In-Body Energy Harvesting Power Management Interface for Post Heart Transplantation Monitoring

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***Abstract*—Deep tissue energy harvesters are of increasing interest in the development of battery-less implantable devices. This paper presents a fully integrated ultra-low quiescent power management interface. It has power optimization and impedance matching between a piezoelectric energy harvester and the functional load that could be potentially powered by the heart's mechanical motions. The circuit has been designed in 0.18-µm CMOS technology. It dissipates 189.8 nW providing two voltage outputs of 1.4 V and 4.2 V. The simulation results show an output power 8.2x times of an ideal full-bridge rectifier without an external power supply. The design has the potential for use in self-powered heart implantable devices as it is capable providing stable output voltages from a cold startup.**

Keywords—Piezoelectric, power harvesting, power interface, power management, regulating rectifier.

I. Introduction

With an increase in end-stage heart failure (HF), the number of heart transplantation surgeries is increasing due to their ability to significantly increase the life expectancy of patients. However, the life quality of heart transplant patients is limited due to increased complications including cardiac denervation. State-of-the-art research innovations focus on prolonging the life expectancy of heart transplant patients by restoring the neural connections lost during the transplantation operation [1]. Other complications after heart transplantation include the possibility that the heart's coronary artery to change in geometry, thicken and harden leading to cardiac allograft vasculopathy (CAV), which is the most common cause of death (40%) and a significant cause of late re-transplantations [2]. CAV is the major cause of limited long term graft survival after heart transplantation, yet early diagnosis of CAV can help in reducing contributing risk factors. Some of the major CAV symptoms include: 1) Difficulty in blood circulation through the heart leading to a heart attack, heart failure, and heart arrhythmias. 2) Rejection of the organ causing an attack by the immune system, and with a possibility of chronic rejection that can take place over many years, slowly damaging the transplanted heart. These complications require deep tissue implantable solutions for further studies.

Powering deep-tissue implantable devices using wireless power transfer is limited to distance constraints of <1 cm depth inside the body. Human organs or bones can also limit the power transfer due to tissue absorption limitations. Self-powered implantable devices with in-body energy harvesters have the potential to address the problem of limited battery lifetime and eliminate periodic surgical replacement in deep tissue medical implants. Research using a piezoelectric energy harvester (PEH) placed between the heart and the pericardium to harvest heartbeat has been reported in Li *et al*. [3]. It

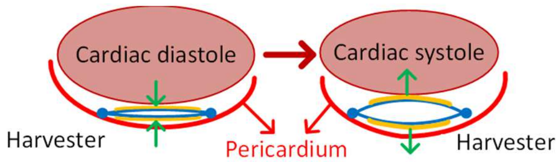

Fig.1 Piezoelectric energy harvester placement in the heart.

presents a proof of concept of the ability to obtain an average of 33 μW power from heartbeats using a conventional full-bridge rectifier as shown in Fig. 1 which consumes 50% of the power efficiency.

To obtain optimum power harvesting, this paper proposes a power interface that can handle unpredictable power/voltage levels received from the PEH, store, and power the system's functional blocks accordingly. In this paper, a novel power management and extraction interface design operates purely on harvesting modes. The proposed system includes an active rectifier with pulse frequency modulation (PFM), shared capacitors between dc-dc converter and extraction interface blocks, and a fractional maximum power point tracking (MPPT), with on chip clock generation, all operating with nW power consumption. The system operates in a discontinuous control mode (DCM), working asynchronously with 0.6-2 Hz on/off clock to achieve low-quiescent current.

The rest of the paper is organized as follows. Section II describes the concept with emphasis on the impedance and frequency matching theory for a PEH electrical model. Section III presents the system design and implementation of the power interface circuit including the regulating rectifier with PFM control, and dc-dc converter. Section IV presents the simulated performance of the design. Concluding remarks are drawn in Section V.

II. Impedance and Frequency matching Theory

Recent progress in the field of in-body energy harvesting reports various PEH designs having the highest bending capabilities to extract the most power output [3]. The energy harvested from the PEH changes according to the heartbeat rhythms of around 40 to 120 beats per minute, which is equivalent to 0.6 to 2 Hz. To extract the maximum power from a PEH, the input impedance of the energy extraction circuits must match the output impedance of the energy transducer. A computational approach to obtain the output electrical power P_{PEH} as follows

$$P_{PEH} = \frac{1}{T}\int_0^T \frac{V^2}{R_L} dt \tag{1}$$

where P_{PEH} depends on time, T, the voltage output, V, and the output resistor load, R_L. An electrical impedance matching circuit for piezoelectric transducers PEH requires

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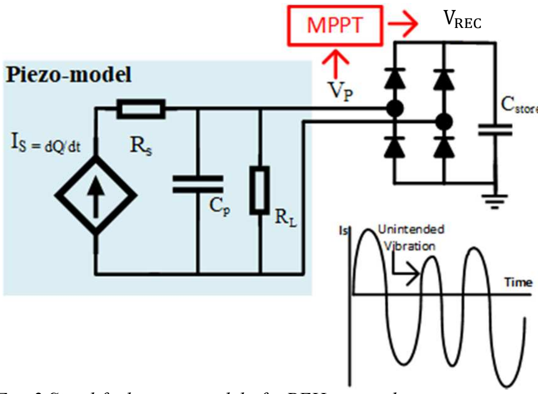


Fig. 2 Simplified circuit model of a PEH energy harvesting system.

consideration of the frequency of operation. To maximize the energy yield, the electrical resistance should be adapted to cope with variations in vibrational frequency. A maximum power point tracking circuit (MPPT) provides power monitoring to calculate the output power of the piezoelectric harvester system and compare it to the current control value. The piezo-model shown in Fig. 2 is used to analyze the nonlinear characteristics of a generic harvester model. The inefficiencies of the system are modeled using a series resistor (R_s), causing voltage drop after boosting, and a parallel resistor (R_L), accounting for the internal power consumption. The piezoelectric effect is solely based on the intrinsic polarization of the material to convert ambient kinetic energy in the form of vibration or shocks into electrical energy. An alternative approach is to use only a resistive load and try to match the source impedance with the power P_{out} delivered from a current source to a load resistor R_L where

$$P_{out} = \frac{R_S^2+X_S^2}{(R_s+R_L)^2+X_S^2} Is^2 R_L. \tag{2}$$

By considering an ac current source $I_s(t) = \sqrt{2} I_s \, sin(\omega t)$, the internal impedance is $Z_s = R_s + jX_s$ .To maximize the power delivered to the load, the optimal load resistance, $R_{L,opt}$ and maximum load power, $P_{L,max}$ are:

$$R_{L,opt} = \sqrt{R_S^2 + X_S^2} \tag{3}$$

$$P_{L,max} = \frac{R_S^2 + X_S^2}{2(\sqrt{R_S^2 + X_S^2} + R_s)} Is^2 \tag{4}$$

The load resistive impedance must match the piezo generator equivalent output resistive impedance. The overall power harvested can be calculated by finding the power output when unmatched power is divided by matched power. The equivalent electrical model shows that the charge and discharge of the internal capacitance will cause energy loss affecting the energy collection.

The traditional full bridge rectifier (FBR) cannot be utilized, as its turn-on voltage is high. A synchronized switch harvesting (SSHI) circuit reduces the charge loss on the capacitor by flipping the internal capacitance voltage at short time intervals to a LC resonant circuit [4]. The SSHI circuit can work at various resonant frequencies. However, the control is sensitive to process, voltage, and temperature (PVT), which degrades the power efficiency introducing timing errors. Multi-step bias-flipping is preferable making the circuit less sensitive to parasitics and improving reliability.

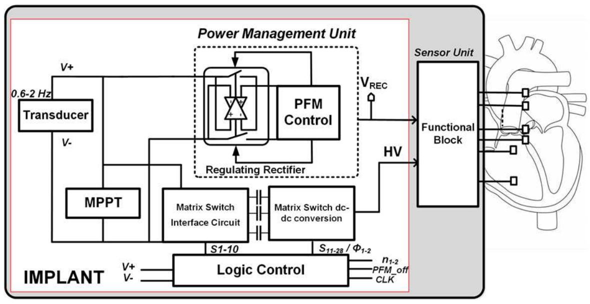


Fig.3 Proposed PMU design of in-body energy harvesting for post heart implant monitoring.

A start-up circuit is also needed when the system faces a mishap such as when there is not enough source of energy. There are limitations to consider when designing a fully in-body harvesting dependent implant: 1) Limitation when there is not enough power source. 2) High power output requires a highly bendable PEH resulting in a complex high voltage CMOS design. 3) Low and unstable frequency of the heartbeat. There are significant advances in circuit design in the area of wireless sensor nodes (WSN), but these designs operate at much higher frequency levels (100 Hz and above), providing higher power output compared to the power that can be extracted from heartbeat.

III. System Architecture

A. System Architecture

As shown in Fig. 3, the power management interface consists of a MPPT, regulating rectifier, matrix switch interface and clock generator to power the functional block. The PFM control is based on voltage to frequency response and changes the switching speed based on the amplitude peaks of the input voltages into frequency-based signals ranging from 0.6-2 Hz switching frequency. The regulating rectifier circuit must be active only when necessary, to ensure that the quiescent current is reduced for system stability. Therefore, the power output of the regulating rectifier is stored in an energy storage unit and is further regulated through a dc-dc unit based on the functional block requirements. A low voltage cold-start functionality is added for when the harvester low energy ambient voltage levels fall below the circuit threshold values.

B. Proposed PFM Detector Controlled Active Rectifier

The basic principle of SSHI circuit is its capability to flip the charge on the internal capacitor through an LC resonant circuit [4], however for low frequency operation a very large inductor is required. A synchronized switch harvesting-on-capacitor (SSHC) system eliminates the use of an inductor allowing the voltage discharge of the internal capacitor C_P, shown in Fig. 2. To present the performance improvement of piezoelectric harvesters, the following figure of merit (*FOM*) is used

$$FOM = \frac{P_{REC}}{(C_P . V_{REC}{}^2 . f)} \tag{5}$$

Where P_{REC}, C_P, V_{REC}, and f are the rectifier output, parasitic capacitance, voltage output and the vibration frequency, respectively. The highest reported FOM for energy-extraction capability is 2.7-6.1x higher for SSHC at 92 Hz [5]. The system proposed shown in Fig. 4 is a SSHC with low power dynamic bias latch-type comparators to match the input

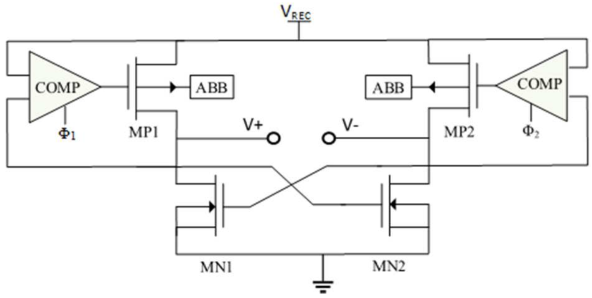


Fig. 4 Proposed SSHC rectifier with PFM control and ABB.

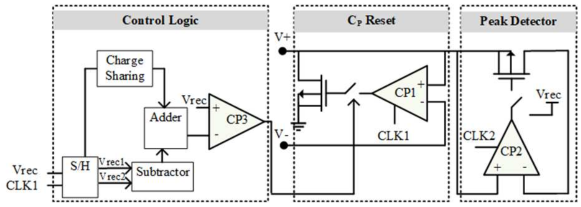


Fig. 5 Proposed MPPT using fractional open-circuit voltage with the waveform.

frequency with the regulation switching frequency in the active rectifier. The PFM consists of an analog hysteresis control Φ_1 and Φ_2 for the ultra-low power comparators. When the load is large, the frequency of switching pulses increases, and when the load is reduced, the frequency is reduced correspondingly. The control is adapted to change the on-time switching frequency, as well as the switch size modulations [6]; also used in this design. The combination of the SSHC with an active rectifier and frequency modulation control optimises the rectification at different output loads and requires ultra-low power. The circuit also contains adaptive body biasing (ABB) to ensure that the bulk is always connected to the highest voltage level between (V_+, V_-, and V_{REC}).

C. Maximum Power Point Tracking (MPPT)

MPPT is required as the output voltage depends on the extracted power that is dependent on the input voltage V_{ac}, whose amplitude is set by V_{REC} in the full bridge rectifier (FBR) or H-bridge rectifier (HBR). The short-circuit MPPT configuration also depends on the resistor load R_{load}. In many cases a discontinuous conduction mode is often utilized for resistive loading and adjustments of the switching timing. In [4], an output power evaluation algorithm for perturb & observe (P&O) MPPT, with both power loss of the rectifier and the dc-dc converter can achieve up to 97% tracking efficiency for the MPPT simultaneously. However, the control requires off-chip digital controls solutions that can be power consuming.

MPPT circuits can be categorized into two main branches: 1) open-loop 'Fractional V_{oc}' methods (FOCV) [8] and 2) closed-loop P&O [7] 'hill climbing methods'. In both methods, the MPPT circuit performs the two tasks of sensing and tuning. In a piezoelectric device, the maximum power transfer occurs at the half open-circuit voltage (V_{oc}/2) of the PEHs with full bridge rectification. The piezoelectric energy harvesting circuit proposed by Lu et al. [8] uses a time-multiplexing mechanism to alternately perform energy harvesting and MPPT. Shi et al. [9] proposed a vibration energy harvester based on a quasi-MPPT with bidirectional intermittent adjustment, using FOCV to sample the open-circuit voltage of the PEH. Shim et al [7] presented a PEH

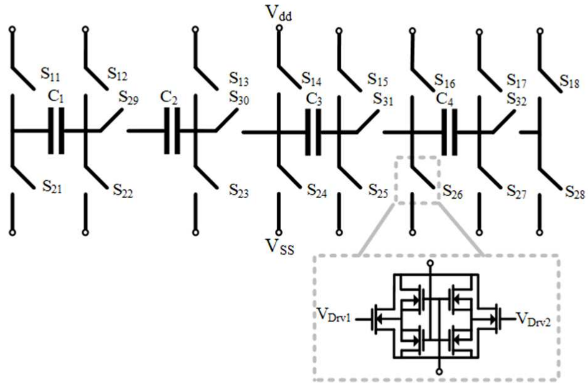


Fig. 6 The 18-Phase switching capacitors with sharing / shorting / recharging phases.

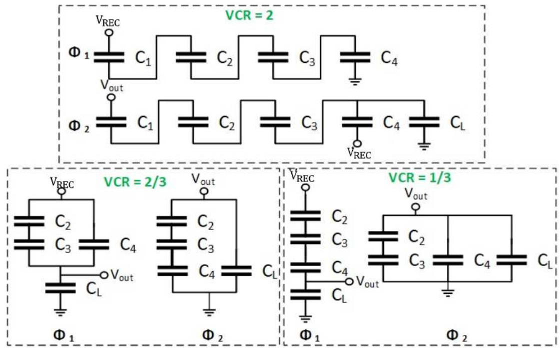


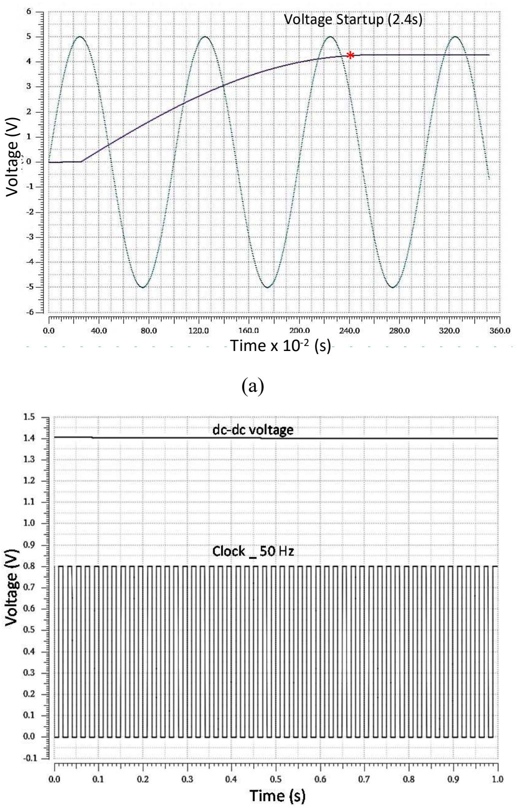
Fig. 7 The buck-boost conversion configurations of the dc-dc converter.

with one-cycle MPP sensing which usually requires a small capacitor to capture the open-circuit voltage within one cycle. Chew and Zhu [10] proposed a novel MPPT technique with a specifically designed high-pass filter, that has a peak output voltage dependent on V_{oc}/2 of the PEH.

The MPPT shown in Fig. 5 employs the FOCV approach that can reduce the voltage stress for SSHC rectifier design when the PEH output voltage is excessive. The system consists of control logic, internal capacitor C_P reset, and a peak detector with dynamic comparators to decrease the overall power consumption. When the internal current I_s is zero, MPPT is enabled and disconnected from the rectifier and dc-dc matrix. The peak detector samples the open circuit voltage, V_{oc}, between the different peaks in the rectifier operation. A power-gating technique is employed to lower the quiescent power further. This system is suitable for ultra-low frequency operation as it charges the C_P with piezoelectric internal current I_s in each cycle.

D. Interface and dc-dc Conversion

Switched inductor circuits (SI) require a large off-chip inductor at low harvested power and frequency levels, which increase the system size. The output power range is limited to 0.54-4 nW and it only operates at minimum 12.8 Hz. The PMU SI in [11] consumes 3.2 nW quiescent power, using asynchronous control to reduce switching power with a power dynamic range limited to 1 μW. However, [11] uses a battery source. Switched capacitor converters are a better solution for fully implantable on-chip converters. However, in nW applications the power efficiency is limited (~87%). For a switch capacitor dc-dc converter, the implemented voltage conversion ratios VCRs are 1/3, 2/3, and 2. A multistep split-merge charge transfer operation can help to reduce the power losses. A four-stage split-merge buck boost converter is



(b)

Fig. 8 Simulated transients of PEH interface circuit: (a) shows the output of the regulating rectifier at 4.2 V and the startup time is at 240 ms. (b) dc-dc converter output at 10 μA input with 30 nF internal capacitor.

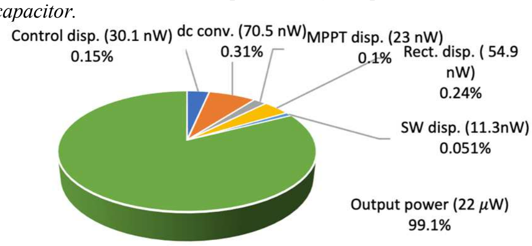


Fig. 9 Power breakdown of the proposed system at frequency of 2 Hz, and voltage output of 1.4 and 4.2 V.

shown in Fig. 6. It improves the overall efficiency and reduces the voltage ripple. Fig. 7 shows the different configurations of the buck boost converter. In VCR = 2 and Φ_1, capacitors $C_{1\text{-}4}$ are connected in series to generate the output during Φ_2. This has less power loss than the parallel-connected $C_{1\text{-}4}$. The value of $C_{1\text{-}4}$ is selected with reference to the flipping time to have the minimum voltage drop. The switching is performed at 50-100 Hz frequency.

IV. Simulated Results and Analysis

The proposed circuits were designed in 0.18-μm CMOS technology. The circuits were simulated using Cadence Virtuoso. To simulate the heart activity, the waveforms in Fig. 8 (a) and (b) were simulated using measured outputs of a piezoelectric (MIDE PPA-1021) at an input frequency of 1 Hz when placed on a shaker (ET-132 Labworks Inc.) and connected to a 100 kΩ output load. The generated waveform is around V_{REC} =4.2 V with 2.4 s startup time. The buck-boost conversion produces 1.4 V output voltage with an overall power consumption of 70.5 nW. The energy generated will be stored in the energy storage unit and is used to power the oscillator to drive the dc-dc converter. The power breakdown is shown in Fig. 9. The overall power efficiency of the rectifier usually depends on the voltage flip efficiency of the capacitor. The PFM control in DCM is preferable for light to moderate loads because of their low switching frequencies and their reduced switching losses. Multiple feedback loops are within the system to control the frequency at the rectifier conduction and provide regulation. The power consumption of the proposed PEH interface circuit includes 30.1 nW for the system control dissipation, and 54.9 nW for the active rectifier with the comparators. The design is capable of a cold start without external power. The FOM of the proposed design has 8.2x higher energy extraction capabilities compared to a standard full bridge rectifier.

V. Conclusion

This paper has presented a power management interface that can operate from an in-body energy source using a novel system for in-body harvesting from heartbeats. The system includes an inductor-less approach for power harvesting with a low overall power dissipation of 189.8 nW. The research focuses on advancement in the design of in-body power supplies for future deep-tissue implantation.

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