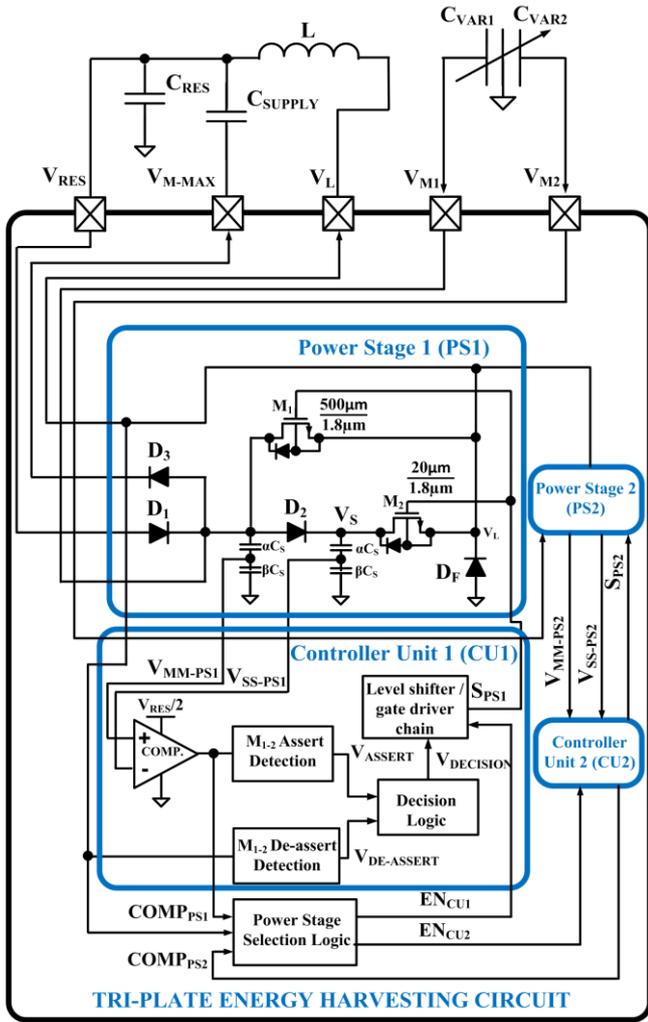


Fig. 1: System overview of the proposed energy harvesting circuit.

The controller units sense the voltage difference across diode D_2 through sensing capacitors αC_S and βC_S of power stages $PS1$ and $PS2$ to assert power MOSFETS M_1 and M_2 and initiate the process of energy transfer from variable and sensing capacitors when an electrode pair of the variable capacitor reaches C_{MIN} . The inductor voltage, V_L is then sensed to de-assert M_1 and M_2 and allow the flyback of energy through free-wheeling diode D_F to the reservoir capacitor.

The power stage selection logic determines which controller, power stage and electrode pair of the variable capacitor is enabled by signals EN_{CU1} and EN_{CU2} based on the position and direction of capacitors C_{VAR1} and C_{VAR2} of the tri-plate variable capacitor. The power consumption of the IC is reduced by designing comparators to operate in the sub threshold regime, down scaling of sensing voltages for lower voltage operation of analog and digital decision blocks and the utilization of low power level shifters and gate drivers stages for efficient driving of power MOSFETs.

The sensing capacitors αC_S and βC_S of the power stages $PS1$ and $PS2$ replace the large storage capacitor

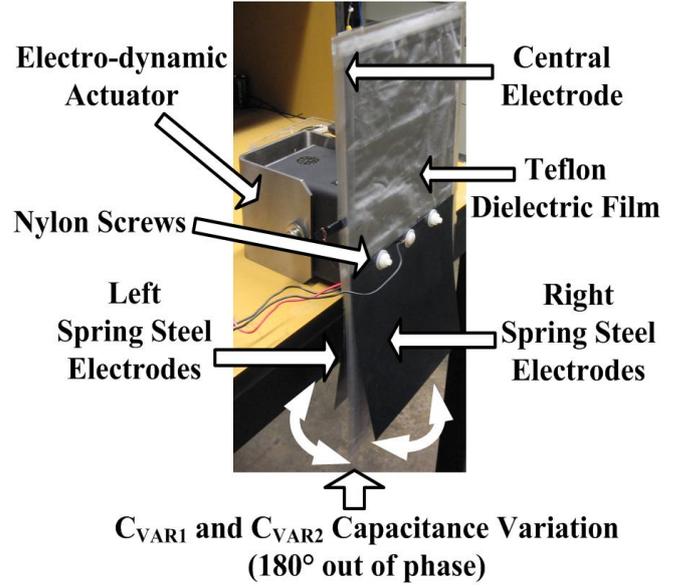


Fig. 2: Macro tri-plate variable capacitor prototype used in the characterization of the fabricated integrated energy harvesting circuit.

C_S in traditional asynchronous converters thus minimizing parasitic capacitive loading effect of the latter during the energy conversion process. The sensing capacitors together with the controller units perform synchronous charge constrained energy conversion maximizing maximum harvestable power.

CHARACTERIZATION OF THE EHC

As shown in Fig. 2, a tri-plate macro variable capacitor consisting of a rigid stainless steel central electrode supporting two spring steel electrodes on either side by nylon screws was fabricated and tested. A Teflon film with dielectric constant of approximately 2.1 is used to insulate the adjacent electrodes and enhance the capacitance of the electrostatic generator. The tri-plate prototype exhibited capacitor variation of 405 pF to 1.15 nF and 405 pF to 1.07 nF of adjacent variable capacitors C_{VAR1} and C_{VAR2} operating complementary to each other, 180° degrees out of phase. The electrostatic transducer was actuated by a 98 Hz vibration signal produced by a Labworks Inc. ET-132-2 Electrodynamic Shaker driven by a high power piezo amplifier. The tri-plate variable capacitors parameters are used in the characterization of the designed controller IC.

The EHC shown in Fig. 1 is designed in the AMI $0.7 \mu\text{m}$ high voltage CMOS process to handle the high voltage excursions across diodes and MOSFET switches. The designed EHC system IC is simulated using a behavioral model for the variable capacitor with the specifications of the fabricated tri-plate macro electrostatic generator. The reservoir is initialized to 3.6 V with $C_{RES}=10 \mu\text{F}$, $L=100 \text{ mH}$ and $C_{SUPPLY}=1 \text{ nF}$ respectively.

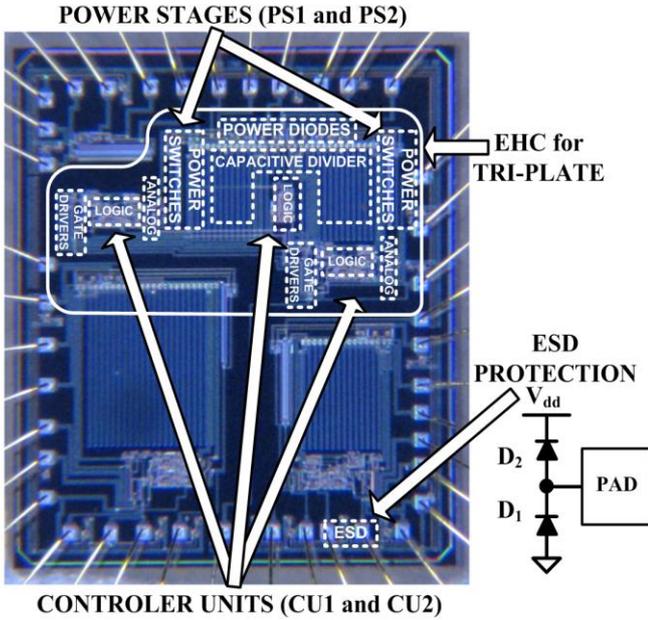


Fig. 3: Fabricated integrated high voltage CMOS energy harvesting circuit.

Simulation results using the AMI 0.7 μm technology parameters show that the proposed architecture harvests approximately 1.26 μW of power from the tri-plate electrostatic generator for a 98 Hz vibration signal, compared to 400 nW of power that can be harvested with one of the capacitors (C_{VAR2}) deactivated, mimicking the traditional case. The controller consumes a maximum of 175.5 nW when synchronizing the EHC to the 98 Hz vibration signal.

EXPERIMENTAL RESULTS

The integrated high voltage EHC is fabricated in the AMI 0.7 μm process and bonded to the DIP40 package. Fig. 3 illustrates the component layout of the fabricated die that consists of power stages $PS1$ and $PS2$ with capacitive dividers that form sensing capacitors αC_S and βC_S . The controller units $CU1$ and $CU2$ comprise of analog and digital decision blocks, level shifters and gate drivers.

Fig. 4 shows the transient measurement results for the fabricated integrated circuit. The energy harvesting circuit synchronizes with the motion of the tri-plate electrostatic generator operating at 98 Hz. During steady state operation, the complementary voltages V_{M1} and V_{M2} on each electrode pair of capacitors C_{VAR1} and C_{VAR2} that form the tri-plate variable capacitor behave similarly to simulation results validating synchronization and flyback of energy. The proposed EHC produces a total measured output power of 1.04 μW to a 10 μF reservoir capacitor, when the system is actuated by a 98 Hz vibration signal.

CONCLUSION

This paper proposes a low power EHC that performs synchronous charge constrained energy conversion on

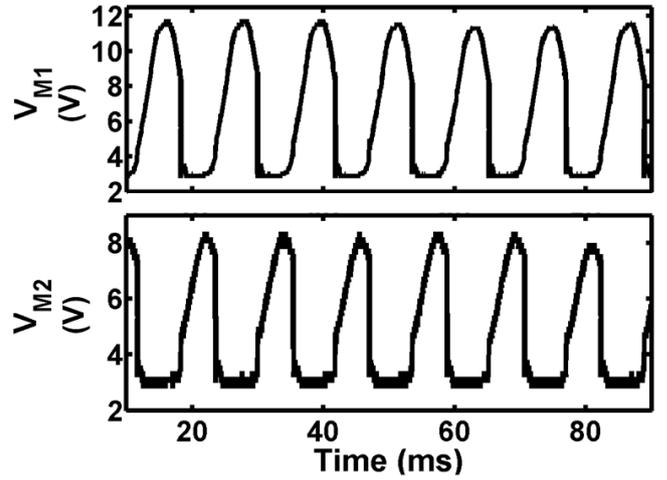


Fig. 4: Measured voltages on capacitors C_{VAR1} and C_{VAR2} that form the macro tri-plate variable capacitor during steady state operation.

a tri-plate variable capacitor to improve the maximum achievable power. Energy conversion is demonstrated from a macro tri-plate electrostatic generator with capacitor variation of 405 pF to 1.15 nF and 405 pF to 1.07 nF and low power integrated circuit fabricated in the AMI 0.7 μm high voltage CMOS process. During steady state operation, the EHC produces a total output power of 1.04 μW to a 10 μF reservoir capacitor from a 98 Hz vibration signal. Tri-plate electrostatic generators combined with low power EHCs spawns a new class of micro-generators with increased potential for energy conversion double that of traditional electrostatic energy harvesters with similar initializing voltage, frequency of operation, capacitor ratio and variation.

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