Microwatt power consumption maximum power point tracking circuit using an analogue differentiator for piezoelectric energy harvesting

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Abstract. A maximum power point tracking (MPPT) scheme by tracking the open-circuit voltage from a piezoelectric energy harvester using a differentiator is presented in this paper. The MPPT controller is implemented by using a low-power analogue differentiator and comparators without the need of a sensing circuitry and a power hungry controller. This proposed MPPT circuit is used to control a buck converter which serves as a power management module in conjunction with a full-wave bridge diode rectifier. Performance of this MPPT control scheme is verified by using the prototyped circuit to track the maximum power point of a macro-fiber composite (MFC) as the piezoelectric energy harvester. The MFC was bonded on a composite material and the whole specimen was subjected to various strain levels at frequency from 10 to 100 Hz. Experimental results showed that the implemented full analogue MPPT controller has a tracking efficiency between 81% and 98.66% independent of the load, and consumes an average power of 3.187 µW at 3 V during operation.

1. Introduction
Energy harvesting technology which converts energy from ambient environment into electrical energy is a promising solution to provide supply energy for fully autonomous systems such as wireless sensor nodes (WSNs) because power density harvested from the surroundings such as vibration, solar and temperature can be more than 100µW/cm³ [1]. In parallel, with the advancement of low-power electronic devices, which power consumption is only a few milliwatts [2, 3], energy harvesting powered WSNs are therefore viable. Vibration-based energy harvesting is of particular attractive because vibration can occur almost everywhere either naturally from the environment or induced by means of other sources. Piezoelectric energy harvesters (PEHs) are most commonly used transducers to scavenge vibration energy because of their simple structures, rigidity, self-contained power generation capabilities and attractive high energy density [1, 2, 4]. However, power harvested by PEH is intermittent, in the form of AC and variable in magnitude of current and voltage. Therefore, energy storage and rectification circuitry are needed for most applications. Furthermore, power harvested by PEH is very sensitive to connected electrical loads. If the electrical load mismatched the impedance of PEHs, the power delivered to the load would be a tiny fraction of power that the PEH is capable of harvesting. Therefore, an effective power management circuit is needed for PEHs to deliver the energy harvested to the electrical load.

Traditional power management circuits for PEHs use a rectifier to convert the AC voltage to the DC voltage and store it in a capacitor. This simplest form of electronics interface is not effective for...
most applications because it is not adaptive to variations from either the ambient vibration subjected by PEHs or the connected electrical load. From literature of [5, 6], it is known that PEHs exhibit linear electrical characteristic in which the maximum power transfer occurs at half the rectified open-circuit voltage $V_{OC}$ of the PEH as shown in figure 1. With this simple electrical relationship of PEHs, an MPPT scheme by tracking the half the rectified open-circuit voltage $V_{OC}$ of PEHs, through using an analogue differentiator and comparators proposed in this paper, could be used instead of the traditional MPPT methods using microcontroller. This leads to a low power overhead of this circuit, allowing energy to be drawn directly from a PEH for operation, and eliminating the need of sensing circuitry external power supply or start-up circuit. Without all these additional circuits and power hungry controller, power consumption of the MPPT controller can be greatly reduced. A prototype was implemented and tested over a wide range of vibrational frequencies and strain levels across the PEH. Experimental results have proven the feasibility of the proposed method.

**Figure 1.** (a) Illustration of PEH as a linear circuit and (b) its maximum power point occurring at half of the open-circuit voltage.

**Figure 2.** Schematic of the proposed MPPT circuit.

2. **MPPT Using Differentiator**

The proposed MPPT controller is shown in figure 2 and the operation is explained using figure 2 to 4. The MPPT circuit is used in conjunction with a rectifier and a DC–DC converter to manage the energy harvested from a PEH at its maximum power point (MPP). The voltage after the rectifier $V_{rect}$ is monitored using a low-power operational amplifier-based differentiator. The theoretical background of this proposed method is based on the voltage charging profile of capacitor in an $RC$ circuit. The DC–DC converter can be seen as open-circuited when it is disabled because no current can be drawn by it. In figure 2, before the MPP is reached, the circuit is effectively an $RC$ circuit formed by the PEH, rectifier and smoothing capacitor because there is no current path through the DC–DC converter which has been disabled. The smoothing capacitor $C_i$ will eventually be charged up to $V_{OC}$ of the PEH if the
DC–DC converter is always disabled. This means $V_{OC}$ of the PEH can be determined using the proposed circuit when the DC–DC converter is always disabled, that is, a simple $RC$ circuit. In the $RC$ circuit, the capacitor can be charged up very fast in an almost linear fashion initially but the increment rate of the voltage across the capacitor will gradually become slow as $V_{rect}$ is increasing towards $V_{OC}$. A high-pass filter is used to pass through the fast changing signal and block the slow changing signal. The input voltage $V_{HP}$ into the differentiator is the resultant voltage of feeding $V_{rect}$ through a high-pass filter that attenuates the slow changing $V_{rect}$ after $V_{rect}$ is equal to $V_{OC}/2$ as shown in figure 3. $V_{HP}$ gradually increases and peaks at $V_{OC}/2$. It should be highlighted that the input of the differentiator and $C_{HP}$ forms a high-pass filter. After the peak, $V_{HP}$ will decrease since the slow changing $V_{rect}$ has been attenuated. Differentiation of $V_{HP}$ is equal to zero at the maxima. Therefore, $V_{OC}/2$ can be determined by differentiating $V_{HP}$. $V_{OC}/2$ is reached when the derivative of $V_{HP}$ is equal to zero. When $V_{rect}$ reaches $V_{OC}/2$ of the PEH, output of the differentiator $V_{diff}$ will drop below $V_{ref}$ which subsequently triggers the comparator to send a signal pulse $V_{comp}$ to enable the DC–DC converter. Energy will be transferred from the PEH at its MPP to an energy storage device. $V_{rect}$ will decrease once the energy transfer begins. After $V_{diff}$ has dropped below $V_{ref}$, the DC–DC converter will be disabled and the energy transfer process stops. $C_i$ will be charged up again by the PEH until $V_{rect}$ reaches $V_{OC}/2$ of the PEH and the energy transfer process begins again.

![Figure 3](image-url) Illustration of the MPP occurring at $V_{rect} = V_{OC}/2$ at the peak of $V_{HP}$.

![Figure 4](image-url) Operation of the proposed MPPT circuit

3. Experiment

A macro-fiber composite (MFC) bonded on a composite material using adhesive glue is used as the PEH in this experiment. An Instron E10000 ElectroPuls dynamic and fatigue test machine was used as the vibration source. Different vibrational frequencies up to 100 Hz and three sets of mechanical loadings with peak-to-peak strain levels of 349.99 µε, 696.70 µε, and 927.24 µε, applied by Instron machine on the MFC PEH were performed. The MPPT efficiency $\eta_{MPPT}$ of the MPPT circuit can be defined as the ratio of the harvested power $P_{in}$ flowing into the power management circuit at the FB rectifier to the power $P_{max}$ dissipated by a perfectly matched load directly connected to the PEH:

$$\eta_{MPPT} = \frac{P_{in}}{P_{max}}$$ (1)
Measurements were made across the input of the FB rectifier to get voltage $v_{in}$ and across a 20 $\Omega$ resistor $R_{sense}$ for the current $i_{in}$ generated from the PEH as shown in figure 2. The root mean square (RMS) value of input voltage and current waveform is calculated from the measured data using and the product of the root mean square of $v_{in}$ and $i_{in}$ gives the average harvested power $P_{in}$ into the power management circuit. Measurements of $V_{diff}$, $V_{rect}$, $V_{ref}$, and $V_{comp}$ were also made using an oscilloscope to verify the operation of the circuit. The power consumption of the MPPT, $P_{MPPT}$, is an important characteristic for the proposed scheme in this paper. To determine the power consumption $P_{MPPT}$ of the core of the controller formed by the differentiator and comparators, the current and voltage were measured between D1 and $C_C$.

4. Results

Figure 5 shows the measured voltages of $V_{diff}$, $V_{rect}$, $V_{ref}$, and $V_{comp}$. The measured result agrees with the simulation result. $V_{diff}$ gradually becomes smaller and falls below $V_{ref}$. This caused $V_{comp}$ to become HIGH, enabling the buck converter for energy transfer. $V_{rect}$ decreases sharply when the energy transfer occurs and gradually increases after the process ends. The energy transfer process and switching of the electronics switches caused large spikes at $V_{ref}$. Powers, $P_{in}$ and $P_{max}$, obtained from the tests are shown in figure 6. It can be seen that the power harvested from the PEH using the proposed circuit closely matches the power obtained using manual resistive matching in the tested conditions. This prototyped MPPT controller shows efficiency of around 81% to 98.66%, which is calculated based on equation (1). This peak efficiency is better than the MCU-based MPPT controller [7]. The power consumption $P_{MPPT}$ of the MPPT controller is shown in figure 7. Initially, there is a large inrush current into $C_C$ because the capacitor is empty. The current eventually became very small when $C_C$ has been fully charged up to around 3.3 V. When $C_C$ is fully charged up and the controller begins to operate, the current consumption is about the same as shown in the inset. By looking into the inset of large scaled current consumption, it can be observed that the peak current during operation is about 10 $\mu$A and the average current consumption of the controller is 1.011 $\mu$A during operation. The supply voltage to the controller is relatively stable without significant drop during operation. This indicates that the current consumption of the circuit is indeed very low. Therefore, the average power consumption of this control circuit is only 3.178 $\mu$W, which is 100 times less than MPPT controller using microcontroller and 16 times less than MPPT controller using combination of analogue circuits and FPGA respectively [7, 8].

![Figure 5. Measured waveforms of $V_{diff}$, $V_{rect}$, $V_{ref}$ and $V_{comp}$ of the implemented MPPT circuit](image-url)
5. Conclusion
A microwatt power consumption MPPT circuit was presented and demonstrated for harvesting energy from an MFC piezoelectric transducer at its maximum power point under various vibrational frequencies and excitation forces. By exploiting the \textit{RC} response of a charging capacitor and linear electrical characteristics of the piezoelectric element, an MPPT scheme based on open-circuit voltage has been successfully implemented to find the MPP of the PEH using differentiator. This innovation has greatly simplifies the MPPT controller and reduces the power consumption of the circuit. Without MCU or FPGA which are usually off-the-shelf products, the proposed circuit can be easily fabricated as a monolithic IC. With the low power requirement and reduced size in the form of IC, this circuit can find applications in other areas such as MEMS energy harvesting.

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