International Journal of Engineering & Technology
CENTRE OF PROFESSIONAL RESEARCH PUBLICATIONS
ISSN 2049-3444

International Journal of Engineering and Technology Volume 2 No. 6, June, 2012

Piezoelectric Energy Harvesting Using Synchronized Switching Techniques

Action Nechibvute[1], Albert Chawanda[1], Pearson Luhanga [2], Adekunle Rufus Akande[2]
[1]Physics Department, Midlands State University, P/Bag 9055, Gweru, Zimbabwe
[2]Physics Department, University of Botswana, P/Bag 0022, Gaborone, Botswana

ABSTRACT

The application of synchronized switching techniques has significantly enhanced the power harvested from ambient vibrations using piezoelectric devices. In some instances the power increase has been demonstrated to be in the order of ten times the power output compared to the standard energy harvesting approach. In this paper, an up-to-date review of synchronized switching techniques employed in conversion of ambient mechanical energy into useful electrical energy using piezoelectric materials is given. The basic concepts involved in the standard energy harvesting approach and synchronized switch harvesting techniques are presented. A comparative analysis of these techniques is discussed, highlighting the strengths and limitations of each approach in terms of power conversion efficiency, load independence, complexity of implementation, and adaptability for wireless self-powered systems applications. Finally, future trends and research needs that are critical to piezoelectric energy harvesting interface electronics for wireless sensor devices are discussed.

Keywords: *piezoelectric, energy harvesting, energy conversion, synchronized, nonlinear, wireless sensors.*

1. INTRODUCTION

Advances in low power electronics, and wireless sensor networks (WSN) in particular, has driven numerous researches in the field of energy harvesting in the past decade [1]-[3]. WSN technology has gained increasing importance in industrial automation [4]-[5], structural health monitoring [6], healthcare [7], agriculture [8], civil and military applications [9]-[11]. The spatial distributed nature of WSNs often requires that batteries power the individual sensor nodes. One of the major limitations on performance and lifetime of WSNs is the limited capacity of these finite power sources, which must be manually replaced when they are depleted [2]-[3], [12]. Moreover, the embedded nature of some of the sensors and hazardous sensing environment make battery replacement very difficult and costly [13]. To make WSNs more ubiquitous and truly autonomous, it would be ideal if they are self-powered and without human intervention for energy replenishment [3], [11], 14]. To make this feasible, ambient energy from the immediate environment of the sensor is harnessed and converted into usable electrical energy, a process called energy harvesting.

Mechanical vibrations are an attractive ambient source mainly because they are widely available and are ideal for the use of piezoelectric materials, which have the ability to convert mechanical strain energy into electrical energy. Compared to finite energy sources such as batteries, energy harvesting presents a potentially infinite source of energy for powering wireless sensor devices. Furthermore, vibration-based piezoelectric energy harvesting technology has advantages of being clean, stable, and of small size in comparison with solar cells, microfuel cells and microturbine generators. From several review journal articles which have been published in literature [15]-[18], the observation is that piezoelectric energy harvesting is an area of substantial research activity and an enabling technology for self-powered systems and low power electronics.

The power output from piezoelectric energy harvesting devices is in the majority of cases lower than required by low power applications. However the application of novel power management techniques such as duty cycling promises to lower the power consumed by WSNs. Alternatively, the power output of the harvester devices could be increased by developing piezoelectric single crystals with better electromechanical coupling and configurations for optimum power output [19]-[26]. However, lack of industrial process for the growth of such materials makes them quite expensive, especially when targeting low cost embedded self-powered devices [27]. The most promising approach is to design efficient interface circuits used to condition the electrical energy for load compatibility [28]-[32]. Synchronized Switch Harvesting (SSH) techniques are the latest and most promising approach employed in the design of nonlinear energy harvesting circuits to artificially enhance the conversion abilities of piezoelectric materials [33]-[37].

The purpose of this paper is to provide an up-to-date review of synchronized switch harvesting interfaces and their most popular variants proposed in literature. The paper is organized as follows: Section II briefly outlines the modeling and configuration of piezoelectric energy harvesting system, highlighting the main principles of nonlinear switching and sequence of energy conversion. Section III recalls the standard energy harvesting interface circuit together with the background and principle of SSH techniques. Section IV presents concise overview of the main synchronized switch harvesting techniques and their variants. Section V is a brief presentation of the performance comparison of the different switching techniques. Finally, Section VI concludes the paper with a discussion of research needs that are critical for the piezoelectric energy harvesting electronics.

2. MODELING AND CONFIGURATION OF PIEZOELECTRIC SYSTEM

The most common energy harvesting systems are resonant cantilever structures (unimorph or bimorph cantilevers). Such structures are popular because they enable relatively high stress levels on the piezoelectric material while minimizing the dimensions of the devices [19]-[32]. Fig. 1 shows such a system composed of a piezoelectric patch which is bonded to the host cantilever beam surface, which is under alternating deformation. When the beam is excited by mechanical vibration in the host structure, a large strain is induced in the piezoelectric and an alternating voltage is generated between the electrodes. The piezoelectric equations for the system are given by (1) which defines the direct piezoelectric effect and (2) which represents the converse piezoelectric effect ([15], [24],[40], [42]):

$$D_3 = e_{31}S_1 + \varepsilon_{33}^{S}E_3 \qquad (1)$$

$$T_1 = c_{11}^{E}S_1 - e_{13}E_3 \qquad (2)$$

Here, subscript ‘1’ refers to the x-axis (defined in the length direction of the beam) and subscript ‘3’ refers to the z-axis (defined in the thickness direction of the beam). The variables D, E, S and T are the electric displacement, electric field, strain, and stress respectively. The constants e, ε and c are the piezoelectric constant, dielectric constant, and stiffness respectively.

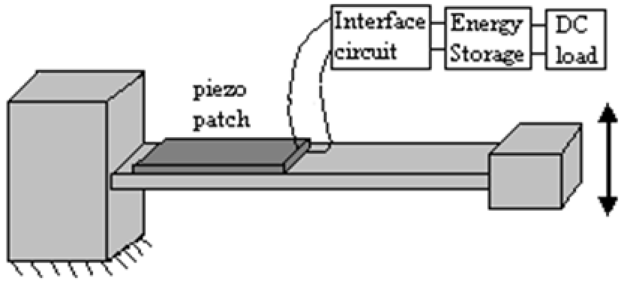

Fig. 1: A typical cantilevered piezoelectric energy harvesting system [41]

The mechanical energy in the host structure is converted to electromechanical energy in the smart piezoelectric material. Alternating electrical energy is outputted from the vibrating piezoelectric and is fed into the interface circuit for conditioning or further processing. It is very important to note that the presence of backward coupling means that the process of extracting electrical energy from the vibrating piezoelectric material significantly alters the amount of mechanical energy available for conversion into electricity [43]-[45]. This means that the processes of optimization of electromechanical energy and energy transfer are so dependent on each other and this observation needs to be carefully considered for the design of efficient energy harvesting devices. Fig. 2 is a single degree of freedom model (spring-mass-damper) of the electromechanical system in Fig. 1. The mechanical parameters of the model are: the viscous damper C_V, the structure stiffness K and the dynamic mass M. Eqs. (3) and (4) represent the electromechanical behaviour of the system ([32]-[34], [36], [38]):

$$M\ddot{u} + C_V\dot{u} + Ku = F - \alpha V_P \qquad (3)$$

$$I = \alpha\dot{u} - \dot{C}_0\dot{V}_P \qquad (4)$$

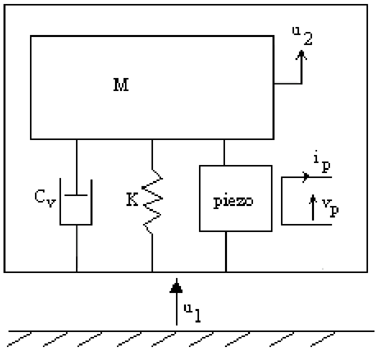

Fig. 2: Spring-mass-damper electromechanical model (note: $u = (u_2\text{-}u_1)$) [32]

where u ($= u_2\text{-}u_1$), F, V_P and I respectively represent the displacement, applied force ,piezoelectric output voltage and current flowing out of the piezo element. α and C_0 stand for the force factor and clamped capacitance of the piezoelectric element.

To have an insight of energy conversion, a simple analysis of the energy flow is important. Multiplying Eq. (3) by the velocity and integrating the resulting product in the time interval [t_0, t] gives the energy equation shown in Eq. (5). Multiplication of Eq. (4) by the voltage and integrating over the same time interval gives another energy equation described by Eq. (6):

$$\frac{1}{2}M[(\dot{u})^2]_{t_0}^{t} + C_V\int_{t_0}^{t}(\dot{u})^2dt + K[u^2]_{t_0}^{t} = \int_{t_0}^{t}F\dot{u}dt - \alpha\int_{t_0}^{t}V_P\dot{u}dt \quad (5)$$

$$\int_{t_0}^{t}V_P I dt - \frac{1}{2}C_0[V_P]_{t_0}^{t} = \alpha\int_{t_0}^{t}V_P\dot{u}\,dt \quad (6)$$

From Eq. (6), it is apparent that the energy conversion is maximized if the forcing factor α is increased. This can be achieved by using a piezoelectric smart material with improved material characteristics. As indicated earlier, this line of research has its own challenges [26]-[27] and is out of scope of this review paper and hence the reader is referred to some of the recent work on single crystal piezoelectric material research found in [46]-[49].

Now consider the speed and voltage approximated by the monochromatic functions given in equations $\dot{u} = \mathrm{u_m}\omega\sin(\omega t)$ and $V_P = V_{Pm}sin(\omega t - \varphi)$ respectively. Here, u_m, V_{Pm} and φ are the peak velocity, peak voltage across piezoelectric element and the phase angle respectively. Using these functions and with $t_0 = 0$ and $t = T = 2\pi/\omega$ the right hand side of Eq. (6) can be reduced to

$$\alpha\int_{t_0}^{t}V_p\,\dot{u}dt = \alpha\int_{0}^{T}V_p\,\dot{u}dt = \frac{\alpha V_{Pm}u_m\omega}{2}cos\varphi \quad (7)$$

Thus energy conversion as described by Eq. (7) can be optimized by maximizing the values of V_{Pm} and setting $\varphi = 0$. In other words, the two ways of enhancing the energy conversion is by increasing the voltage, and reducing the time shift between voltage and velocity to the minimum possible.

3. THE STANDARD INTERFACE AND SYNCHROIZED SWITCH HARVESTING (SSH) TECHNIQUES

3.1 The Standard Energy Harvesting Interface

To understand the strengths of synchronized switching techniques, it is necessary to recall the standard energy harvesting approach and use it as a basis of comparison for the latest interface circuits and techniques. Fig. 3 shows the standard energy harvesting interface circuit which is widely applied in linear processing of harvested power. 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. As shown in Fig. 3(a), the piezoelectric element is directly connected to the load R_L through a full wave diode bridge rectifier and a smoothing capacitor C_r. Despite its simplicity, the harvesting capability of the standard interface circuit is difficult to further enhance. From the power waveform shown in Fig. 3(b), 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 [41]. To improve the energy conversion efficiency, SSH techniques have been proposed and the principle behind their operation is discussed in the next section.

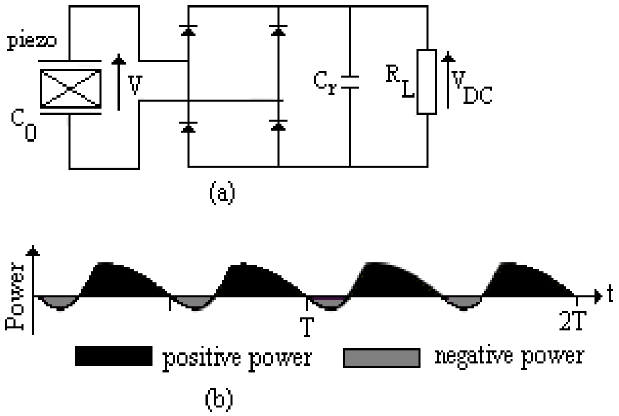

Fig 3: The standard interface and the associated power waveform

3.2 SSH Techniques: Background and Principle

The principles of synchronized switch harvesting were previously developed by Richard et al [38] to address the problem of vibration damping on structures. The synchronized techniques are based on the synchronization between charge extraction from a piezoelectric element and the input vibrations, and makes use of the clamped capacitance of the piezoelectric material to enhance energy conversion efficiency. The SSH techniques basically involve an electrical switch (typically a combination of a digital switch and an inductor) that enables nonlinear power processing. The process artificially increases the piezoelectric transducer output voltage, resulting in a significant increase in the electrical power output. The switch device is triggered on the maxima and minima of the displacement, and it briefly realizes the inversion of the voltage through an oscillation process. The nonlinear approach adopted in the synchronized switching techniques has been demonstrated to substantially enhance the power harvested using piezoelectric devices and in some instances, the power increase is up to ten times the power output compared to the standard rectifier interface circuit [34]-[39]. Techniques of performing this voltage inversion and hence enhancement of energy conversion are outlined in the next sections

4. SYNCHRONIZED SWITCHING TECHNIQUES

4.1 Synchronized Switch Harvesting on Inductor (SSHI) and its Variants

The technique is a way of processing the voltage delivered by the piezoelectric harvesting device in a non-linear manner, such as to take advantage of the mechanical position (displacement) of the generator in order to boost the power output of the device. The technique can be implemented as parallel SSHI or as series SSHI

4.1.1 Parallel SSHI

The technique is implemented with a switched inductor connected in parallel with the capacitance of the piezoelectric harvesting device, as shown in Fig. 4. The time t_1 represents the time for the maximum displacement and t_2 the time for minimum displacement of the piezoelectric transducer. The switch is closed at times t_1 and t_2 allowing the inductor (L) and the capacitance of the piezoelectric generator (C_0) to form an oscillator with a frequency given by $f = 1/(2\pi\sqrt{(LC_0})$). The value of the inductor L is chosen such that the oscillator frequency is much higher than the generator vibration frequency. This has the advantage that the technique does not require a large-value inductor, and thus the circuit can remain small-scale. After a half-period of the LC oscillator the polarity of the charge on the generator has been reversed, and the switch is then opened. The three main steps involved in the conversion and harvesting process are: **(1)** Open-circuit phase, **(2)** Harvesting phase and, **(3)** Inversion phase. The overall effect of these processes is that the generator voltage is always increasing, as can be seen in the waveforms in Fig. 4(b).

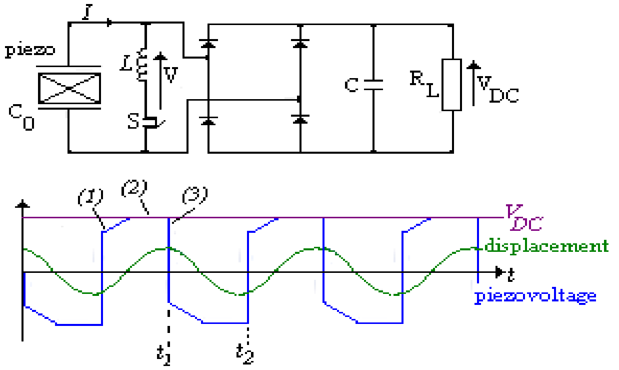

Fig. 4: The parallel SSHI concept and the resultant waveforms [33]

4.1.2 Series SSHI

Unlike the parallel SSHI technique, the harvesting process with the series SSHI occurs at the same time as the inversion process. A shown in Fig. 5, there are two steps in the operation of the series SSHI: (1) Open-circuit phase, and (2) Harvesting and inversion phase. Compared to the parallel SSHI, the parallel SHHI produces slightly more power. However, the series SSHI may have more adaptability in electronic devices whose input impedance is less than that set by the dielectric behaviour of the piezoelectric element.

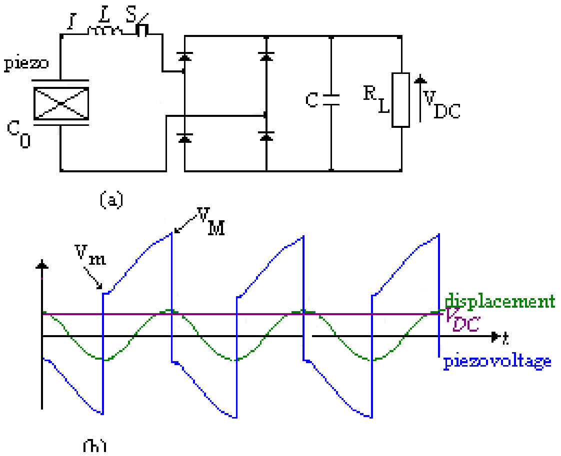

Fig. 5: (a) Series SSHI and (b) Series SSHI waveforms [50-52]

4.1.3 SSHI-MR

The Synchronized Switch Harvesting on Inductor using Magnetic Rectifier (SSHI-MR) is a technique that has evolved from the original series SSHI by replacing the switching inductor by a transformer (Fig. 6). Thus the SSHI-MR is suitable for low output voltage levels since it can allow artificial change in the load seen by the piezoelectric element by manipulation of the transformer turns ratio. While the SSHI-MR does not practically enhance power output relative to the standard SSHI approach, it nevertheless increases load flexibility in the design of low power electronics for energy harvesting systems that are otherwise sensitive to load matching.

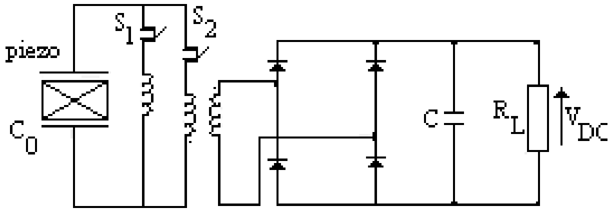

Fig. 6: The SSHI-MR circuit implementation

4.1.4 Hybrid SSHI

The hybrid SSHI circuit is principally a result of combination of the parallel SSHI and the SSHI-MR approaches (Fig. 7). This allows for harvesting four times a period both during inversion and conduction of the rectifier. This is in contrast with two harvesting times for the previous individually implemented approaches.

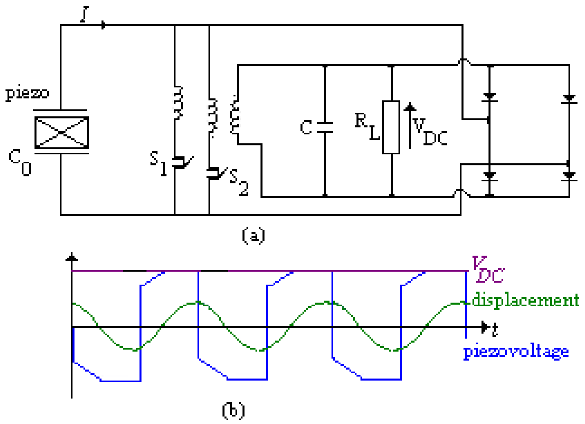

Fig. 7: (a) Hybrid SSHI (b) Hybrid SSHI waveforms [33,51]

4.1.5 SSDCI

The Synchronized Switching and Discharging to a storage Capacitor through an Inductor (SSDCI) is another technique which also evolved from the standard series SSHI. It involves the transfer of electrostatic energy available on the piezoelectric element on to a storage capacitor through an inductor (see Fig. 8). However, the switching process is naturally stopped by a diode bridge rectifier when the piezovoltage equals zero. At this instant there is still energy in the inductance, which is then transferred to the storage capacitor. However, for high load values (high rectified voltage), the piezoelectric voltage does not reach zero, and the circuit performs in a similar fashion to the series SSHI. Such an approach therefore permits harvesting four times more energy than the standard case over a wide load range.

4.2 Synchronized Charge Extraction and its Close Variants

4.2.1 Synchronous Electric Charge Extraction (SECE)

In the SECE approach, the inductance is used as an energy storage element. The SECE energy harvesting process is performed in two steps. During the first step the energy available on the piezoelectric element is transferred to the inductance. Then, the piezoelectric element is disconnected from the circuit, and the energy stored on the inductor is transferred to the storage capacitor (Fig. 9). Hence the SECE technique can be considered to be a load decoupling interface since it prevents the direct connection of the piezoelectric element to the load, and thus leads to a harvested energy independent of the connected system. Other than being an effective load decoupling interface, the SECE permits a gain of four times in terms of harvested energy compared to the standard/classical approach. However, the operation of the SECE technique is mechanically equivalent to the Synchronized Switch Damping on Short-circuit (SSDC) technique [51]. A variant technique, Double Synchronized Switch Harvesting (DSSH) has been evolved in order to control the trade-off between the energy extraction and damping effect

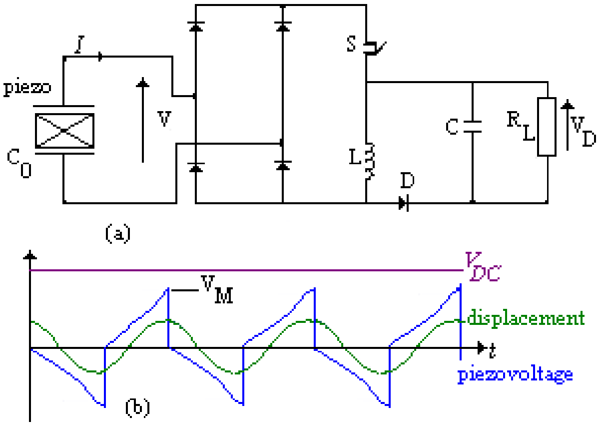

Fig. 9: (a) SECE technique (b) SECE waveforms

4.2.2 DSSH and ESSH Techniques

The DSSH technique is a result of combining the series SSHI and the SECE techniques (Fig. 10). The DSSH technique consists of initially transferring part of the electrostatic energy on the piezoelectric element to an intermediate capacitor and using the remaining energy for the inversion process, and then transferring the energy on the intermediate capacitor to an inductance. Finally the energy on the inductor is transferred to a storage capacitor. By carefully choosing the ratio of the intermediate capacitor to the clamped capacitance of the piezoelectric element, the DSSH technique permits the control of the extracted energy. For a constant displacement of the piezoelectric transducer, it can be demonstrated that the DSSH approach output energy is six times that delivered by the standard interface. As demonstrated by Lallart *et al* [53], the DSSH technique ensures an optimal harvested power irrespective of the value of the load connected to the piezoelectric microgenerator. However, the DSSH developed by Lallart et al [53] employed an externally powered DSpace interface connected to a personal computer. In other words, the DSSH approach reported is not a self-powered version of the switching approach and hence not adaptable for truly autonomous devices. To overcome these challenges, a new technique called *Enhanced Synchronized Switch harvesting (ESSH*) has been proposed. The ESSH is a further enhancement to the DSSH technique achieved by leaving a small amount of energy on the intermediate capacitor , which allows a finer control of the trade-offs between energy extraction and voltage increase, and between extracted energy and damping effect [51]. In addition, the ESSH approach also permits a lower sensitivity to a mismatch in the capacitance ratio [51]. Shen *et al* [54] reported a piezoelectric energy harvesting system based on the ESSH technique and demonstrated that the ESSH technique can result in a system that is truly self-powered (see Fig. 11).

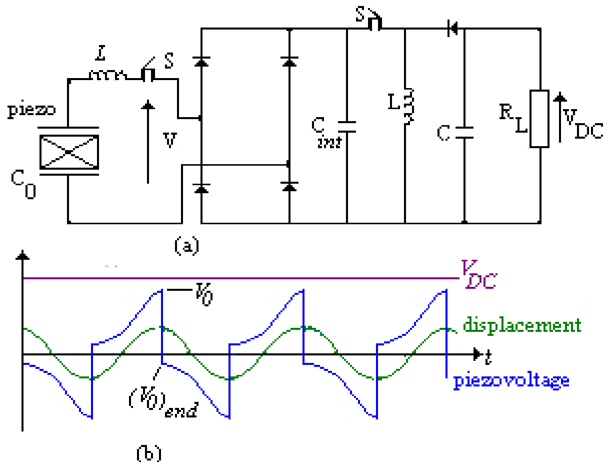

Fig. 10: (a) The DSSH technique (b) DSSH waveforms

Fig. 11: PCB prototype of a self-powered energy harvesting circuit based on ESSH technique [54]

5. PERFORMANCE COMPARISON OF SWITCHING TECHNIQUES

This section summarizes the main strengths and drawbacks of the SSH techniques. Table 1 gives the expressions for the optimum values of the standard interface and several SSHI techniques. Table 2 also gives a comparison of SSH techniques. As shown in Table 2 under the normalized power under constant vibration, it is clear that SSH techniques can significantly enhance the harvested energy as compared to the standard energy harvesting interface. It may be important to note that the series SSHI technique can be implemented with the rectifier diodes removed [55]. The resultant diodeless SSHI allows a great reduction in limitations imposed by discrete electronic components, particularly the voltage gap of the diodes. It has been demonstrated that SSHI techniques cause a significant increase of the electromechanical conversion process, without and with the consideration of electrical losses (i.e., considering either the extracted energy or the harvested energy) [55]-[56].

Table 1: Optimum values for the standard interface and SSHI Techniques

(Note: α-force factor, γ-inversion coefficient,f_0-frequency of operation,C_0-capacitance of piezoelement,V_D-threshold voltage of rectifier diode, *m*-coupling factor, and U_M vibration amplitude)

Technique	**Optimum resistance, R_{opt}**	**Optimum Voltage,$V_{DC_{opt}}$**	**Maximum power,P_{max}**
Standard	$\frac{1}{4f_0C_0}$	$\frac{\propto U_M - 2C_0V_D}{2C_0}$	$\frac{f_0}{C_0}(\propto U_M - 2C_0V_D)^2$
Series SSHI	$\frac{(1-\gamma)}{4f_0C_0(1+\gamma)}$	$\frac{\propto U_M - 2C_0V_D}{2C_0}$	$\frac{f_0}{C_0}\frac{(1-\gamma)}{(1+\gamma)}(\propto U_M - 2C_0V_D)^2$
Parallel SSHI	$\frac{1}{2f_0C_0(1-\gamma)}$	$\frac{\propto U_M - 2C_0V_D}{C_0(1-\gamma)}$	$\frac{f_0}{C_0}\frac{2}{1-\gamma}(\propto U_M - 2C_0V_D)^2$

SSHI-MR	$m^2 \dfrac{(1-\gamma)}{4f_0C_0(1+\gamma)}$	$\dfrac{\propto U_M - 2C_0\dfrac{V_D}{m}}{2C_0}$	$\frac{f_0}{C_0}\frac{(1-\gamma)}{(1+\gamma)}\left(\propto U_M - 2C_0\frac{V_D}{m}\right)^2$

Table 2: Comparison of Energy Harvesting Switching Techniques

	Normalized power (a.u) under constant vibration amplitude	How is the energy harvested under low electromechanical coupling regime?	How is load independence?	How is low voltage harvesting?	Implementation complexity?
Standard	1	poor	poor	poor	none
Series SSHI (diodeless)	9	good	poor	good	low
Parallel SSHI	10	good	poor	poor	low
Hybrid SSHI	9-10	good	good	good	low
SSDCI	4	good	good	good	low
SECE	4	good	poor	good	medium
DSSH/ ESSH	7	Very good	Very good	good	medium

6. CONCLUSION AND FUTURE RESEARCH NEEDS FOR PIEZOELECTRIC ENERGY HARVESTING ELECTRONICS

The paper has reviewed the main synchronized switching techniques which are used to enhance the power harvested from mechanical vibrations. The principles behind each technique have been presented together with the interface circuits. While the application of synchronized switching techniques has significantly increased the power harvested using piezoelectric generators, the energy losses in the switching elements cannot be neglected. Specifically, the losses in switching inductors reduce the voltage inversion efficiency in nonlinear interface schemes and this is the main challenge in the design of energy harvesting interface circuits. To overcome such losses, a novel technique called, the *active energy harvesting scheme*, which employs an Ericsson thermodynamic cycle may be adapted since it has been demonstrated that its inversion efficiency is the highest recorded to date [56]-[57]. In this promising technique, the switching process involves an assisted voltage inversion through the use of an inverter, employing pulse-width modulation (PWM) approaches [57]. However, there is need for further research to minimize the external energy required for driving the PWM commands without compromising the operations of the resultant interface circuit.

The design of energy harvesting systems entails the incorporation of the best material properties of the transducer material, mechanical optimization of the generator and an efficient interface circuit for power processing. Future research in the application of SSH techniques and their integration in Microsystems need further investigation to ascertain their level of implementability in MEMS.

The main challenge in harvesting ambient mechanical energy with microscale energy harvesting devices is conditioning and transferring energy and synchronizing the system to vibrations without dissipating considerable power in the process. Small-scale piezoelectric micro-generators produce little power, losing considerable portion to otherwise negligible conduction, switching, and quiescent losses, even if functional blocks operate only a fraction of the vibration period within a nanoampere current regime [58]. Even with carefully designed synchronized switching interfaces and energy conditioning electronics, the energy harvested by piezoelectric devices is typically below a miliwatt due to the energy consumption of the currently available control circuits. This calls for control circuits which consume extremely low power to be implemented in the power processing electronics of piezoelectric energy harvesting systems.

Nevertheless, a net continuous power output of a few microwatts is enough to charge a micro-battery to supplement the energy needs of a microsensor. After all, the primary goal may not necessarily be to replace the battery completely, but to supplement the system with enough power over time to significantly extend its operational life. The development and realization of wireless microsensor systems powered by piezoelectric energy harvesting devices requires tight power management algorithms to implement duty-cycling requirements and an extremely energy efficient design paradigm [59]. Furthermore, harvesting–aware power management present an added challenge of determining the optimal duty cycle for a microsensor node at a given point in time requires information about the harvested energy availability in the future . This challenge may be overcome by learning the daily energy generation profile for the piezoelectric harvesting device and use this profile data to predict the ambient energy availability for the near future. Since wireless sensor networks operate on a strict power budget, ultra-low power microcontroller units (MCU) are required for processing and power management. A typical MCU like the Texas instruments MSP430 is ideal for energy harvesting since it has a low standby current of less than 1µA and low active current 160µA/MHz ,and quick wakeup time of less than 1µs, and operate on the range 1.8V to 3.6V [60]. Research and development of efficient energy harvester devices, together with ultra-low power MCU and novel storage elements is likely to result in self-sustained wireless sensor networks.

REFERENCES

[1] G.K. Ottman, H.F. Hofmann, A.C. Bhatt, and G.A. Lesieutre,‘‘Adaptive Piezoelectric Energy Harvesting Circuit for Wireless Remote Power Supply, “*IEEE Trans. Power Electron.*, vol.17,no. 5, pp.669–676, Sep. 2002.

[2] S. Roundy, P.W. Wright, and J. Rabaey, “A study of low level vibrations as a power source for wireless sensor nodes”. *Comput. Commun.*, vol. 26, pp.1131-1144,2003

[3] X. Jiang, J. Polastre and D. Culler, “Perpetual environmentally powered sensor networks” in *IEEE Information Processing in Sensor Networks*, 2005, pp. 463–468.

[4] D. Christin ,P. S. Mogre and M. Hollick, “Survey on Wireless Sensor Network Technologies for Industrial Automation: The Security and Quality of Service Perspectives”, *Future Internet* 2010, vol.2,no. 2,pp. 96-125,2010.

[5] J. Chen, X. Cao, P. Cheng, Y. Xiao, and Y. Sun, “Distributed Collaborative Control for Industrial Automation with Wireless Sensor and Actuator Networks”, *IEEE Trans. on Industrial Electronics*, vol. 57, no. 12,pp. 4219-4230, Dec.2010

[6] G. Park, T. Rosing, M. D. Todd, C. R. Farrar, and W. Hodgkiss, “Energy Harvesting for Structural Health Monitoring Sensor Networks”, J. Infrastruct. Syst. vol. 14, no. 64. pp. 1076-0342,2008.

[7] J.-G. Ko, C. Lu, M.B. Srivastava, J.A. Stankovic, A. Terzis, and M. Welsh, “Wireless Sensor Networks for Healthcare”,*Proc. of the IEEE*, vol. 98, no. 11, pp. 1947-1960,Nov. 2010.

[8] L. R-Garcia , L. Lunadei , P. Barreiro and J. I. Robla, “A Review of Wireless Sensor Technologies and Applications in Agriculture and Food Industry: State of the Art and Current Trends”, *Sensors* 2009, vol.9, pp. 4728-4750,2009.

[9] W. H. Liao, D. H. Wang and S. L. Huang, “Wireless monitoring of cable tension of cable-stayed bridges using PVDF piezoelectric films”, *J. Intell. Mater. Syst. Struct.* vol. 12, pp. 331–9, 2001.

[10] L. Chalard, D. Helal, L. Verbaere, A. Wellig, and J. Zory, “Wireless sensor networks devices: Overview, issues, state-of-the-art and promising technologies”, *ST Journal of Research*, vol. 4,no. 1,pp.4-8,2007

[11] F.G Carlos, H.I. Pablo, G.H. Joaquin, and A.P. Jesus, “Wireless Sensor Networks and Applications: A survey”, *Inter. Journal of Computer science and network security”*, vol. 7, 2007

[12] M.V Christopher, G. Deepak, and A.G. Barto, “Adaptive control of duty cycling in energy harvesting wireless sensor networks”, *IEEE Comm. Society Conf. on Sensor Mesh Ad-hoc comm. and networks (SECON)*,2007

[13] V Raghunathan, C Schurgers, S Park and M. B. Skrivastava 2002 “Energy-aware wireless microsensor networks”, *IEEE Signal Process. Mag.* vol 19. ,pp. 40–50

[14] C.Y. Chong, and S.P. Kumar, “Sensor Networks: evolution, opportunities and Challenges’, *IEEE Proc.* vol. 91, no. 8, pp. 1247-1256, 2003.

[15] H. A. Sodano, G. Park and D. J. Inman, “A review of power harvesting using piezoelectric materials”,

Shock Vibration Digest vol.36, pp.197–205, May 2004.

[16] S. P. Beeby, M. J. Tudor, and N. M. White, “Energy harvesting vibration sources for microsystems applications,” *Meas. Sci. Technol.*, vol. 17, no. 12, pp. R175–R195, 2006

[17] S. R. Anton and H. A Sodano, “A review of power harvesting using piezoelectric materials (2003–2006)”, Smart Mater. Struct. vol.16, pp.R1–R21,2007.

[18] K. A. Cook-Chennault, N. Thambi and A. M. Sastry, “Powering MEMS portable devices—a review of non-regenerative and regenerative power supply systems with special emphasis on piezoelectric energy harvesting systems”, *Smart Mater. Struct.* vol. 17, 2008.

[19] N. E. duToit, B. L. Wardle, and S. G. Kim, (2005), “Design Considerations for MEMS-Scale Piezoelectric Mechanical Vibration Energy Harvesters”, *Integrated Ferroelectrics* vol.71, pp. 121–160.

[20] C. D. Richards, M. J. Anderson, D. F. Bahr, and R. F. Richards, (2004). Efficiency of Energy Conversion for Devices Containing a Piezoelectric Component, *Journal of Micromechanics and Microengineering*, vol.14, pp.717–721,2004

[21] F. Lu, H. P. Lee, and S. P. Lim, “Modeling and Analysis of Micro Piezoelectric Power Generators for Micro-Electro-Mechanical-Systems Applications”, *Smart Materials and Structures* vol. 13, pp. 57–63, 2004.

[22] S. Roundy, and P. K. Wright, A Piezoelectric Vibration Based Generator for Wireless Electronics, *Smart Materials and Structures* vol.13,pp. 1131–1142, 2004.

[23] H. Kim, Y. Tadesse and S. Priya, “Piezoelectric Energy harvesting”, in Energy Harvesting Technologies. S. Priya and D. J. Inman, Ed. New York, NY: Springer, 2009.

[24] A. Badel, A. Benayad, E.Lefeuvre, L. Lebrun, C. Richard, and D. Guyomar, ‘‘Single Crystals and Nonlinear Process for Outstanding Vibration Powered Electrical Generators, “*IEEE Trans. Ultrason. Ferroelect. Freq. Contr.*”, vol.53, pp.673-684, 2006.

[25] A. Erturk, O. Bilgen, and D.J. Inman, ‘‘Power Generation and Shunt Damping Performance of a Single Crystal Lead Magnesium Niobate-lead Zirconate Titanate Unimorph: Analysis and Experiment,’’ *Appl. Phys. Lett.*,vol. 93, 2008.

[26] C. Sun, L. Qin, F. Li, and Q.-M. Wang ‘‘Piezoelectric Energy Harvesting Using Single Crystal Pb(Mg1/3Nb2/3)O3-xPbTiO3(PMN-PT) Device,’’ *J. Intell. Mater. Syst. Struct.*, vol. 20, pp.559-568,2009.

[27] S.-E. Park, W. Hackenberger, “High performance single crystals, applications and issues”, *Curr. Opin. Solid State Mater. Sci.*, vol.6, pp.11-18,2002

[28] M. J. Guan, and W. H. Liao, “On the Efficiencies of Piezoelectric Energy Harvesting Circuits towards Storage Device Voltages”, *Smart Materials and Structures* vol. 16, pp. 498–505, 2007.

[29] K. D. Ngo, A. Phipps, T. Nishida, J. Lin, and S. Xu, Power Converters for Piezoelectric Energy Extraction, *Proc. ASME International Mechanical Engineering Congress and Exposition*, pp. IMECE2006–14343, 2006.

[30] M. B.Tayahi B. Johnson, M. Holtzman and G. Cadet, “Piezoelectric materials for powering remote sensors”, in *Proc. IEEE 24th Int. Perform.,Comput., Commun. Conf.* pp.383-386,2005.

[31] G. K. Ottman, Hofmann, H. F. and G. A. Lesieutre, Optimized Piezoelectric Energy Harvesting Circuit Using Step-Down Converter in Discontinuous Conduction Mode, *IEEE Trans. Power Electron.*, vol.18, pp. 696–703, 2003.

[32] E. Lefeuvre, G. Sebald,D, Guyomar,M. Lallart and C. Richard, “Materials, structures and power interfaces for efficient piezoelectric energy harvesting”, *J. Electroceram*, vol. 22, pp.171–179,2009.

[33] D. Guyomar, A. Badel, E. Lefeuvre, and C. Richard, “Toward Energy Harvesting Using Active Materials and Conversion Improvement by Nonlinear Processing”, *IEEE Trans. Ultrason., Ferroelectr. Freq. Control*, vol. 52, pp.584–595, Apr.2005.

[34] E. Lefeuvre, A. Badel, C. Richard, L. Petit, D. A. Guyomar, “Comparison between several vibration-powered piezoelectric generators for standalone systems”, *Sens. Actuat. A: Phys.* vol.126, pp. 405-416,2006,

[35] K. Makihara, J. Onoda, T. Miyakawa, “Low energy dissipation electric circuit for energy harvesting”, *Smart Mater. Struct.*, vol.15,pp.1493-1498,2006.

[36] Y.C Shu, I.C Lien, W.J. Wu, “An improved analysis of the SSHI interface in piezoelectric energy harvesting”, *Smart Mater. Struct.*, vol 16. pp. 2253-2264, 2007.

[37] J. Qiu, H. Jiang, H. Ji, K Zhu, “Comparison between four piezoelectric energy harvesting circuits”, *Front. Mech. Eng. China* 2009, vol. 4, pp.153-159,2009.

[38] D. Guyomar, Y. Jayet, L. Petit, E. Lefeuvre, T. Monnier, C. Richard, and M. Lallart, ‘‘Synchronized Switch Harvesting applied to Self-powered Smart Systems:Piezoactive Microgenerators for Autonomous Wireless Transmitters,’’ *Sensor. Actuat. A: Phys*., vol.138, no.1. pp. 151-160, Jul. 2007.

[39] C. Richard, D Guyomar; D. Audigier, and G. Ching, Semi passive damping using continuous switching of a piezoelectric device, *Proceedings of SPIE conference on Smart Struct. Mater. Passive Damping and Isolation*, vol. 3672, pp. 104-111, March 1999.

[40] *IEEE standard on piezoelectricity*, ANSI/IEEE Std. 176-1987.

[41] J. Liang and W-H. Liao, “Energy flow in piezoelectric energy harvesting systems”, *Smart Mater. Struct.*, vol. 20,2011.

[42] S. Roundy, “On the effectiveness of vibration-based energy harvesting”, *J. Intell. Mater. Syst. Struct.*, vol.16,pp. 809-23,2005

[43] A. Erturk and D. J. Inman, “Issues in mathematical modeling of piezoelectric energy harvesters”, *Smart Mater. Struct.*, vol. 17,pp. 065016-1-065016-14,2008.

[44] A. Ertuk and J.D. Inman, “A Distributed Parameter Electromechanical Model for Cantilevered Piezoelectric Energy Harvesters”, *J. Vib. Acoust.* vol. 130, no. 4, August 2008.

[45] Y. Yang and L. Tang, “Equivalent Circuit Modeling of Piezoelectric Energy Harvesters”, *J. Intell. Mater. Struct.*, vol. 20, December 2009.

[46] B. Ren, S. W. Or, F. Wang, X. Zhao, H. Luo, X. Li, Q. Zhang, W. Di, and Y. Zhang, “Piezoelectric Energy Harvesting Based on Shear Mode 0.71Pb($Mg_{1/3}Nb_{2/3}$)O_3-0.29PbTiO_3 Single Crystals”, *IEEE Trans. Ultrason. Ferroelect. Freq. Contr*, vol. 57, no. 6, June 2010

[47] S. E. Moon, S-K. Lee, H-K. Lee, J-W. Lee, Y-S. Yang and J. Kim, “Analysis of Vibration-energy-harvesting Devices based on a Piezoelectric Single Crystal Beam”, *Journal of the Korean Physical Society*, vol. 58, no. 3, pp. 645-649, March 2011.

[48] R. Ambrosio, A. Jimenez, J. Mireles, M. Moreno, K. Monfil and H. Heredia, “Study of Piezoelectric Energy Harvesting System Based on PZT”, *Integrated Ferroelectrics*, vol. 126, no. 1, 2011.

[49] O. Bilgen, M. A. Karami, D. J. Inman and M. I. Friswell. The actuation characterization of cantilevered unimorph beams with single crystal piezoelectric materials, *Smart Mater. Struct*. vol. 20, 2011.

[50] E. Lefeuvre, M. Lallart, C.Richard and D. Guyomar, “Piezoelectric material-based energy harvesting devices: advances of SSH optimization techniques (1999-2009)”, in Piezoelectric Ceramics.

[51] D. Guyomar and M. Lallart, “Nonlinear Conversion Enhancement for Efficient Piezoelectric Electrical Generators, in Ferroelectrics. I. Coondoo, Ed. InTech, pp 258-280, 2010.

[52] M. Lallart and D. Guyomar, “Self-Powered and Low-Power Piezoelectric Vibration Control Using Nonlinear Approaches”, in Vibration Control. M. Lallart, Ed. InTech, pp.265-291, 2010.

[53] M. Lallart, L. Garbuio, L. Petit, C. Richard and D. Guyomar, “Double synchronized switch harvesting (DSSH): a new energy harvesting scheme for efficient energy extraction”, *IEEE Trans. Ultrason. Ferroelectr. Freq. Control* ,vol. 5,pp. 2119–2130,2008

[54] H. Shen, J. Qiu, H. Ji, K. Zhu and M. Balsi, “Enhanced synchronized switch harvesting: a new energy harvesting scheme for efficient energy extraction”, *Smart Mater. Struct.* vol.19, 2010.

[55] D. Guyomar and M. Lallart, “Recent Progress in Piezoelectric Conversion and Energy Harvesting Using Nonlinear Electronic Interfaces and Issues in Small Scale Implementation”, *Micromachines*, vol.2, pp. 274-294,2011.

[56] D. Guyomar, G. L. Sebald, S. Pruvost, M. Lallart,A. Khodayari and C. Richard, “Energy Harvesting from Ambient Vibrations and Heat”, *J. Intell. Mater. Syst. Struct.*, vol. 20, March 2009.

[57] Y. Liu, G. Tian, Y. Wang, J. Lin, Q. Zhang and H. F. Hofmann, “Active Piezoelectric Energy Harvesting: General Principle and Experimental Demonstration”, *J. Intell. Mater. Syst. Struct.*, vol. 20, March 2009.

[58] D. Kwon, G. A. Rincon-Mora, and E. O. Torres, “Harvesting Ambient Kinetic Energy with Switched-Inductor Converters”, *IEEE Trans. On Circuits and*

Systems-I: Regular papers, vol. 58, no. 7, pp.1551 - 1560, July 2011.

[59] A. Kansal, J. Hsu, S. Zahedi, and M. B. Srivastava, “Power management in energy harvesting sensor networks”, *Trans. on Embedded Computing Sys.*, vol.6, no. 4,pp.32, 2007

[60] Texas Instruments, [online]: *http://focus.ti.com/mcu*

AUTHORS PROFILES

Action Nechibvute received a Bsc in Physics and Mathematics from Midlands State University and University of Zimbabwe in 2001. He received an Msc in Physics from the University of Botswana in 2008. He is currently employed as a Lecturer in the Physics Department at Midlands State University where he is pursuing a PhD. in Physics. His research interest is piezoelectric energy harvesting for wireless sensor networks, with special emphasis on low power interface electronics

Albert Chawanda received Bsc(Hons) Physics, Msc Applied Physics from the University of Zimbabwe and PhD in Physics from University of Pretoria. Since 2000 he has been the Executive Dean of the Faculty of Science and Technology at Midlands State University, where he is Associate Professor of Physics. His research interests include areas of solar energy and electronic materials.

Pearson Luhanga received a Bsc in Physics and Mathematics from the University of Malawi in----. He received an Msc and PhD in Physics from the University of Southampton-UK. He has over 35 years of teaching and research experience and is currently employed as Associate Professor of Physics at the University of Botswana. He is also a member of IEEE-USA since 1979 and a member of ISES since 1988.

His research interest includes electronic instrumentation, low power electronic and energy harvesting using smart materials.

Adekunle Rufus Akande received the B.Sc.(Hons) Physics from University of Ibadan- Nigeria, MSc in Physics from Obafemi Awolowo University (formerly University of Ife), Nigeria and the Ph.D. in Physics from the University of Manchester Institute of Science and Technology, Manchester, UK. He is currently a Senior Lecturer in Physics University of Botswana. Dr. Akande is Chartered Physicist and a member of IOP-UK, a member of the Nigeria Institute of Physics and Electrostatic Society of America (ESA). He has published and presented many articles on electrostatics, material science and energy harvesting. He latest research interest includes ferroelectric thin films fabrication using sol-gel technique.