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Piezoelectric energy harvester interface with real-time MPPT

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Abstract. Power of resonant piezoelectric harvesters can be severely limited if the damping force cannot be dynamically altered as the mechanical excitation level changes. The single-supply pre-biasing (SSPB) technique enables the Coulomb damping force to be set by a single voltage and so by varying that voltage, real-time adaptation to variations in the mechanical force can be implemented. Similarly the conduction angle of a diode bridge rectifier circuit can be altered by changing the biasing voltage applied. This paper presents a method of achieving this by altering the amount of energy transferred from the pre-biasing capacitor used in SSPB and the diode bridge rectifier to a storage battery via a buck converter. The control system was implemented on a FPGA and consumed 50 μW.

1. Introduction

The proliferation of wireless sensors has seen a dramatic increase with the development of ultra low power electronics and energy scavenging devices. However the capability of these sensors is limited by the variability in the applied mechanical excitation source from which energy is being harvested. This paper presents a complete system, which maximises the power extracted and transfers this to typical coin-cell battery, whilst adapting in real-time to variations in the mechanical excitation source.

Mechanical vibrations can be converted to electrical energy by mechanically stressing piezoelectric material. If we assume the mechanical stress takes a sinusoidal excitation form, the piezoelectric material will induce a sinusoidal output voltage. This voltage must be rectified before transferring to an energy storage device (e.g. battery [1]).

The simplest method of achieving this is through use of bridge rectifier circuit (Figure 1(a)). Maximum power extraction for the bridge rectifier technique (1) is achieved by setting the storage device voltage to an optimal value [2].

$$P_{diode_{max}} = f_0 C_p \left(V_{po} - 2V_D\right)^2 \text{ when } V_{opt_{BR}} = \frac{1}{2}\left(V_{po} - 2V_D\right) \tag{1}$$

where f_0 is the mechanical excitation frequency, C_p is the piezoelectric capacitance, V_{po} is the open-circuit voltage induced across the piezoelectric element with no electrical damping connected, and V_D is the voltage drop across the diode [3].

However more power can be extracted by modifying the charge on the piezoelectric material [3, 4]. The greatest improvement can be achieved using the single-supply pre-biasing (SSPB)

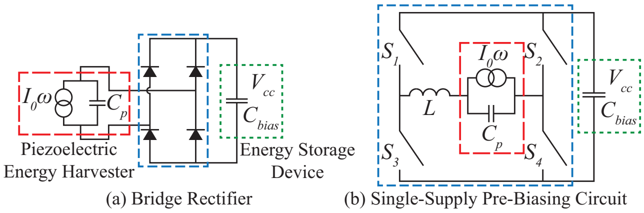

Figure 1. Piezoelectric energy harvester (where $I_0 = V_{po}\omega C_p$) with (a) bridge rectifier and (b) SSPB circuit.

technique (Figure 1(b)) [5], which operates as follows. Every half mechanical cycle, charge is placed on the piezoelectric material which will induce a force opposing the motion of the piezoelectric material. This acts to dampen the beam's motion, causing an increase in the power extracted. SSPB changes the circuit from a velocity-damped resonant generator (VDRG) to a coulomb-damped resonant generator (CDRG) [6], enabling the level of damping applied to be readily set by the pre-bias voltage, V_{cc}, applied. At the piezoelectric beam's extreme points of travel, charge from the pre-biasing capacitor, C_{bias}, is transferred on to the beam. This generates a Coulomb force to oppose the beam's motion until it reaches the opposite extreme position. The energy on the beam is then discharged back into C_{bias}, and the process repeats. Similarly to the bridge rectifier, the damping force can be optimally set by setting the voltage on the storage device in order to achieve maximum power extraction (2).

$$P_{SSPB_{max}} = {V_{po}}^2 f_0 C_p \left(\frac{8Q}{\pi}\right) \text{ when } V_{opt_{SSPB}} = 2V_{po}\frac{\gamma}{1-\gamma^2} \tag{2}$$

where Q is the Q-factor of the resonant current discharge path through the inductor and γ is the fraction of the magnitude of the voltage conserved on the capacitor of an RLC oscillator with Q-factor Q after a half-cycle of the oscillator [3].

Both techniques face an issue when the mechanical excitation force varies as the optimal voltage changes requiring the bias voltage to be changed in real time in order to maintain maximum power extraction. In this paper we present a system capable of detecting a change in the piezoelectric induced voltage (due to variance in the mechanical excitation force) and adjusting the damping force applied automatically by varying the amount of energy transferred from an intermediate energy storage element and a battery.

2. Maximum Power Point Tracking

Maximum Power Point Tracking (MPPT) for piezoelectric energy harvesters requires a system capable of monitoring the harvester and adjusting the conduction angle (rectifier case) or damping force (SSPB case) applied. The system must detect a change in the piezoelectric induced voltage, quantify the magnitude of the change, and apply an appropriate response. Since both the bridge rectifier and SSPB techniques use a voltage on a bias capacitor to apply the optimal conduction angle and damping force respectively, adding a buck converter with battery enables the bias capacitor voltage to be independently set. The MPPT scheme operates by adjusting the off-time of the buck converter causing the energy on the bias capacitor to be more or less frequently transferred, resulting in a decrease or increase in voltage respectively.

Figure 2 shows the suggested topologies to adjust the voltage applied for both (a) the bridge rectifier and (b) the SSPB circuit. The voltage on the biasing capacitor, C_{bias}, is controlled by varying the power transferred through the buck converter. If the time between energy transfers is increased, C_{bias} voltage will rise and a greater damping force will be applied to the piezoelectric material.

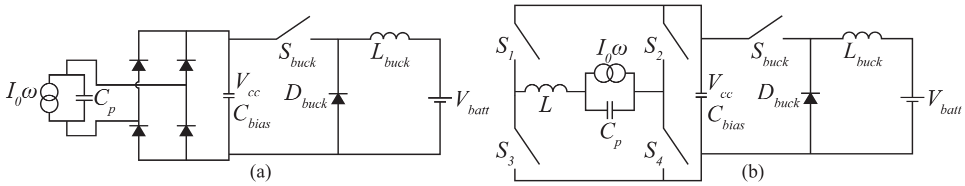

Figure 2. (a) Bridge rectifier and (b) SSPB circuit with buck converters and batteries.

A PSPICE simulation of the effect on power generation as energy is transferred from the pre-biasing capacitor to the storage battery is shown in Figure 3. The induced current was increased representing an increase in mechanical excitation. The power per cycle was measured over four energy transfer periods for two different buck converter off-times. The results show that the system with the longer buck converter off-time generated more power on average.

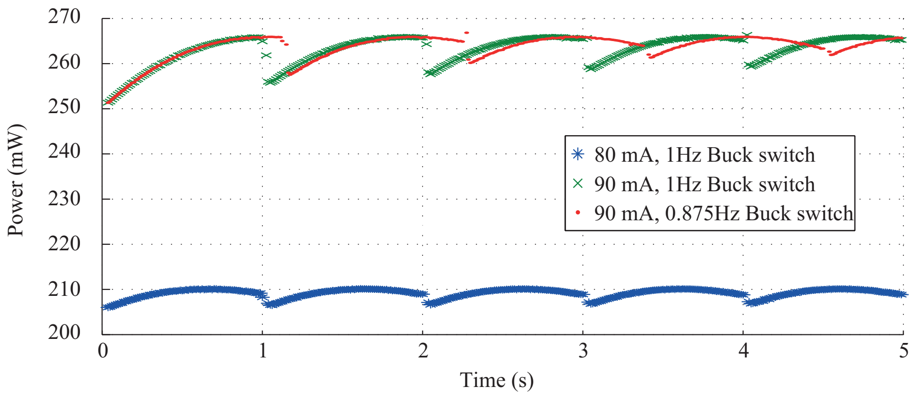

Figure 3. PSPICE simulation of the effect of adjusting the off-time of the buck converter on the power generated by a SSPB circuit for two different mechanical excitation forces.

3. Implementation

Implementing the proposed system requires three elements, a circuit capable of measuring the power generated, a controller to decide whether the power has increased or decreased since the previous measurement and a buck converter to transfer the energy. In designing all three circuits, power consumption must be minimised to ensure a high efficiency. Figure 4 shows the implementation used in this paper to demonstrate the MPPT technique.

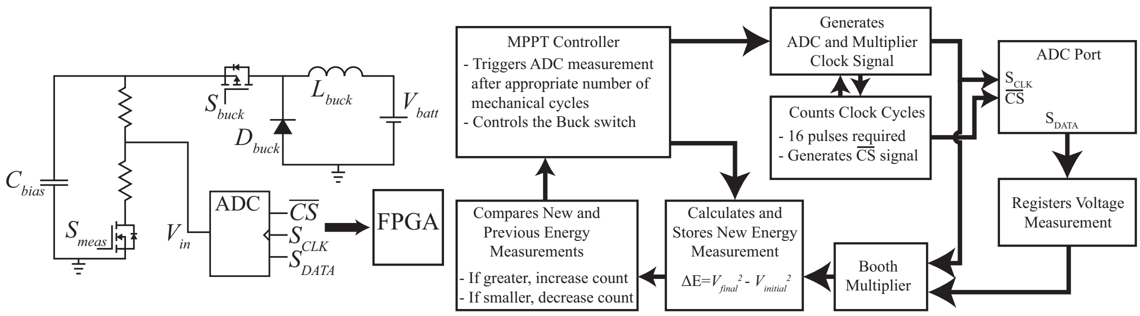

Figure 4. MPPT implementation and controller for either the bridge rectifier or SSPB circuit.

3.1. Change detection

The system needs to identify when the damping force needs to be adjusted due to a change in the mechanical excitation force to maintain maximum power extraction. A change can be detected by periodically measuring the energy transferred to the bias capacitor, C_{bias}. The energy being generated is found by comparing the square of C_{bias} voltage at the start, V_{init}, and end, V_{end}, over a set number of cycles (3). This result can then be compared to a previous measurement taken many cycles ago so that the trend for increasing or decreasing power extraction can be determined.

$$\Delta E = \frac{1}{2} C_{Bias} \left({V_{end}}^2 - {V_{init}}^2 \right) \tag{3}$$

Measuring the voltage on the capacitor with sufficient accuracy presents several difficulties which need to be overcome. Any power consumption used to measure the voltage detracts from the efficiency of the energy harvester. The measurement and control circuitry therefore should operate at the lowest voltage possible, however the voltage on the biasing capacitor maybe several times larger than this. The solution proposed in this paper is to use a potential divider which is switched in across the biasing capacitor during a measurement (Figure 4). The switch is an n-type MOSFET (BSS138) which can be driven by a low power FPGA (Igloo Nano), which can also be used to implement the SSPB scheme [7]. A low power Analog-to-Digital Converter (ADC AD7468) can then be used to measure the voltage and a Booth Multiplier algorithm [8] on the FPGA can square the value.

3.2. Controller

The controller shown in Figure 4 was implemented on the low power FPGA for MPPT. The controller works as follows: initially the buck converter transfers energy every 80 cycles, therefore at a count of 38 and 42 cycles the voltage is measured as V_{init} and V_{end} respectively. Both values are squared and V_{init} is subtracted from V_{end}. The result is compared against the previous energy measurement, 80 cycles previous. If the result is greater than the former, the count is increased allowing the voltage to rise and increasing the damping force. If the result is less, the counter is decreased, reducing the voltage the bias capacitor will attain, decreasing the damping force. However if it is the same, the counter stays the same and the damping force is not altered. The cycle counter signal for the SSPB signal is naturally generated by the switching pulses used to implement the scheme. The bridge rectifier however requires a secondary sense piezoelectric beam to be mechanically coupled to the generating beam and a zero crossing detector with an over-voltage protection MOSFET to generate the same signal [9].

The ADC and Booth Multiplier algorithm both need a clock signal in order to operate. The simplest solution is to use a crystal oscillator [10]. However the start-up time and power for a clock signal that may only be operating for a few microseconds, once a second renders this solution undesirable. Instead it is more efficient to generate the clock signal using a RC circuit. This technique is also used in SSPB circuit to generate the on-time pulses for the switches [7].

4. Results

The MPPT circuit was tested with a bridge rectifier circuit connected to a buck converter with a 1.2 V power supply representing the battery. The on-time for the buck switch was set to 118 μs and the off-time was varied by an Igloo Nano FPGA. A 50 nF piezoelectric loudspeaker was used to represent the harvester, which was mechanically excited at 200 Hz with different accelerations causing different induced open-circuit voltages, Vpo. Power generation on the biasing capacitor was measured using a Yokogawa WT210 power meter at 5 second intervals. The results were compared with the theoretical limit given in (1) demonstrating the circuit's functionality (Figure 5). It can be seen at high degrees of acceleration (corresponding to large

V_{po}), the system achieves close to the theoretical limit. However at lower excitation levels, performance is degraded due to the number of cycles between transfers and the number of cycles between measurements converging. This issue could be alleviated by increasing the resolution of the ADC so fewer cycles are required between measurements. The power consumption of the controller was measured as 50 μW when the piezo was inducing an open-circuit voltage of 6.75 V.

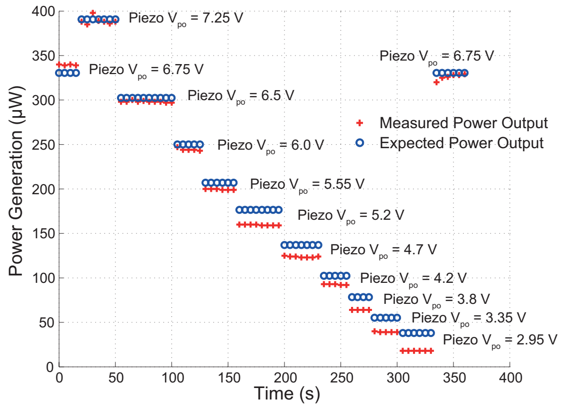

Figure 5. Comparison between measured power generation using MPPT implementation and bridge rectifier theoretical maximum power limit for several different excitation forces.

5. Conclusion

An algorithm and implementation have been presented which enable a piezoelectric energy harvester to automatically adapt to variation in mechanical excitation. The system is designed to track the maximum power point by adjusting either the conduction angle or the damping force for the bridge rectifier and SSPB circuit respectively. Future work will be focussed on reducing the power consumption of the controller and combining it with a SSPB circuit.

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