Optimization of Piezoelectric Energy Harvesting Systems by Using a MPPT Method

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Abstract— **This paper proposes an optimization of a piezoelectric energy harvesting system by using a maximum power point tracking (MPPT) method. A full-bridge rectifier is implemented with a MPPT unit to obtain maximum extracted power by controlling a DC-DC converter following the rectifier. By using the MPPT unit, the extracted power efficiency of the rectifier is always larger than 80% regardless of the load condition. Furthermore, another DC-DC converter is applied to regulate the output voltage to the desired level. The simulation results show that the system can extract a maximum of 51 uW power with 64% total efficiency.**

Keywords- AC-DC converter, MPPT, rectifier, piezoelectric energy harvesting system.

I. Introduction

Energy harvesting is becoming increasingly important in our lives. Energy can be harvested from the ambient environment, including mechanical, thermal, light, and electromagnetic sources, the human body, and others, to replace traditional sources. Mechanical energy harvesting is the most promising energy harvesting technique: it uses piezoelectric (PE) component that transfer vibration energy to electrical energy. This electrical energy can be regulated and stored before being used by an electronic device. This is particularly useful in applications where the replacement of batteries is impractical, such as wireless micro-sensor networks, implementable medical electronics, and tire pressure sensor systems [1].

Fig.1 illustrates a general piezoelectric energy harvesting system that consists of five major components [2-4]. A transducer is a sensor PE transducer that deforms vibration energy into electrical energy. The PE transducer is usually modeled by an AC current source in parallel with a capacitor and a large resistor [1,2,4,5]. The electrical energy at the output of the transducer is a strong and irregular function of time; an AC-DC converter is hence required to produce a DC supply source. The energy after the rectifier is stored in an energy storage device such as a battery or supercapacitor. Before the system is used under load, normally a voltage regulator is operated to ensure suitable voltage.

A rectifier, which has been proposed and demonstrated in recent work, is the most commonly used AC-DC converter [1-5]. There are two types of conventional rectifiers: full-bridge rectifiers and voltage doubler rectifiers. The limitations of the

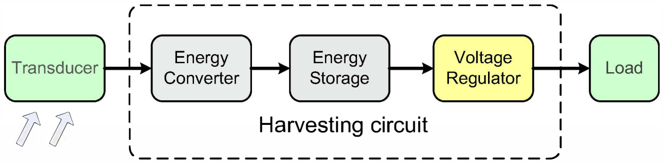

Fig 1. A Piezoelectric energy harvesting system

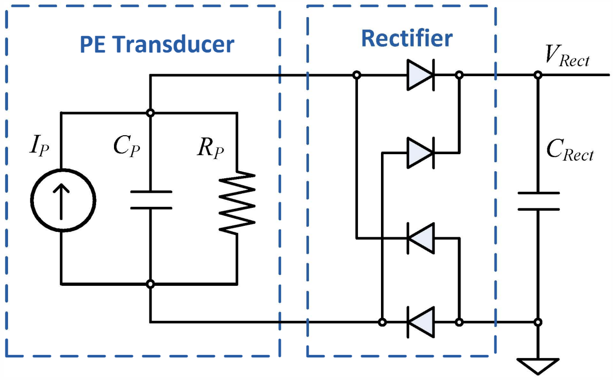

Fig.2 Piezoelectric transducer model and full-bridge rectifier

conventional architectures are low efficiency due to the voltage drop in each passive diode and power loss during discharging and charging for the internal capacitor [1-2]. There are two directions for improving the efficiency of power extracted from the PE transducer. The first approach is replacing the passive diode with an active diode to reduce the voltage drop in each diode. The second approach is improving the efficiency of the conventional rectifier by resetting [1,2,5]or flipping [2,5] the internal capacitor when the internal current source of the transducer crosses zero. However, the extracted power in the previous rectifier [1-5] depends on the load condition. The rectifiers can only obtain high extracted power efficiency at a small range of output load resistance. If the load resistance is outside of this range, the extracted power of the rectifier is significantly reduced. The MPPT method is used to extract more power in a PE energy harvesting system in [6]. However, in this study MPPT is implemented by using a MCU –TI eZ430-RF2500, and therefore the area and cost are significantly increased.

In this study, a MPPT unit is added to the rectifier to ensure that the system always obtains maximum extracted power despite load variation. The MPPT is used in this paper can be

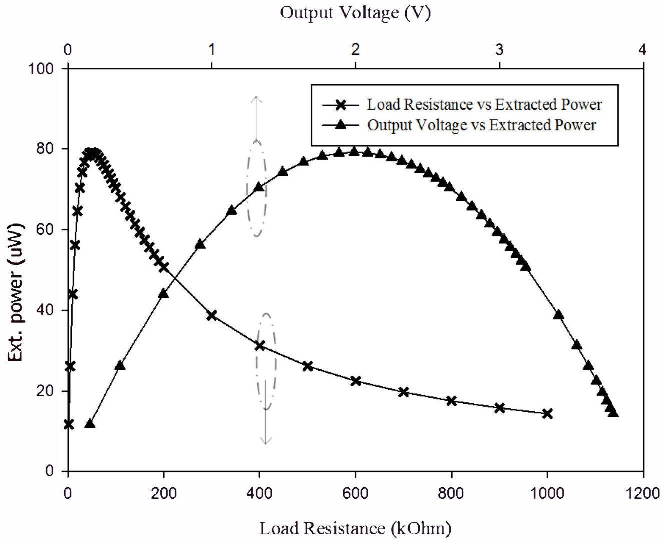

Fig.3. Extracted power of conventional rectifier

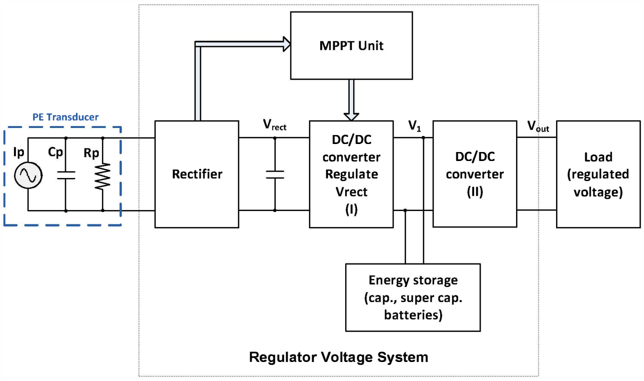

Figure 4. The proposed piezoelectric energy harvesting system.

integrated in system. Furthermore a full system for piezoelectric energy harvesting also introduces in this paper.

This paper is organized as follows. Section II proposes an architecture for the PE energy harvesting system with a MPPT unit. Section III provides the simulation results and a discussion of the proposed system. Finally, Section IV briefly concludes this paper.

II. ARCHITECTURE OF PEH SYSTEM

As shown in the left side of Fig.2, a PE transducer is usually modeled as a sinusoidal current source $i_P(t) = I_P \sin 2\pi f_P t$, in parallel with a capacitor C_P and a large resistor R_P. The magnitude of the PE current, I_P, varies with the mechanical excitation level of the PE element, although it is assumed to be relatively constant regardless of the external load; f_P is the excited frequency of the PE harvester [1]. The output of the transducer has an AC waveform, which must be converted to DC by an AC-DC rectifier before it can be transferred to the battery or supercapacitor.

Several techniques have been proposed to improve extracted power by resetting or flipping the internal capacitor [1,2,5] when the internal current source crosses zero [2,5]. Although the reported techniques improve the maximum extracted power, the range of output load resistance to obtain high extracted power is narrow. Thus, if the load resistance is outside of this narrow range, the efficiency of system will be significantly reduced.

For the conventional full-bridge rectifier, as shown in Fig. 2, the extracted power Eq. (1) and maximum extracted power Eq. (2) are given by [2] with the assumption that the voltage drop in each active diode is zero.

$$P_{out} = 4C_P f_P (V_{OC} - V_{rect}) V_{rect} = \left(\frac{4C_P f_P V_{OC} \sqrt{R_L}}{1 + 4C_P f_P \sqrt{R_L}} \right)^2 \quad (1)$$

$$P_{out,\,\text{maximum}} = C_P f_P V_{OC}^2 \quad (2)$$

where $V_{oc} = \dfrac{I_P}{2\pi C_P f_P}$ is the open circuit voltage of the rectifier. V_{rect} is the output voltage of the rectifier and R_L is the load resistance. The output voltage obtains maximum extracted power when $V_{rect}=V_{rect,opt}=V_{OC}/2$ or the load resistance at $R_{L,opt} = \dfrac{1}{4C_P f_P}$. Eq.(2) shows the extracted power of the rectifier is a function of the load resistance. The extracted power is only maximal at one point when the load resistance equals $R_{L,opt}$.

Fig. 3 shows the function of the extracted power P_{out} with the output voltage and load resistance, as expressed in Eq. (1) and Eq. (2) with the following input PE transducer parameters: I_P=125 µA, f_P=200 Hz, C_P=25 nF, and R_P=1 MΩ. The output power is high in a small range of load resistance from 70KΩ to 130KΩ, and the extracted power is reduced significantly when the load resistance changes. However, in a real system, the load is continuously changing, and thus the system cannot operate only in the maximum point area. If the system operates with small or large resistance load, the extracted power of the rectifier is very small. Fig. 3 also illustrates that the maximum extracted power of the rectifier is only obtained in a small area of V_{rect} from 1.5V to 2.5V. If the value of V_{rect} is outside of that range, the efficiency of the system will be significantly reduced. To improve the efficiency of the system, a PE energy harvesting system with MPPT is proposed in this paper. The MPPT is designed to regulate the output voltage of the rectifier, V_{rect}, by an active or inactive DC-DC (I) converter following the rectifier.

A. *Proposed Optimized PE Energy Harvesting Sytem*

Fig. 4 shows the proposed PE energy harvesting system. A PE transducer is connected to the full bridge rectifier to change the AC waveform to a DC waveform. A DC-DC converter (I) follows the rectifier to regulate V_{rect}. The operation of the DC-DC converter (I) is controlled by the MPPT unit. The MPPT unit monitors the output voltage of the rectifier and then adjusts the duty cycle of the DC-DC converter (I) to set the output voltage at the output of the rectifier at the optimum value, $V_{rect,opt}$. Because the output voltage of the rectifier is regulated at $V_{rect,opt}$, the output voltage at V_1 can be larger or smaller than V_{rect}. The buck-boost converter is thus suitable for a DC-DC converter (I). The purpose of the DC-DC converter (I) is to

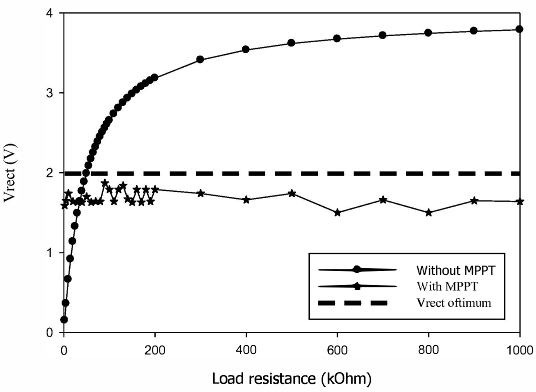

Figure 5. Comparison between Vrect of PE system with and without MPPT when load change from 2kΩ to 1MΩ

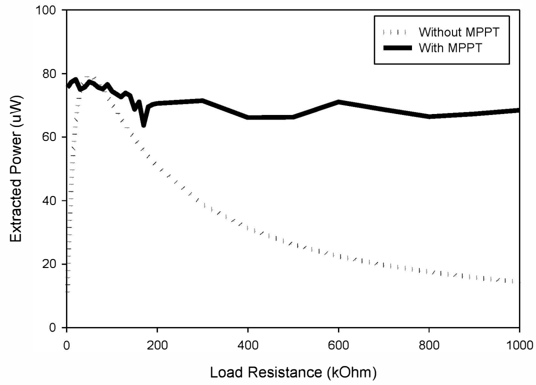

Fig. 6. Comparison extracted power with and without MPPT

keep V_{rect} at the optimum value; the voltage at V_1 is therefore not controllable. The second DC-DC converter is used for regulating the output voltage of the system at a desired level.

In comparison with the conventional PE energy harvesting shown in Fig. 1, a MPPT unit and a DC-DC converter are added to the system. The MPPT unit and DC-DC converter (I) help ensure that the rectifier always operates near the optimum range of V_{rect} to derive high extracted power.

B. Rectifier and MPPT Unit.

The first block of the regulator voltage system is the rectifier. With implementation of a full-bridge rectifier, the AC waveform of the transducer is deformed to a DC waveform. To reduce the power loss across the rectifier, all diodes in the rectifier are implemented as active diodes to reduce the voltage drop. Because the excited frequency of the PE harvester is small (smaller than 1000Hz) the active diodes can be implemented by a transistor and one comparator. By adopting the active diode, the voltage drop in each diode is reduced from 400mV to 10 mV.

The MPPT unit is implemented to detect the maximum extracted power point in Fig.3, and to control the rectifier operating at the optimum $V_{rect,opt}$. At the optimum $V_{rect,opt}$, the rectifier can extract the maximum output voltage. The MPPT is designed by monitoring the change of V_{rect}. As mentioned before, the optimum value of V_{rect} equals half of V_{OC}. The proposed system uses a MPPT to detect V_{OC} every 2 minutes. To obtain the value of V_{OC}, the converter (I) is disabled. During detection of the V_{OC} period, the rectifier operates as an open circuit, and then the MPPT can obtain the V_{OC} value of the rectifier. This value is stored in one capacitor and used as the reference voltage of V_{rect}. By monitoring the change of V_{rect}, the MPPT controls the DC-DC converter (I) to regulate V_{rect} at the optimum value ($V_{OC}/2$). Vrect is controlled by the DC-DC converter (I); when V_{rect} is larger than $V_{rect,opt}$, the DC-DC converter (I) is activated, and conversely it is deactivated when the value is smaller. The time for sampling the value of V_{OC} is 20ms. During the detection period value of V_{OC}, the system operates by reserve energy from energy storage.

As mentioned before, the DC-DC converter (I) is implemented by a buck-boost converter; the conversion ratio of the converter is given by:

$$V_{out} = -\frac{D_1}{1-D_1} V_{in} \tag{3}$$

where D_1 is the duty cycle of the DC-DC converter, and V_{out} and V_{in} are the output and input voltage of the converter at the steady state, respectively.

D_1 and V_{rect} move in opposite directions, where increasing D_1 causes increased power flow to the output, and therefore V_{rect} will decrease. Conversely, if D_1 decreases, V_{rect} will increase. In the system the value of V_1 is not constant, and depends on the output power consumption and the duty cycle D_1.

C. DC-DC Converter.

With use of MPPT, V_{rect} is kept at $V_{rect,opt}$, and therefore if the output load resistance at V_1 is larger than R_{opt}, V_1 will be larger than $V_{rect,opt}$; conversely, if the resistance at V_1 is smaller than R_{opt}, V_1 will be smaller than $V_{rect,opt}$. Therefore, the range of V_1 is larger than that of V_{rect}. For this reason, a buck-boost converter is suitable for DC-DC converter (I). The duty cycle of the DC-DC converter (I) is controlled by MPPT to ensure the rectifier operates at the optimum point. In the system, a simple buck-boost converter is operated with a switching frequency of 100kHz, and the duty cycle depends on the load condition.

The task of DC-DC converter (I) is to regulate V_{rect}, and therefore it cannot regulate the output voltage V_1. DC-DC converter (II) is added to regulate the output voltage at a level suitable to the desired voltage of the system. Because the output power of the PE energy harvesting is very small the entire design must minimize quiescent current. On this basis one more switch capacitor is used as the second DC-DC converter. The switch capacitor architecture optimizes power loss of the control circuit, and a hysteresis comparator defines the ripple of the output voltage.

III. SIMULATION RESULTS

The system was simulated with the following transducer parameters: I_P=125 µA, f_P=200 Hz, C_P=25 nF, and R_P=1 MΩ. Under the same input conditions, the load resistor changes from 2kΩ to 1MΩ. With the simulation input parameters, from (2), the optimum value of V_{rect} ($V_{rect,opt}$) equals to 1.98mV. Fig.5 shows a comparison of the output voltage of the rectifier

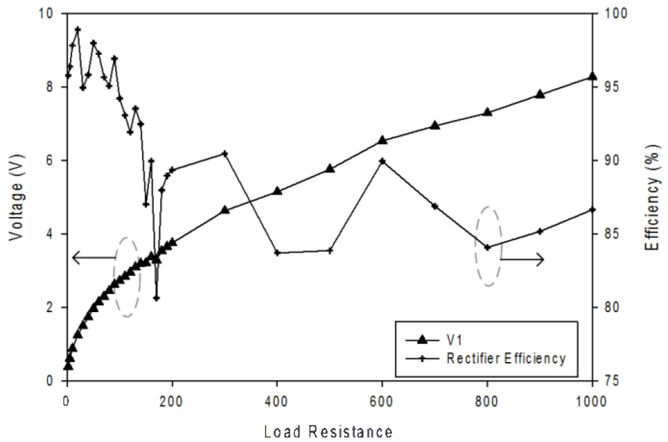

Fig. 7. Output voltage and output efficiency of the rectifier and DC-DC I

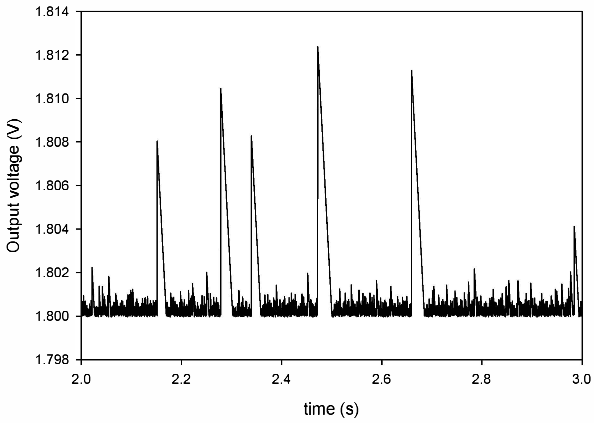

Fig. 8. Output voltage of system

with and without MPPT and the optimum value. The optimum value of V_{rect} is constant, while the value of V_{rect} without MPPT is an increasing function of load resistance, and there is a point where an optimum value is obtained. By adding the MPPT unit, the output voltage of the rectifier is always near the optimum value with respect to the load resistance. Because the rectifier operates in the optimum output value range, the system can extract more power.

Fig. 6 shows the extracted power of the rectifier with and without MPPT when the load condition is changed. Without MPPT, the shape of the extracted power is a function of the load resistance and the extracted power has efficiency larger than 90% at a small range of load from 25kΩ to 95KΩ, and outside of this range, the efficiency of the rectifier is low. Fig. 6 also illustrates that with MPPT, the output power of the extracted power is almost constant and is approximately equal to the maximum of the system without MPPT. The efficiency of the system with MPPT is larger than 90 % in the full range from 2kΩ to 1MΩ.

Fig. 7 shows the output voltage at V_I, where the DC-DC converter at V_I only regulates the voltage for V_{rect}; it does not control the output at V_I. With the same power, when the load resistance increases, the output voltage will also increase, as shown in Fig.7. The output efficiency of the rectifier is also shown in Fig. 7, where is is seen that the output efficiency is always larger than 80% regardless of the load resistance.

Fig. 8 shows the output voltage of the system with a 10uF output capacitor, and the output ripple of the system is about 12mV. The total efficiency of the proposed PE energy harvesting system is 64%.

IV. CONCLUSION

This paper has identified problems of rectifiers that are used in piezoelectric energy harvesting systems. The proposed system overcomes the drawbacks of previous rectifiers by adding a MPPT unit and one DC-DC converter. MPPT and the DC-DC converter help ensure that the rectifier always operates near the maximum area. The MPPT helps the transducer achieve power extraction efficiency that is always larger than 80%. With simple and efficient regulation of voltage, the overall efficiency of the piezoelectric system is 64%.

ACKNOWLEDGMENT

This research was financially supported by the Ministry of Science, ICT & Future Planning and National Research Foundation of Korea (NRF) through the Human Resource Training Project for Regional Innovation. Chip fabrication and simulation tools were supported by IDEC, KAIST

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