EXPERIMENTAL STUDY OF SELF-POWERED ELECTRONIC CIRCUITS FOR PIEZOELECTRIC ENERGY HARVESTING

1Action Nechibvute *, 1Albert Chawanda and 2Pearson Luhanga

1Department of Applied Physics and Telecommunications Midlands State University, P/Bag 9055, Gweru, ZIMBABWE

2Department of Physics, P/Bag 0022, University of Botswana, Gaborone, BOTSWANA

*Corresponding Author: nechibvutea@msu.ac.zw

ABSTRACT

The Recently, there has been growing interest in power conditioning interface circuits used to enhance energy harvesting using piezoelectric devices. Among there interface circuits, the Synchronised Switch Harvesting on Inductor Interfaces (SSHI) and Synchronous Electric Charge Extraction (SECE) are the most promising. In this paper we the results of design and performance characterisation of self-powered SSHI and SECE interface circuits. The self-powered SSHI interface demonstrated a record enhancement of close to 300 % while the self-powered SECE interface shoed an enhancement of 70 % more power relative to the standard energy harvesting (SEH) interface.

KEY WORDS

Alternative energy, mechanical vibrations, piezoelectric, energy harvesting. Wireless sensor node, embedded.

1. Introduction

The most important applications of piezoelectric energy harvesting devices are in wireless sensor networks (WSNs), embedded medical electronics and low power portable electronics [1-7]. In all these targeted applications, the electrical output from the energy harvesting system must be direct current (DC). This means that an interface circuit is needed to convert the alternating electrical output from the piezoelectric transducer into usable DC. Traditionally, the standard energy harvesting (SEH) interface is the most commonly used. The SEH circuit, also called the classic energy harvesting circuit, consists of a full-bridge rectifier for the AC to DC conversion. The SEH interface circuit does not need any control units hence it is easier to implement compared to non-passive interfaces [8, 9]. However, the power harvested using the SEH interface is generally limited in output value and has poor load independence [10]. DC-DC converter circuits for improved impedance matching and voltage regulation have also been investigated in order to improve the output from low-power energy harvesting devices [11-14].

In order to extract more power from piezoelectric generators, nonlinear switching techniques such as synchronous switch harvesting on inductor (SSHI) and synchronous electric charge extraction (SECE) have been employed [15-17]. These synchronised switching techniques are based on the synchronised switch damping on inductor (SSDI) whereby an electrical switch -typically a combination of a digital switch and an inductor- is employed to enable nonlinear power processing. The process artificially increases the piezoelectric transducer output voltage, resulting in a significant increase in the electrical power output [16-18]. The switching device is triggered on the maxima and minima of the displacement, and it briefly realises the inversion of the voltage through an oscillation process. The switching device is fairly complex and is typically an externally powered microcontroller or a dedicated digital signal processing (DSP) unit which is externally powered.

While there many studies reported on the use of SSHI and SECE techniques, the majority of these studies are limited to theoretical simulations and cases where the switching and control circuitry is externally powered [15-21] . There still remain challenges in designing efficient truly self-powered energy harvesting system. Richard et al. [22] have proposed a fully self-powered switching circuit called the electronic breaker whose typical power consumption is less that 5 % of the electrostatic energy available on the piezoelectric transducer [19,20,23]. Recently Zhu et al. [24] investigated the mechanism of the self-powered circuit breaker and also established that the electronic breaker circuit can be taken to be an efficient way for implementing self-powered piezoelectric vibration generators. In the reported power on the self-powered SSHI interfaces, the performance of the self-powered SSHI interfaces is mostly evaluated only under a specified vibrational excitation level [17-21]. The performance of these nonlinear switching interfaces relative to the SEH interfaces is hardly reported in literature. It is against this background that this research seeks to experimentally study the energy harvesting performance of self-powered SSHI and SECE interface circuits.

In this paper a self-powered SSHI and the SECE interface circuits circuit based on the electronic breaker circuit proposed in [24] are experimentally studied. The performance of these circuits relative to the SEH interface is studied under different vibration excitation levels. Section 2 gives an overview of the working principles of the SEH, SSHI and SECE interface circuits. Section 3 introduces the experimental details and procedures employed to study the self-powered SSHI and SECE circuits employing a geometrically optimised piezoelectric bimorph device. Section 4 presents results from experimental measurements. Finally section 5 concludes the paper.

2. Overview of the Self-Powered Circuits.

2.1 Standard Energy Harvesting (SEH) Interface

The electrical voltage generated by piezoelectric transducer device is essentially alternating (AC), yet the electronic devices in many practical applications work on a regulated direct current (DC) voltage. Electrical interface circuits are required to convert the AC signal from the piezoelectric transducer into a usable DC signal compatible with the terminal electrical load. The most common interface circuit consist of a full-wave rectifier and filter capacitor. The standard energy harvesting (SEH) interface, also called the classic interface is the simplest of all power conditioning circuits. The SEH circuit together with the associated energy waveforms is shown in Fig. 1. The standard interface circuit is fully passive, that is it does not need any control and therefore it is easier to implement and as a result is considered to be more reliable compared to non-passive interfaces [28, 29]. As shown in Fig. 1 (a), the piezoelectric element is directly connected to the load RL through a full wave diode bridge rectifier and a smoothing capacitor Cr. The power harvested with the standard interface neglecting the rectifier diode threshold voltage is given by [30]:

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where f0 is the vibration frequency, C is the clamped capacitance of the piezoelectric material, θ is the force-voltage coupling factor and u0 represent the applied displacement.

Fig. 1 (a) Standard energy harvesting (SEH) interface (b) SEH waveforms (c) Power output

Despite the simplicity and popularity of SEH interface circuit, its harvesting capability is difficult to further enhance. From the waveform shown in Fig. 1(b), in the greater part of the cycle mechanical energy is converted to electrical energy and this is represented by the positive power. However, in some intervals, the power is negative indicating that the energy returns from the electrical domain to the mechanical domain. This return phenomenon significantly inhibits the energy conversion efficiency of the standard energy harvesting approach [31].

2.2 Self- Powered SSHI interface Circuit

The electronic circuit breaker circuit (shown in Fig. 2), originally proposed by proposed by Richard et al. [22] has been successfully applied in the design of synchronised switching circuits by previous researchers [17,19-25] self-powered electronic design (see Fig. 2) has]. Liang and Liao [23] also presented an improved analysis of the parallel SSHI self-powered interfaces and proposed an improved circuit.

Fig. 2 : Self-powered electronic breaker circuit [22, 24]

The circuit in Fig. 2 consists of an envelope detector, comparator and switch. The comparator's function is to compare the piezoelectric voltage with that of the envelope voltage on capacitor C1. When envelope voltage is greater and the piezoelectric voltage, the PNP transistor T1 is in non-conducting mode. When the envelope voltage is greater than the threshold voltage, T1 is set into conducting mode. This leads to the NPN transistor T2 being triggered on and the nonlinear processing is initiated. The electronic breaker for switch on minimum displacement operates on a similar principle only that the diodes and switching transistors are of opposite polarities. Fig. 3 shows the complete circuit implementing both the maximum and minimum circuit breakers [24]. It is this self-powered SSHI circuit which is implemented in this experimental study.

Fig. 3: Self-powered parallel SSHI interface [24]

2.2 Self- Powered SECE interface Circuit

The self-powered SECE interface employed in this study is shown in Fig. 4. This self-powered SECE interface circuit was initially proposed and theoretically analysed by Zhu et al [17].

Fig. 4: Self-powered SECE interface (After Zhu [17])

As noted earlier, the piezoelectric element is in open circuit phase most of the time. In this phase, transistors T1 and T2 in the electronic breaker circuit blocked and hence are non-conducting. When the peak displacement of the vibrating structure is reached, the transistors T1 and T2 are now in conducting mode, and results in the charge accumulated on piezoelectric capacitance Cp being transferred into the inductor L through D3 and T2. The energy transfer process is completed when the current through the primary winding of the flyback transformer reaches its maximum value and the voltage across the transformer drops to zero. Unlike the standard transformer whose only function is to coupling energy from the primary to the secondary windings, the flyback transformer also functions to store energy within the air gap.

3. Experimental Procedures and Materials

A geometrically optimised piezoelectric series bimorph device with a proof mass was used as the energy harvesting transducer. The device was fabricated using two PSI-5H4E ceramic patches with nickel-plated electrodes (Piezo Systems Inc, USA) bonded to a stainless steel using conducting epoxy glue (Circuit Works, USA). The piezoelectric patches were electrically connected in series. The total device volume is about 5.5 mm3. Table 1 gives the dimensions of the piezoelectric bimorph beam. The values of electrical components for the self-powered SSHI are given in Table 2 while those for self-powered SECE are shown in Table 3. Fig. 5 shows a photograph of the self-powered SSHI interface circuit on breadboard.

Table 1 Dimensions of the piezoelectric device.

	Dimensions (Thickness x Width x thickness)
Substrate (Stainless Steel)	0.120 mm x 4.0 mm x 28.25 mm
Piezoelectric material (PSI-5H4E)	0.127 mm x 4.0 mm x 9.41 mm
Proof mass-(lead metal)	7.000 mm x 4.0 mm x18.83 mm

(MCU) that is used to control all sensor node activities and performs some local processing. The communications subsystem comprises mainly the RF transceiver with the amplifiers and associated electronics. The RF transceiver enables the wireless module to communicate and transmit the processed sensor data. The power unit (which is usually an on-board battery or an embedded energy harvesting power generator) and external and/or on chip memories are also part of the system.

The total power consumed in the wireless sensor node is the sum of the powers dissipated by the individual subsystems of the sensor electronics. The sensing subsystem consumes 6 % – 20 %; computing subsystem 15 % – 30 %; and the communication subsystem ~ 60 %, of the total consumed power [10]. Table 1 shows the power consumption levels of some commercial wireless sensor devices for WSNs.

The supply voltage of sensor nodes might be achieved by two lithium AA-batteries in series, where one AA-battery has a nominal voltage of 1.5 V and an effective capacity of 3000 mAh [11]. Power availability is a critical constraint in wireless sensor devices and power consumption is minimised by optimising the relative amount of time spent in low-power sleep mode and reducing the active mode time. That is, wireless sensor nodes spend most of their time in sleep mode. The only part of the system that stays awake is the real time clock (RTC) and is responsible for keeping the time and waking up the wireless sensor node to measure a sensor input. A fast processing core enables the microprocessing unit to execute the control algorithm very quickly, enabling a rapid return to low-power sleep mode and thereby minimising the power-hungry area under the current consumption curve. With a well-managed power control management and duty-cycling techniques, an ideal wireless sensor node has a power consumption of about 100 µW for a life time operation [12-13].

Li-ion and thin film batteries still dominate energy sources for low power devices. They are generally considered a cheap, convenient and the best solution available in terms of energy density. Replacement, recharging, and environmental disposal of batteries present hazardous and costly challenges [14-16]. Furthermore, the size of the batteries is often larger compared to the devices they are meant to power while at the same time reducing the battery dimensions compromises the power density. For these reasons, alternative solutions to batteries need to be sought, and ambient energy harvesting devices are the potential alternatives. Advances in energy harvesting research together with improvements in node integration will make battery-less infinite-life sensor networks realisable [9].

Table 1 Power consumption of some commercial wireless sensor nodes [17-20].	**Tinynode [17]**	**MICAz [18]**	**Tmote Sky[19]**	**Imote2 [20]**
Sensor node				
Microcontroller	TIMSP430	ATmega128L	TIMSP430	Intel PXA271
RAM memory	10 kB	4 kB	10 kB	256 kB
Flash Memory	48 kB	128 kB	48 kB	32 MB
External/SDRAM	512 kB	512 kB	1024 kB	32 MB
Radio chip	XE1205	CC2420	CC2420	CC2420
Radio frequency	868 MHz	2.4 GHz	2.4 GHz	2.4 GHz
Data Rate	152.3 kbps	250 kbps	250 kbps	250 kbps

Power voltage	2.4~ 3.6 V	2.7~ 3.3V	2.1~ 3.6 V	3.2~ 4.5 V
MCU sleep	6.5 µA	15 µA	5.1 µA	390 µA
MCU on, Radio off	2.1 mA	8mA	1.8 µA	31 mA
MCU on, Radio Tx	27 mA(+0dBm)	25.4 mA(+0dBm)	19.5 mA	66 mA
MCU on, Radio Rx	18 mA	27.7 mA	21.8 mA	66 mA