Reconfigurable System for Electromagnetic Energy Harvesting With Inherent Activity Sensing Capabilities for Wearable Technology

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***Abstract*—This brief presents a power management system for wearable technology based on a custom made electromagnetic (EM) transducer and a front-end circuit for energy harvesting (EH) and activity sensing. Due to the ac-output nature of the EM transducer, this brief proposes a reconfigurable rectifier that can switch from passive operation to a more power-efficient active topology depending on the available power in the system. The passive mode operates as a negative voltage converter during start-up, while the active configuration is enabled and driven by a control block after the available voltage at an output storage capacitor surpasses 1.8 V. This brief also introduces an activity detection circuit that enables the use of the inherent sensing capabilities of the EM transducer. The combination of both, a reconfigurable rectifier and an activity detection circuit, allows the system to gather information similar to that of an accelerometer regarding the activity of the user, but at net-zero power consumption and lower cost. The EH front-end described in this brief was implemented in a 130 nm CMOS process with an area of 0.0254 mm^2. Measurements show that the circuit has a peak power conversion efficiency of 92.04%, while the power management system can extend the battery's charge of a Fitbit Charge HR by four hours for every 30 effective minutes of a sprint interval training routine.**

***Index Terms*—Activity sensing, electromagnetic transducer, energy harvesting, human-motion sensing, wearable technology.**

I. Introduction

Wearable technology is a dynamic and growing industry that is increasingly offering popular insights about the users well-being [1] as exemplified by health monitors [2]. Activity trackers, specifically, have two important characteristics: first, their limited set of features, makes them one of the most power efficient consumer electronics. Second, because these wearables are mainly intended to gauge user's activity, they are very likely to be at the core of high physical movement [3]. These two characteristics make activity-tracking devices a unique candidate for body-motion energy harvesting (EH), which can harness the mechanical energy and recycle it back to the wearable itself, to not only extend their battery life, but to potentially fully power it [4].

Human movement is an attractive substitute for batteries in consumer electronics [5], and a very cost-effective and highly scalable kinetic EH source can be found in electromagnetic (EM) transducers [6]. Such transducers consist of a coil made from a magnetic wire and a magnet assembled to allow its axial back and forth movement throughout the magnetic coil. The motion required to displace the magnet can be found in the natural wrist motion of a person walking or running.

Previous EH systems based on EM transducers for wearables have been reported. In [7], an active-resistance-matching technique allows an improved input matching efficiency, and in [8], an AC/DC chopper was designed to use the self-inductance of the electromagnetic transducer to generate dc power. Other works have explored novel solutions for harvesting power from low-voltages inputs, such as adaptive rectification techniques that can switch between two independent passive and active rectification blocks depending on the available power which have been implemented using discrete-component [9] and integrated on-chip [10], [11]. However, the intrinsic sensing capacity of the EM transducer to provide data regarding the user's activity has been rarely exploited.

This brief presents a system designed to harness energy from body motion while providing sensing capabilities which consist of an end-to-end EH system with inherit activity sensing tailored for wearable devices. The proposed work, shown in Fig. 1, involves the development of a compact EM transducer, a front-end circuit designed for rectification and sensing purposes, a power conversion block based on the Texas Instruments BQ25505 DC-DC converter, and an efficient control block. The rectification stage proposed here, reconfigures from passive to active mode to improve its efficiency by rectifying lower input voltages from the source. A key characteristic of the proposed rectification stage is its ability to completely isolate the EM transducer to the power conversion stage to exclusively use it as a sensor and provide sensing information with proper logic levels to allow a subsequent

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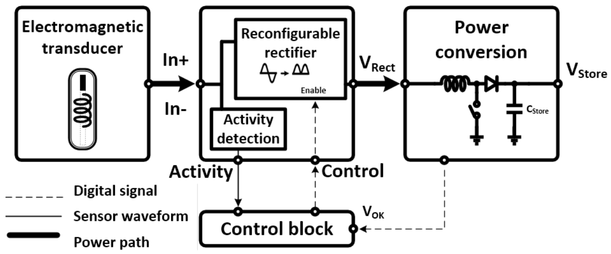

Fig. 1. Top-level system implementation of EH-based system for wearables.

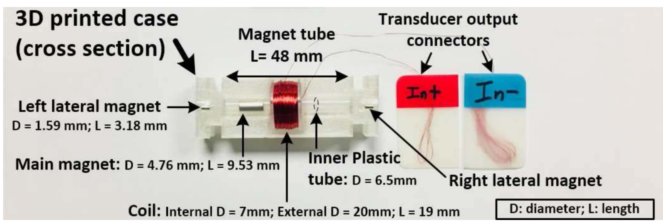

Fig. 2. Electromagnetic transducer structure.

TABLE I
TRANSDUCER SPECIFICATIONS

Specification	Value
DC resistance	61.68 Ω
Inductance	18.7 mH
Peak output voltage	2.5 V
Output power	7m W @ 100 Ω
Magnetic material	Neodymium
Magnetic wire	36 AWG

digital-based data analysis. This digitalized sensor-data, makes this EH and sensing system a good substitute to supplementary sensors to gauge activity, such as an accelerometer or a gyroscope, traditionally needed to determine a user's number of steps or activity intensity.

II. SYSTEM DESIGN

A. Electromagnetic Transducer

The electromagnetic transducer, designed to be worn on the wrist can capture the mechanical energy from movement while walking or running. The design of the transducer follows the analysis presented in [6], with peak power delivered and final dimensions as the main design specifications.

A plastic casing was modeled and 3D printed using acrylonitrile butadiene styrene (ABS) filament to accommodate the different elements of the custom transducer shown in Fig. 2. The relative-axial movement of the main neodymium (NdFeB) magnet, with a diameter of 4.76 mm and length of 9.53 mm produces the magnetic flux linkage that can be harvested by the system when it crosses the 36 AWG magnetic coil. A plastic inner tube placed along the full axial movement of the magnet through the coil, and two lateral magnets placed at the ends of the housing are intended to reduce mechanical friction losses. Due to the low operation frequency of the system (5 Hz) this transducer was modeled according to its specifications listed in Table I.

Acceleration sensors are commonly integrated into wearable devices to perform activities such as step counting. This information is often presented in the form of performance analytics that correlate steps and its intensity to the amount of energy spent by a user during exercising. In Fig. 3, the output waveform of the EM transducer is compared to the information provided by a Bosch BMA280 acceleration sensor. Both waveforms were retrieved when the user moved his hands with both sensors moving together. As it is observed, the EM transducer can be used to gather basic information similar to that provided by an accelerometer.

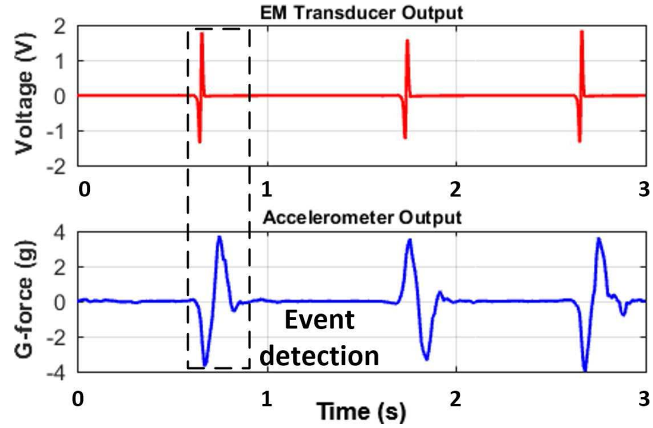

Fig. 3. Electromagnetic transducer waveform output (top) and accelerometer y-axis waveform output (bottom) comparison.

Albeit simple, the information contained in the EM transducer waveform successfully showed the hand movements of the user as compared to an acceleration sensor x-axis output. The simplicity of the information of the kinetic transducer's waveform can be employed to easily determine the number of hand movements and its speed for example. All this information comes from an element that not only no consumes power, but provides energy to the wearable system.

B. Reconfigurable Rectifier

A reconfigurable rectifier is required to convert the AC voltage from the EM transducer to DC. To achieve this, a rectifier topology is proposed that adopts a passive or active rectification configurations depending on the available power in the system as illustrated in Fig. 4.

The passive rectification mode illustrated in Fig. 4(a), is employed when the storage capacitor voltage V_{Store} is less than $1.8V$, no enough energy is stored in the system to power the control circuit for an active rectification stage to operate. Passive rectification is achieved during startup when transmission gates $TG_1 - TG_4$ have a zero voltage on gate, operating as a short circuit, resulting in a standard negative voltage converter (NVC) topology, where the difference in voltage of the EM transducer connected at In+ and In− can enable either M_1 and M_4 or M_2 and M_3 for positive and negative AC input voltage swings, respectively. This NVC circuit presents a rectified signal at V_{Rect} and GND.

When $V_{Store} > 1.8V$, then the active configuration of the rectifier is enabled as presented in Fig. 4(b). Signals V_{OK} and $\overline{V_{OK}}$, provided by the DC-DC converter in the power conversion block, open transmission gates $TG_1 - TG_4$, reconfiguring from an NVC to the active rectification topology where $M_1 - M_4$ are controlled by signals $C_1 - C_4$ through $M_5 - M_8$,

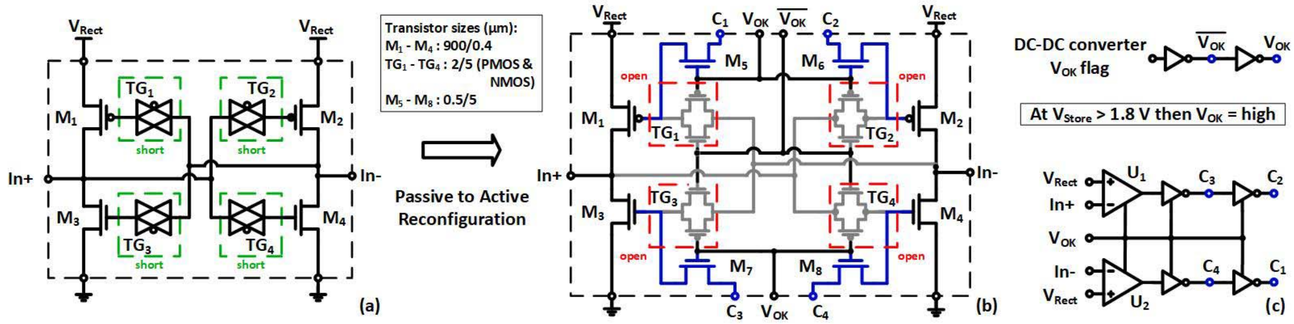

Fig. 4. Reconfigurable rectifier, (a) Passive configuration, (b) Active configuration detailed schematic view and (c) Control circuit sub-block.

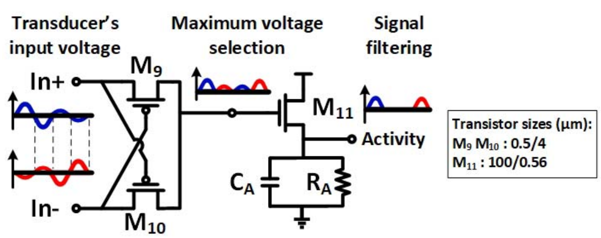

Fig. 5. Activity detection transistor level circuit.

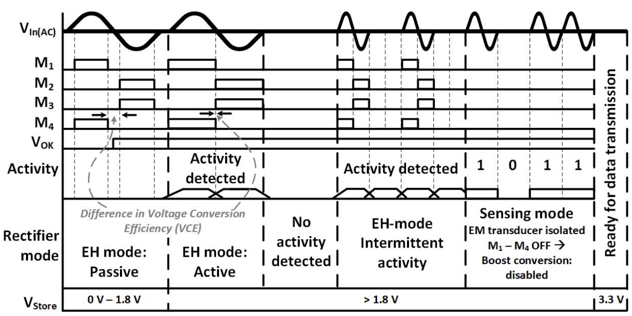

Fig. 6. Energy harvesting system operation time diagram.

instead. This active configuration can rectify low input voltage swings commonly found in low-pace movements, such as walking. This is achieved with two TLV3691 nano-power comparators, referred to as U_1 and U_2 in Fig. 4(c), which enables branches M_1 and M_4 or M_2 and M_3 by comparing the polarity of the EM transducer and V_{Rect}.

An important feature of the active rectification topology is that transistors $M_1 - M_4$ can be turned off to fully isolate the transducer from the power path of the EH system and to enable the system's sensing capabilities. Since sensing is not permanently performed but intermittently performed due to power efficiency restrictions, the EH operations are not affected in a significant way; however, if the application does not require sensing, then EH mode can be enabled permanently.

A minimum length for transistor M1-M4 was avoided to reduce its voltage threshold, while maximum conductive resistance and current specifications were limited to transducers resistance and power available mentioned in Table I.

C. Activity Detection

The activity detection sub-block is shown in Fig. 5. The EM transducer is connected to this block through inputs In+ and In−. Transistors $M_9 - M_{10}$ allows the higher input voltage to be copied at the gate of the transistor M_{11} to provide a rectified sensing signal at the activity node. Lastly, the leak current, represented by R_A, defines the output voltage at no input condition while C_A filters the sensed signal.

The activity detection circuit is connected to the EM transducer in parallel with the input of the reconfigurable rectifier to provide a sensing signal to the system while providing energy to the system. However, the sensed signal is expected to be distorted if the transducer is used for both EH and sensing purposes. To accommodate these dual functions, the system must add the flexibility of choice - to work in either the EH-mode or sensing-mode.

The active-mode rectification can remove the EM transducer from the power path by opening $M_1 - M_4$. By fully isolating the transducer through the rectification stage, it can be used exclusively for sensing operations. Notably, the ability to isolate the EM transducer was designed to provide a cleaner sensing signal and full-rail voltage swings.

D. Power Conversion Block

A Texas Instruments BQ25505 DC-DC converter for low power applications is used to boosts the V_{Rect} to a programmed 3.3 V. This component provides a voltage-okay flag $V_{OK} = high$, when $V_{Store} > 1.8V$, which triggers the active mode of the EH-based wearable system presented here.

III. System Operation

The EH-based wearable system operation diagram is presented in Fig. 6. At the top of the diagram is the input signal from the kinetic transducer, which can be continuous or intermittent depending on the movement provided by the user; thus, signals $M_1 - M_4$ represent the state of the transistors of the rectifier, and V_{OK} determines the passive or active EH-mode. At the same time the activity detector output in the time diagram represents the output node of the activity detection block. The rectifier mode along with the V_{Store} voltage levels are presented at the bottom of the diagram.

Initially, the reconfigurable rectifier starts in its passive mode, where the NVC-like configuration allows a passive AC to DC rectification. The rectified signal is fed to the DC-DC boost converter of the power conversion block.

When the voltage at the output storage capacitor reaches a minimum of 1.8 V, the boost converter sets up the V_{OK} flag

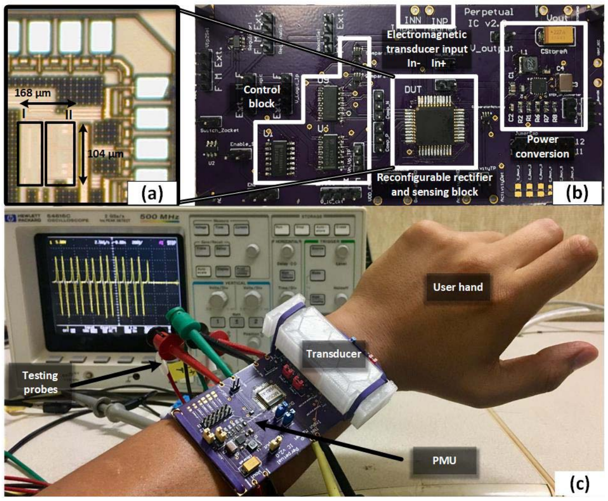

Fig. 7. Proposed power management system, (a) IC micrograph (I. rectifier, II. Activity detector), (b) EH and sensing system printed circuit board and (c) Picture of the measurement setup mounted on the user.

that enables the active mode of the reconfigurable rectifier. If activity is sensed from the transducer, then the operation of the comparators for active rectification is enabled, whereas when no activity is detected, the input of the transducer to the DC-DC converter is disconnected to avoid any possible back-leakage. Any further activity by the user enables the system to restart in the EH-mode. An active rectification allows a lower In+ and In− rectification, as compared to its passive rectification counterpart, associated with low-pace activity, such as walking.

The system also integrates the capability to enter a sensing-mode by turning off transistors $M_1 - M_4$ to isolate the EM transducer from the power conversion stage. The cleaner signal at the output of the activity detector node can reach full logic levels that can be represented as digital values that correlates to the activity from the user. Such digital information can potentially be used to know the number of steps or to determine walking speed if the time between pulses is measured and processed.

The resulting data obtained from the sensing mode can also be stored and transmitted to a larger system for a more comprehensive data analytics using the Bluetooth wireless module already integrated in a commercial wearable device.

Finally, if the output voltage drops below 1.8 V then the system configures as a passive rectifier and the process repeats.

IV. Measurement Results

The energy harvesting front-end was fabricated in a 130 nm TSMC CMOS technology with an active area of 0.0254 mm^2. The IC micrograph, the printed circuit board of the EH system for wearables and the measurement setup is shown in Fig. 7.

Figure 8 presents the passive operation of the circuit. At startup, a brief low pace movement section illustrates the drop in kinetic energy harvested during this period. At 1.8 V the active rectification is enabled. In this transition, a drop in the V_{Rect} amplitude can be appreciated, due to a change to a lower input impedance presented by the front-end circuit because the control circuit allows an improved charge conduction of the rectification transistors $M_1 - M_4$ in the power path, which in turn translates to a higher efficiency. The operation reaches its nominal output voltage at 3.3 V, and the test activity ends.

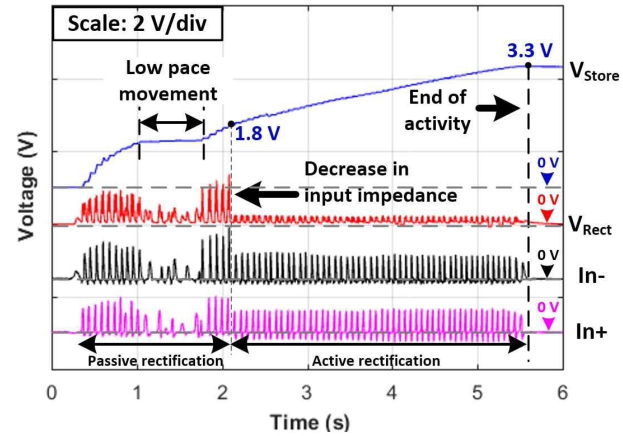

Fig. 8. System operation waveforms: V_{Store} (top) V_{Rect} (bottom).

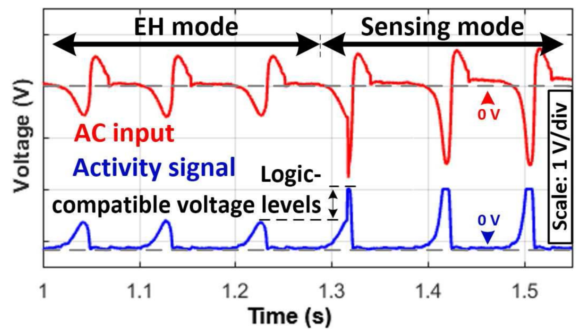

Fig. 9. EH and sensing modes of operation output waveforms for AC input (top) and activity signal (bottom).

The activity detection measurement at the transition of the EH to the sensing mode is presented in Fig. 9. As expected, the isolation of the kinetic transducer to be used solely for sensing can provide digital logic compatible voltage signal levels, this feature not only prevents the signal to be further degraded due to the loading impedance in EH harvesting mode but also provides data of digital levels that can be used to analyze user activity without the need of a power hungry analog to digital converter but a faster and more efficient digital circuit. Applications of this feature include step-count estimation, and the implementation of gestures, which are particular hand movements to control a music player, for example.

Voltage conversion efficiency (VCE) was tested using (1). Measurements showed over 90% efficiency starting at 90 mV for active rectification, whereas a passive rectification configuration shows a VCE over 90% at around 390 mV. As shown in Fig. 10, the VCE remains relatively constant for higher input voltages at 99%.

$$VCE = \frac{\mathrm{V}_{Rect}}{\mathrm{V}_{Input_{(Peak)}}} \tag{1}$$

The power conversion efficiency (PCE), defined in (2), was measured using the setup shown in Fig. 11, where V_{Source} is a 1Hz sine waveform voltage source in series with a test resistance within conditions shown in Table I, and it showed a peak efficiency of 92.4% at 1 V, 32.4 μA load. The power efficiency, presented in Fig. 11, decreases at low R_L because of a reduced

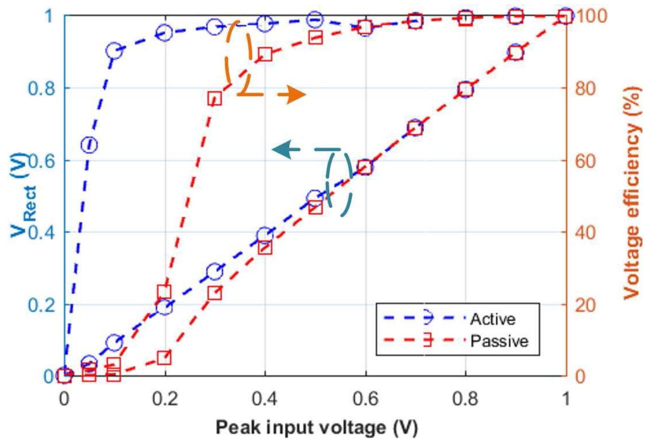

Fig. 10. Measured voltage conversion efficiency output voltage (V) and voltage efficiency (%).

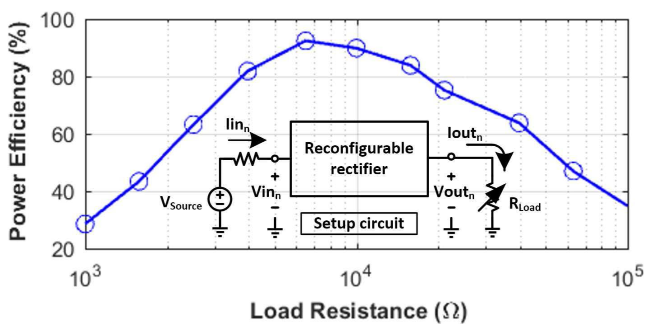

Fig. 11. Measured power conversion efficiency.

TABLE II
COMPARISON TABLE WITH PRIOR ART

Reference	[7]	[8]	[11]	THIS WORK
Transducer	EM	EM	EM	EM
Process	180 nm	130 nm	180 nm	130 nm
Rectifier PCE_{Peak} (%)	97*	89*	86	92.4
Reg. Level (V)	-	-	3.0	3.3
Inherent sensing	No	No	No	Yes

*Simulated

input voltage derives in a lower VCE, as previously presents, which directly and negatively affects the PCE. At a higher R_L, the current consumed by the active rectification comparators becomes more significant compared to the power delivered to the load; consequently, the efficiency is deteriorated.

$$PCE = \frac{1/T \int_0^T v_{out_n} i_{out_n}}{1/T \int_0^T v_{in_n} i_{in_n}} \tag{2}$$

As a proof of concept, the power management system presented here was used to recharge a Fitbit Charge HR commercial wearable. Measurements showed that after 30 minutes of a Sprint Interval Training routine the system was capable of recharging 6.90% of the wearable device using an 80 mAh Li-ion battery or 4.02 hours of extra battery life.

Table II compares the performance of the EH system presented here to other state-of-the-art works [7], [8], [11]. The final figures are based on the energy harvesting transductor results, process, PCE peak power and sensing capabilities.

V. CONCLUSION

In this brief, a reconfigurable energy harvesting power management system with inherent activity sensing capabilities was designed for wearable applications and implemented in a 130 nm CMOS process. A custom-made EM transducer was employed to power the system considering output power density and portability. The AC to DC power conversion is handled by a reconfigurable rectifier operating in a passive-mode configuration during startup, and under a more power efficient active-mode configuration for $V_{Store} > 1.8V$ with a peak 92.4% power conversion efficiency.

This brief introduces an activity detection circuit to exploit the inherent sensing capabilities of the transducer used in the EM-based EH. The combination of the reconfigurable rectifier, the activity detection circuit, and the EM transducer allows the system to gather information similar to that of an accelerometer, traditionally needed to determine the user's number of steps or activity intensity, but at net-zero power consumption and lower cost.

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