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A self-powered power conditioning circuit for battery-free energy scavenging applications

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Abstract A controllable power conditioning circuit is proposed for battery-free energy harvesting applications. The circuit is designed for piezoelectric energy harvester applications and it has only 11 transistors and consist a simple feedback loop and switched capacitor that conditionally allows the power to be applied to the load (circuit to be powered in this case). The area- and power-efficient digital design that does not include any inductors makes the topology easy to apply to any low-power sensor applications. The power conditioning circuit relies on a digital Schmitt trigger that controls the voltage threshold values of the power supply where the load circuit would operate within. The hysteresis (hence the threshold) levels were set to 435 and 710 mV and the overall energy conversion efficiency is around 65 %. The theory of the piezoelectric harvester was also studied.

Keywords Power conditioning circuit · Switched capacitor · Energy harvesting applications · Piezoelectric conditioning circuit

1 Introduction

With the increasing need for compact self-sustaining devices on the rise, power consumption control for non-steady power sources is vital. The power source can be any form of ambient energy such as solar power, thermal energy, wind energy, and vibrations [1]. One of the most popular energy harvesting methods is the use of piezoelectric material which converts mechanical energy from vibration into electrical energy [1–3]. Although this form of power production is much smaller than batteries, it can ultimately be very useful for low-power sensor applications [4, 5]. Therefore, effective and simple power conditioning circuits are much needed in order to successfully convert the harvested energy into useable steady voltage levels.

Several interface circuits were developed in order to efficiently control a vibrational energy harvester's relatively low power levels. In order to control the power output regarding to the available power at the input, adaptive switching schemes are highly needed. There are several attempts to achieve controlling the power, conditionally, however, they require an additional power source, employ large area consumption due to inductors, or the interface circuitry itself draws a significant current due to the circuit complexity [3, 5–7]. Techniques include synchronous rectifiers [2], step-down converters [6], adaptive adjustment of maximum available output power [7], and resistive impedance matching [8].

In this work we designed a power conditioning circuit based on a Schmitt trigger which would be used to conditionally power a sensor circuit only if there is enough voltage generated. The circuit operates solely with the power harvested from the vibrations, constitutes only 11 transistors, and does not employ inductors hence area efficient. The proposed circuit would only turn on the power that is on a storage capacitor if the set threshold accumulated voltage is attained. The circuit would turn off after a certain amount of charge is depleted, which could also be controlled. Mostly digital operation and simplicity of the

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proposed circuit ensures the minimum current consumption, hence the suitability for low-power applications.

2 Basic blocks of proposed system

The block diagram of the proposed power conditioning system is presented in Fig. 1. The proposed system consists a rectifying circuit, a capacitor-based energy bank, a digital Schmitt trigger and a controlling unit utilized by NMOS and PMOS transistors. The Schmitt trigger along with the controlling unit allows the load circuit to work in a discontinuous conduction mode (DCM), which has the following advantages: (1) comparing with traditional continuous conduction mode, DCM could reduce the power consumption of the circuit significantly, (2) contrary to traditional step-up converters, DCM conditioning circuit does not require inductors, which greatly reduced the area requirement and design complexity.

3 Theory and the circuit model of the piezoelectric energy source

In this design, piezoelectric energy harvester was considered as the energy source. Therefore, it is necessary to understand the basics of piezoelectric energy harvesting. A piezoelectric harvesting element converts the vibrational excitations into alternating electrical energy. This is because when piezoelectric materials are physically deformed, the electric dipole moments in these materials are induced due to the characteristics of the materials like asymmetric surround charge (such as lead–zirconate–titanate) or large molecular clusters (sucrose) [10].

Piezoelectric harvesters can be modelled as a sinusoidal current source $i_p(t)$ in parallel with the harvester's plant capacitance C_p or a sinusoidal voltage source $V_p(t)$ in series with the plant capacitance as shown in Fig. 2. The
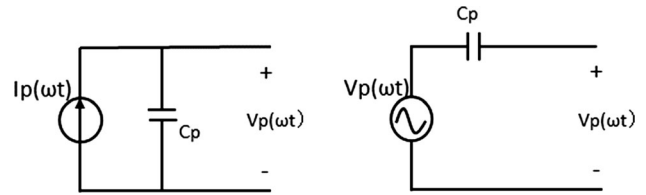

Fig. 2 Equivalent circuit of piezoelectric harvester

magnitude of the polarization (herein the polarization means the polarization of the electric dipole moments) current or voltage depends on the materials, geometry of the designed harvester and the vibrational excitation level.

The electrical power generated by the vibrational excitations is given by (1) [1], where ζ is the damping ration; Y is the vibrational level; ω_n is the natural frequency which depends on both materials and the geometry of the harvester; and ω is the excitation frequency.

$$P = \frac{m\zeta Y^2 \omega_n^3}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\zeta\frac{\omega}{\omega_n}\right]^2} \quad (1)$$

Furthermore, the natural frequency ω_n could be theoretically calculated by (2) [9], where V is the modulus of elasticity of the material, T is the thickness, L is the length and ρ is the density of the material.

$$\omega_n = \frac{0.16T}{L^2}\sqrt{\frac{V}{\rho}} \quad (2)$$

From (1), it is clear that the piezoelectric harvester yields the highest electrical charge when it oscillates at its natural frequency. Therefore, the theoretical maximum output power can be derived as:

$$P_{max} = P_{\omega=\omega_n} = \frac{mY^2\omega_n^3}{4\zeta} \quad (3)$$

Generally, the piezoelectric harvesters could generate an AC voltage with 1–2 V amplitude [11].

Fig. 1 Block diagram of DCM power conditioning circuit
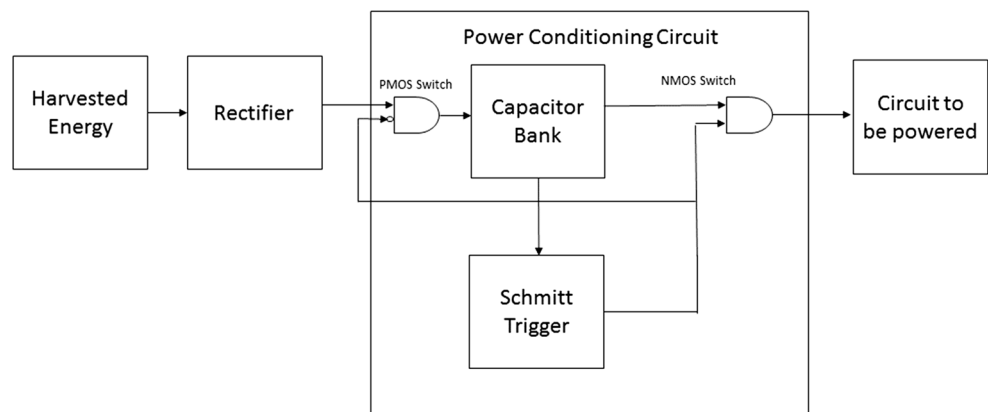
4 DCM power conditioning circuit

The proposed circuit relies on capacitor charge sharing where the threshold voltages of the switching voltage values are altered via a digital Schmitt trigger. The proposed power conditioning circuit is represented in Fig. 3 with the aspect ratios depicted. The harvested source's voltage is first rectified by a half-bridge rectifier and the rectifier storage capacitor, C_S (1 mF). Initially, the PMOS switch transistor, M_S, is on, hence the load storage capacitor, C_L (1 mF) is also charged by the harvested energy. Once the voltage on C_L reaches the higher threshold voltage level set by the Schmitt trigger, the output of the trigger, V_{ctrl}, will generate a digital output of "1". Logic 1 applied to the switching transistor, M_S, will turn off M_S. Simultaneously, the load transistor, M_L, will be turned on and C_L will be discharged through the load allowing the circuit to be powered. When C_L is discharged below the lower threshold voltage, the Schmitt trigger will output logic "0" to disconnect the load and allowing C_L to be charged again. It must be noted here that all the circuit components are powered through the storage capacitor C_S including the transistor switches M_S, M_L and the Schmitt trigger. Therefore, no external power supply is needed.

5 Simulation results

The operation of the proposed circuit was simulated using OrCad^{TM} and TSMC 0.5 μm CMOS process parameters. Since most current Piezoelectric harvester' output voltage has a range of 1–2 V amplitude [10] a sinusoidal voltage source with 2 V amplitude and 10 Hz frequency has been used as the harvested source. Figure 4(a) shows the working scheme of the power conditioning circuit. While the Schmitt trigger outputs logic 1, C_L starts discharging
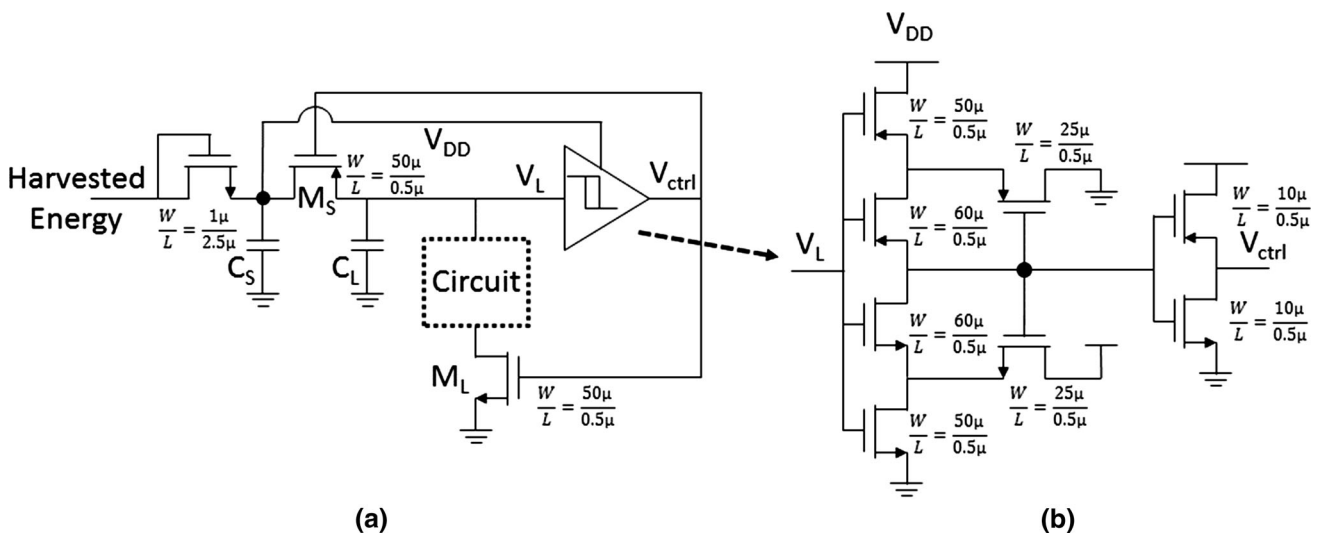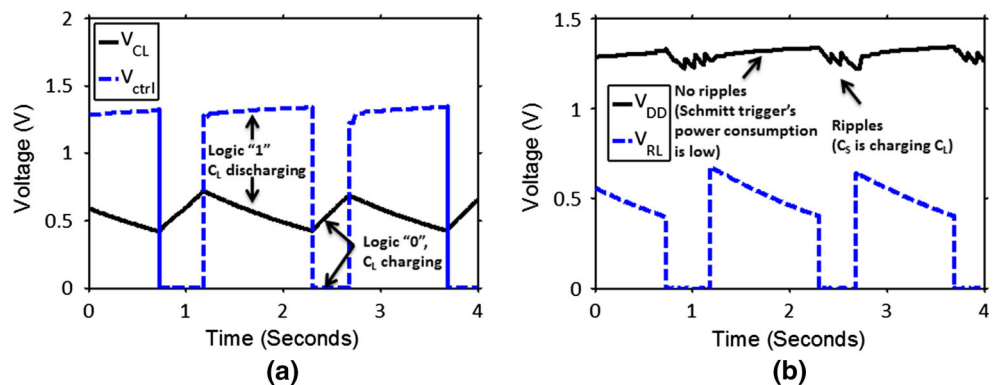

Fig. 3 Proposed circuit has only 11 active components and two storage capacitors; **a** overall circuit schematic. **b** Schmitt trigger circuit schematic

Fig. 4 Simulation results of the proposed power conditioning circuit; **a** voltages on the load capacitor and the control voltage. **b** Voltages on the load circuit and the power supply of the Schmitt trigger circuit
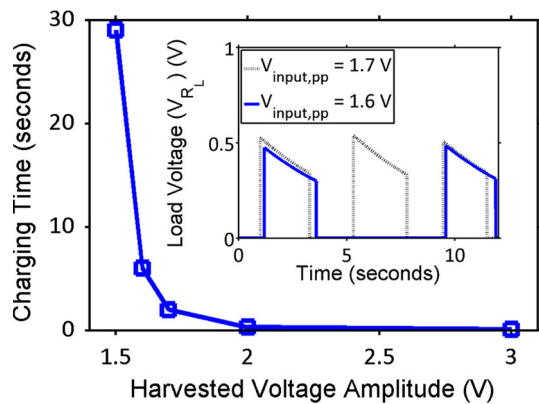
Fig. 5 The charging time (working-cycle) decreases as the amplitude of the harvested voltage increases. Two representative voltages at the load circuit are shown in the *inset*

through R_L (the circuit to be powered) causing a gradual decrease in voltage. When the Schmitt trigger outputs logic 0, C_L begins to be charged by C_S. Due to the continuous discharge by C_L and the discontinuous charge by the rectified harvested energy, the voltage on C_S (V_{DD} in this case) starts rippling as shown in Fig. 4(b). It should be noted that since the Schmitt trigger is powered by V_{DD}, the ripples may significantly affect the performance of the Schmitt trigger, so careful configuration must be implemented. Large aspect ratio transistors were used to minimize the voltage drop for proper Schmitt trigger operation for low voltages.

Figure 5 shows the dependence of charging time of the circuit on the harvested voltage amplitude. Higher harvested amplitude allows faster charging time, which means the load circuit may function longer with a cost of lower efficiency. It should be noted that since the Schmitt trigger is powered by V_{DD}, which determined by the amplitude of harvested voltage, different harvested voltage amplitude may also affect the output voltage by altering the threshold voltage of the Schmitt trigger. Therefore, specific configuration should be made based upon the type of the energy harvester and load.

The overall efficiency of the power conditioning circuit was calculated to be 5.7 % by probing the voltage and current values on the load circuit and the harvested input voltage. Biggest efficiency lost is due to the half wave rectifier diode. With improved rectifying schemes, the efficiency can be increases significantly. In fact, the efficiency of the circuit from the rectified signal to the output was around 65 % with 2 V amplitude voltage source and a 1 kΩ load resistor.

6 Conclusion

A controllable power conditioning circuit that is suitable for energy harvesting applications was proposed. Key advantages of the design are that it does not require any external power supply, it only constitutes less than 11 circuit components, and area/power consumption is ultimately low thanks to no-inductance and fully digital design. The power conditioning circuit only powers a sensor circuit when there is enough voltage generated by the harvester, making the circuit adaptive. The threshold voltages of the interface circuit are controlled by manipulating transistor sizes, which also determines how long the sensor circuit will be powered and at what voltage levels. Threshold voltages can be manipulated to different levels. The proposed topology enables the use of low-level vibration energy usage in low-power wireless sensor networks.

References

1. Priya, S., & Inman, D. (2009). *Energy harvesting technologies*. New York: Springer.
2. Le, T. T., Han, J., von Jouanne, A., Mayaram, K., & Fiez, T. S. (2006). Piezoelectric micro-power generation interface circuits. *IEEE Journal of Solid-State Circuits, 41*(6), 1411–1420.
3. Dicken, J., Mitcheson, P. D., Stoianov, I., & Yeatman, E. M. (2012). Power-extraction circuits for piezoelectric energy harvesters in miniature and low-power applications. *IEEE Transactions on Power Electronics, 27*(11), 4514–4529.
4. Kaya, T., Koser, H., & Culurciello, E. (2006). A low-voltage temperature sensor for micro power harvesters in silicon-on-sapphire CMOS. *Electronics Letters, 42*, 526–528.
5. Paradiso, J. A., & Starner, T. (2005). Energy scavenging for mobile and wireless electronics. *IEEE Pervasive Computing, 4*(1), 18–27.
6. Ottman, G. K., Hofmann, H. F., & Lesieutre, G. A. (2003). Optimized piezoelectric energy harvesting circuit using step-down converter in discontinuous conduction mode. *IEEE Transactions on Power Electronics, 18*(2), 696–703.
7. D'hulst, R., Sterken, T., Puers, R., Deconinck, G., & Driesen, J. (2010). Power processing circuits for piezoelectric vibration-based energy harvesters. *IEEE Transactions on Industrial Electronics, 57*(12), 4170–4177.
8. Kong, N. A., Ha, D. S., Erturk, A., & Inman, D. J. (2010). Resistive impedance matching circuit for piezoelectric energy harvesting. *Journal of Intelligent Material Systems and Structures, 21*, 1293–1302.
9. Han, J. (2004). Novel power conditioning circuits for piezoelectric micro power generators. In *Applied Power Electronics Conference and Exposition, 2004*.
10. Kaya, T., & Koser, H. (2005, October). A study of nonlinear deflection dynamics of a piezoelectric accelerometer. *FEMLAB Conference*, Boston, MA.
11. Piezo generator/sensor kit manual. Retrieved December 4, 2014 from http://piezo.com.

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