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Optimized Technique for Piezoelectric Harvesting Scheme Using DSSH Technique

Ravi shekhar[1], Dr.E.Vijaykumar[2], Deep Mala[3]
M.Tech, 4th Semester, RKDF Institute of Science & Technology, Bhopal, India
Assistant professor, Electrical Engg. Department, RKDF Institute of Science & Technology, Bhopal,India
Assistant professor, Electrical Engg. Department, RKDF Institute of Science & Technology, Bhopal,India

***Abstract*-This paper presents a new technique of electrical energy generation using mechanically excited piezoelectric materials and a nonlinear process. This technique, called Double synchronized switch harvesting (DSSH), was derived from the synchronized switch damping (SSD), which was a nonlinear technique previously developed to address the problem of vibration damping on mechanical structures. This technique results in a significant increase of the electromechanical conversion capability of piezoelectric materials. An optimized method of harvesting vibrational energy with a piezoelectric element using a dc–dc converter was presented. In this configuration, the converter regulates the power flow from the piezoelectric element to the desired electronic load. Analysis of the converter in discontinuous current conduction mode results in an expression for the duty cycle-power relationship. Using parameters of the mechanical system, the piezoelectric element, and the converter; the "optimal" duty cycle can be determined where the harvested power was maximized for the level of mechanical excitation. . A circuit was proposed which implements this relationship and experimental results show that the converter increases the harvested power by approximately 365% as compared to when the dc–dc converter was not used.**

***Index Terms*- Adaptive control DC–DC Conversion, discontinuous conduction mode, energy harvesting, piezoelectric devices**.

I. INTRODUCTION

The need for a wireless electrical power supply had spurred an interest in piezoelectric energy harvesting, or the extraction of electrical energy using the vibrating piezoelectric device. The piezoelectric effect was a two way process.

Piezoelectric materials that generate electrical energy as charge on application of mechanical force (called direct piezoelectric effect) can also been show as a mechanical strain on application of electric field (called reverse piezoelectric effect).Piezoelectric effect is among the most investigated way of electromechanical conversion in the field of vibrational energy conversion [1] – [2].

The piezoelectric micro generator consists of a piezoelement which acts as a generator. These generators are given the required mechanical stress or force using some sort of mechanical driven or device. The output of piezoelement was connected to the electrical network. The electrical network consists of the energy receiver. Depending of the electromechanical coupling and the nature of the energy receiver, alternating nature of voltage was generated on the piezoelectric element.

A power supply of this type will be suitable for the systems such as an actively tuned vibration absorber [1], a foot powered radio "tag" [2], [3], or a Pico-Radio [4]. Currently, piezoelectric elements are being investigated and searched for this purpose due to their small in size and their nature of non-invasive harvesting method.

A vibrating piezoelectric device are different from a typical electrical power source in that its internal impedance was capacitive in nature rather than inductive, and it can be driven by mechanical vibrational force of varying amplitude and frequency. While there had been some previous approaches to harvest energy with a piezoelectric device [2], [3], [5], [6], there had not been an attempt to develop an adaptive circuit that maximizes power transfer from the piezoelectric device.

Earlier the analysis of the different authors consisting in [7] introduces a piezoelectric element model and develops the analytical expression for the power production characteristics of the model when used in with conjunction to an ac–dc rectifier. Using this relationship, a DSP-controlled, adaptive dc–dc converter is been used to maximize the output power harvested from the piezoelectric device. Result shows that the use of the converter increases the power of the energy storage element. The adaptive control circuit is powered by the prohibited circuit implementation while provide enough power when the single piezoelectric element have low power level for an additional electronic load described herein was to develop an approach that maximizes the power transferred from a vibrating piezoelectric transducer to an electrochemical battery. The paper initially presents a simple model of a piezoelectric transducer. The paper then introduces an adaptive approach to achieving the optimal power flow through the use of a switch-mode dc–dc converter. Finally, the paper presents experimental results that validate the technique.

II.OPTIMAL POWER FLOW OF PIEZOELECTRIC DEVICE

To determine its power flow characteristics, a vibrating piezoelectric element was modeled as a sinusoidal current source I_p (t) in parallel with its internal electrode capacitance C_p. This model will be validated in a later section. The magnitude of the polarization current Ip varies with the mechanical excitation level of the piezoelectric element, but was assumed to be relatively constant regardless of external loading. A vibrating piezoelectric device generates an ac voltage while electrochemical batteries require a dc voltage, hence the first stage needed in an energy harvesting circuit was an ac–dc rectifier connected to the output of the piezoelectric device, as shown in Fig. 1. In the following analysis, the dc filter capacitor C_{rect} was assumed to be large enough so that the output voltage V_{rect} was essentially constant; the load was modeled as a constant current source I_{load}; and the diodes are assumed to exhibit ideal behavior.

The voltage and current waveforms associated with the circuit are shown in Fig. 2. These waveforms can be divided into two intervals. In interval 1, denoted as V_{rect} , the polarization current was charging the electrode capacitance of the piezoelectric element. During this time, all diodes are reverse-biased and no current flows to the output. This condition continues until the magnitude of the piezoelectric voltage V_p (t) was equal to the output voltage V_{rect} . At the end of the commutation interval, interval 2 begins, and output current flows to the capacitor C_{rect} and the load

$$i_o(t) = \begin{Bmatrix} 0 & , \ 0 \le \omega t \le n \\ \frac{C_{rect}}{C_{rect}+C_p} Ip \ |\sin(\omega t)| & , n \le \omega t \le \pi \end{Bmatrix} \quad (1)$$

By assuming Crect >> Cp, the majority of the current will be delivered as output current

$$\frac{C_{rect}}{C_{rect}+C_p} I_p \approx I_p \quad (2)$$

The dc component of io(t)can then be shown to be

$$\left(io(t)\right) = 2\frac{I_p}{\pi} \frac{2V_{rect}\,\omega Cp}{\pi} \quad (3)$$

The output power can be shown to vary with the value of the output voltage V_{rect} as follows

$$\left(i_p(t)\right) = \frac{2V_{rect}}{\pi} \ (\, I_p V_{rect}\,\omega Cp) \quad (4)$$

It can then be shown that the peak output power occurs when or one-half the peak open-circuit voltage of the piezoelectric element (refer Appendix for complete analysis).

$$V_{rect} = \frac{I_p}{2\omega Cp} \quad (5)$$

The step-down converter was a natural choice for this application, where the piezoelectric voltage can be very high and reducing it to a level that was lower was required for the battery and the electronic load. The analysis of the interaction between the piezoelectric element and the step-down converter reveals a simplified control scheme to achieve maximum power flow, allowing the circuit to be self-powering while harvesting enough energy for additional low-power electronic loads

III. ENERGY HARVESTING STUCTURE

The magnitude of the polarization current I_p generated by the piezoelectric transducer, and hence the optimal rectifier voltage may not be constant as it depends upon the vibration level ex- citing the piezoelectric element. This creates the need for flexibility in the circuit, i.e., the ability to adjust the output voltage of the rectifier to achieve maximum power transfer. To facilitate the attainment of the optimal voltage at the output of the rectifier, a dc–dc converter was placed between the rectifier output and the battery as shown in Fig. 3. Typically the controller of such a converter was designed to regulate the output voltage [11]; however, in this circuit the converter will be operated to maximize power flow into the battery. If effective, the piezoelectric element would be at peak power, which corresponds to the output voltage of the rectifier V_{rect} being maintained at its optimal value, approximately one-half the open-circuit voltage, as described previously.

The purpose of this circuit was to maximize the power flowing into the battery. As the battery voltage was essentially constant or changes very slowly, this was equivalent to maximizing the current into the battery, . By sensing this current, the duty cycle can be adjusted to maximize it. A control scheme such as this was general enough to be effective for many dc–dc converter topologies. To illustrate the theoretical principles of maximum power transfer and the control of the converter, a step-down or buck converter will be discussed in this paper. The following analysis reveals that the power flow from the piezoelectric element was maximized at an optimal duty cycle and, as it departs from this optimal value, the output power drops significantly

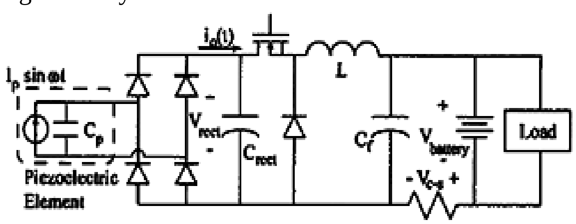


Fig. 1. *Energy Harvesting Circuit*

Where Δ_1 was the time period that the transistor was off and current flows through the free-wheeling diode (4) Can be used to provide an expression for Δ_1

$$\Delta_1 = D^2\left(\frac{v_{in}}{v_{out}} - 1\right) \tag{6}$$

And substituted into (5)

$$I_{out} = D^2 \frac{V_{in}}{2LF_s V_{out}}\left(\frac{V_{in}}{V_{out}}\right) \tag{7}$$

By conservation of power for the converter (assuming losses are minimal); the output current can be expressed as a function of the input voltage and current and output voltage

$$i_{out} = \frac{i_{in} v_{in}}{v_{out}} \tag{8}$$

The input current of the converter can now be determined by Equating (7) and (8)

$$I_{in} = D^2 \frac{V_{in}}{2LF_s}(V_{in}\ V_{out}) \tag{9}$$

Substituting the output current of the piezoelectric device, (1) as the input current to the converter and the rectifier capacitor voltage as the voltage into the converter, (9) becomes

$$\frac{2I_p}{\pi} - \frac{2V_{rect}\omega C_p}{\pi} = \frac{D^2}{2Lf_s}\ (V_{rect} - V_{out}) \tag{10}$$

Solving (10) for the rectifier voltage

$$V_{rect} = \frac{\frac{2I_p}{\pi} + \frac{D2}{2Lf2}V\,out}{\frac{D2}{2Lf} + 2\omega cP/\pi} \tag{11}$$

The input current to the converter can be determined as a function of the duty cycle by substituting (11) into (1)

$$I_{in} = \frac{2I_p}{\pi}\frac{2\omega C_p}{\pi}\left[\frac{\frac{2I_p}{\pi} + \frac{D^2}{2Lf_x}V_{Out}}{\frac{D^2}{2Lf_x} + \frac{2\omega C_p}{\pi}}\right] \tag{12}$$

Power developed by piezoelectric device as regulated by the converter can now be expressed as the product of the rectifier voltage (converter Input voltage) and the input current, (11) and (12)

$$P_{in} = \left(\frac{\frac{2I_p}{\pi} + \frac{D^2}{2Lf_x}V_{Out}}{\frac{D^2}{2Lf_x} + \frac{2\omega C_T}{\pi}}\right)\left(\frac{2I_p}{\pi}\frac{2\omega\,C_p}{\pi}\left[\frac{\frac{2I_p}{\pi} + \frac{D^2}{2Lf_x}V_{out}}{\frac{D^2}{2Lf_x} + \frac{2\omega C_p}{\pi}}\right]\right) \tag{13}$$

The rectifier voltage and power flow from the piezoelectric element as regulated by the step-down converter for any excitation level, as specified by the magnitude of polarization current I_b , can now be determined.

IV. CIRCUIT IMPLEMENTATION

Building upon the relationship between the optimal duty cycle and the mechanical excitation, a dual method of energy harvesting was proposed. At higher excitation levels of the piezoelectric device, when the optimal duty cycle was nearly constant, the step-down converter will operate at the fixed duty cycle. This allows for a simple controller consisting of a fixed-duty cycle pulse-width-modulated signal to drive the switching MOSFET. Because the converter was only operated at high excitations, two advantages are realized: first, the optimal duty cycle was relatively fixed, so operation at the optimal power point was ensured; and secondly, the higher excitations provide sufficient energy to offset converter and control circuitry losses. At lower excitations, the optimal duty cycle was still varying substantially with the excitation, requiring a more complex, adaptive control circuit with higher power consumption. An initial study of the power levels in this range suggests harvesting would be marginal given even the lowest power control circuitry. Therefore, at lower excitations, the battery will be charged by a pulse-charging circuit connected to the piezoelectric element rectifier circuit with the step-down converter bypassed. The threshold level of mechanical excitation that divides these two modes of operation will depend on several criteria: the power produced by the piezoelectric element, the losses of the step-down converter, the power consumption of the control circuitry, and the optimal duty cycle stabilization at higher excitation

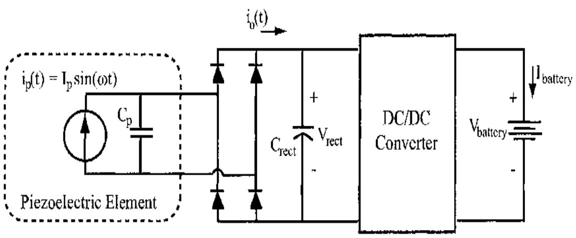


Fig. 2. *Adaptive harvesting circuit with step down converter*

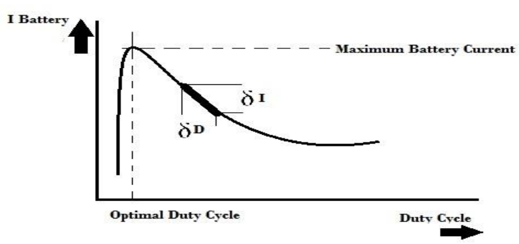


Fig. 3. Steady-State battery current as function to Duty cycle.

The duty cycle was then filtered and used to generate the PWM signal for the driver circuitry of the step-down converter. The additional filtering of the PWM signal was necessary to slow the rate of change of the duty cycle so the change in current can be measured and evaluated. Without the LPF, the controller was prone to duty cycle oscillations, as the perturbing signal reacts faster than the finite settling time of the battery current signal.

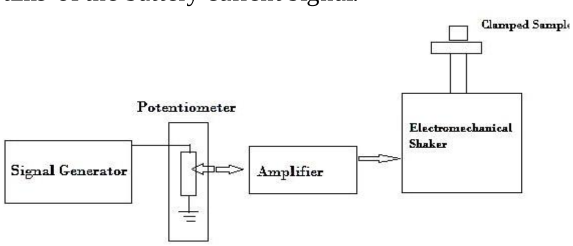


Fig. 4. *Standard Block Diagram*

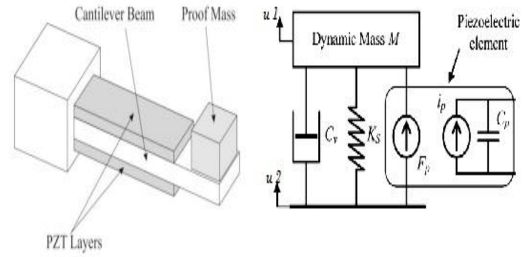
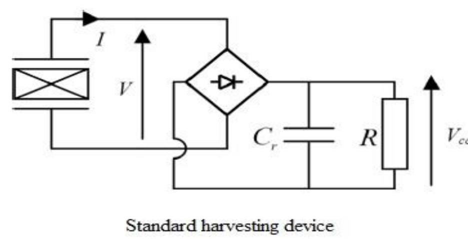


Fig. 5. *Micro generator and its model*



V. RESULT

Data were taken to validate the energy harvesting approach presented in this paper and to demonstrate the operation of the energy harvesting circuitry. For comparison purposes, direct charging of the battery across the rectifier circuit represents a simple, non-optimal method of energy harvesting that was sought to be improved upon. The available power of the rectified piezoelectric element was determined by placing various resistors across the piezoelectric device/rectifier circuit to determine the "optimal" resistance that results in the maximum power dissipation. The first experiment considered was to determine the optimal switching frequency of the converter. Due to the low power levels expected from the piezoelectric element, overall circuit efficiency was greatly affected by frequency dependent loss mechanisms, i.e. controller and gate drive, MOSFET switching, and inductor core losses. Switching frequencies from 0.5 to 50 kHz were considered and the maximum output power for a fixed mechanical excitation of 45.0 V was determined (for each switching frequency the optimal duty cycle was determined).

System losses, including the power consumption of the controller, can be calculated as the difference between the available power and that harvested with the converter.

The efficiency of the step-down converter was between 0 and 70%; the efficiency initially increases

With the excitation due to the lessening proportion of the controller power consumption. At excitations above 50.0 V , the efficiency begins to degrade as the input-output voltage difference across the converter increases. At the highest excitation, the total losses were estimated to be 15.8 mW. At low excitations, below 40 V , the losses account for less than 4.5 mW, indicating that the controller power consumption was less than the estimated value of 5.74 mW. The efficiency where the converter will operate, excitations above 45 V , was about 72%.

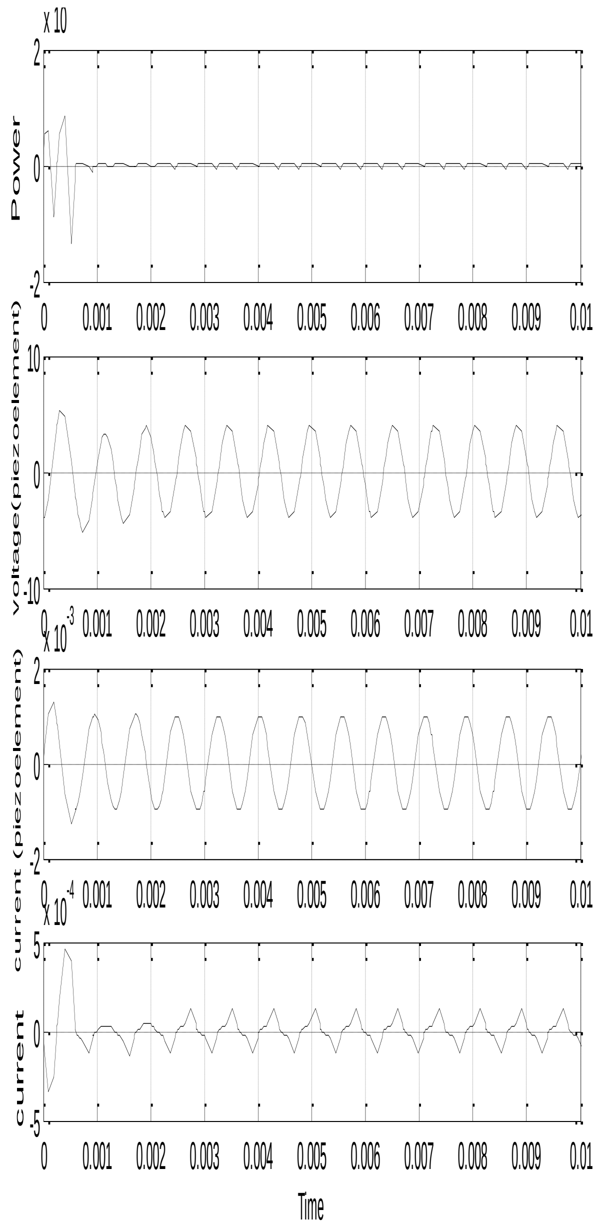


Fig. 6. *Output for Standard Circuit*

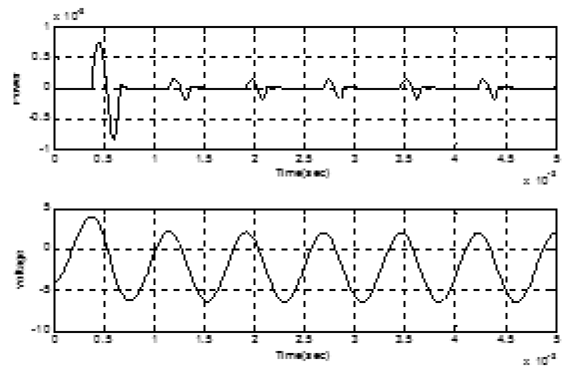


Fig. 7. *Output power and voltage for Standard Circuit before Swirtch*

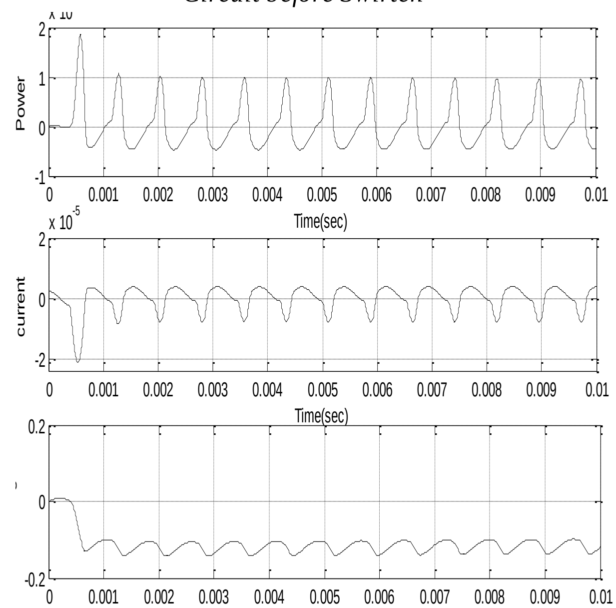


Fig. 8. *Output power and voltage for Standard Circuit before Swirtch*

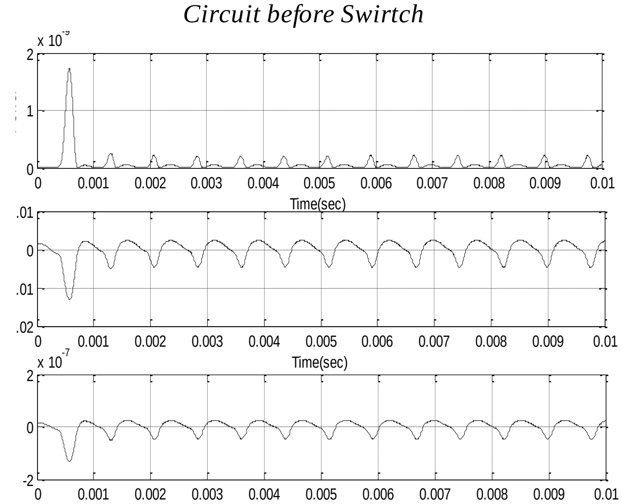


Fig. 9. *Output Power for DSSH circuit.*

VI. CONCLUSION

This paper presents an adaptive approach to harvesting electrical energy from a mechanically excited piezoelectric element. An expression for the optimal duty cycle for a step-down converter operating in discontinuous conduction mode was developed and reveals that, as the level of mechanical excitation was increased, the optimal duty cycle becomes relatively constant. The dc–dc converter with an adaptive control algorithm harvested energy at over four times the rate of direct charging without a converter. Furthermore, this rate was expected to continue to improve at higher excitation levels.

The flexibility of the controller allows the energy harvesting circuit to be used on any vibrating structure, regardless of excitation frequency, provided a piezoelectric element can be attached. Also, external parameters such as device placement, level of mechanical vibrations or type of piezoelectric devices will not affect controller operation. The control algorithm can also be applied to other dc–dc converter topologies. This would allow the development of optimized system designs based upon the expected excitation or the electronic load that was to be powered and because the system was designed to be self-powering, no external power supply was needed, making the system suitable for remote operation. Future work will focus on the design of an optimized system design using standalone control circuitry.

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