Efficient Maximum Power Tracking of Energy Harvesting Using a µController for Power Savings

Sewan Heo, Yil Suk Yang, Jaewoo Lee, Sang-kyun Lee, and Jongdae Kim

This letter describes an efficient technique for maximum power point tracking (MPPT) of an energy harvesting device. It is based on controlling the device voltage at the point of maximum power. Using a microcontroller with a power saving technique, the MPPT algorithm maintains the maximum power with low power consumption. An experiment shows that the algorithm maximizes the energy transfer power using an energy management IC fabricated in a 0.18-µm process. Compared to direct energy transfer to a battery, the proposed technique is more efficient for low-energy harvesting under variable conditions.

Keywords: Energy harvesting, maximum power point tracking, energy management.

I. Introduction

Wireless sensor network technology was developed in an attempt to achieve automatic monitoring by gathering environmental information from distributed sensor nodes. A sensor node consists of a sensor, processor, and radio transceiver, allowing it to sense and transmit data after the data is processed. The node requires sufficient energy for a long lifetime and needs ample power for wireless communication over long distances. An energy-efficient architecture and energy-aware operation of the sensor node [1] are thus required for a long life. To overcome these energy limitations, energy harvesting (or energy scavenging) can be applied to generate electrical energy from the environment, including solar, vibrational, and thermal energy. However, these sources produce little energy and are inconsistent because they vary depending on the time and operation conditions. Thus, energy needs to be harvested at the maximum power considering the operating conditions of the harvesting device.

Numerous maximum power point tracking (MPPT) methods have been proposed for various harvesting devices, such as solar cells [2], piezoelectric generators (PEGs) [3], [4], and thermoelectric generators (TEGs) [5]. Although these methods can achieve the goal of maximum power, they are not appropriate for application to a sensor node because continuous power monitoring and control consume considerable energy compared to the levels that can normally be generated. Thus, an efficient power saving technique is required for MPPT without continuous power monitoring and control.

II. Numerical Approach for MPPT

Since the amount of energy harvested from a device such as a PEG or TEG depends on the vibration magnitude or thermal difference, respectively, energy needs to be generated at maximum power under the given conditions. To obtain a solution for the maximum power problem, a simple and accurate numerical model of energy harvesting devices such as PEGs or TEGs is necessary. These devices can be modeled by the ideal voltage (or open-circuit voltage) source V_{oc} and the

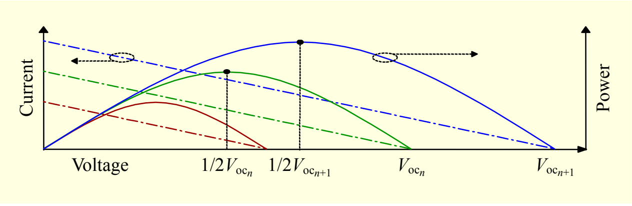

Fig. 1. I-V and P-V characteristics of energy harvester.

Manuscript received Apr. 13, 2011; revised Aug. 1, 2011; accepted Sept. 6, 2011.

This research was supported by the IT R&D program of MKE/KEIT, Rep. of Korea [KI002077, EPMIC Based on Self-Chargeable Power Supply Module].

Sewan Heo (phone: +82 42 860 1269, email: sewany@etri.re.kr), Yil Suk Yang (email:ysyang@etri.re.kr), Jaewoo Lee (email: jaewoo@etri.re.kr), Sang-kyun Lee (email: sklee526@etri.re.kr), and Jongdae Kim (email: jdkim@etri.re.kr) are with the Convergence Components & Materials Research Laboratory, ETRI, Daejeon, Rep. of Korea.

http://dx.doi.org/10.4218/etrij.11.0211.0149

internal series resistor R_s. Although a PEG is generally modeled by the ideal current source and parallel capacitor, according to Thevenin's theorem, it can be converted to a simple model. The current flows from the voltage source to the output through a resistor, while the output voltage V_o is lowered. As the current varies, the power delivered to the output changes. The output power P_o and the maximum value P_{omax} are calculated and derived below from the model:

$$P_o = V_o \times \frac{V_{oc} - V_o}{R_s}, \quad P_{omax} = P_o' = \left.\frac{V_{oc}^2}{4R_s}\right|_{V_o = \frac{1}{2}V_{oc}}. \tag{1}$$

According to (1), P_o is maximized when V_o is half of V_{oc}. Rather than using the value of P_{omax}, it is more important for the maximum point to be determined by V_o regardless of R_s. Because V_{oc} varies depending on the device conditions and the power is parabolic as a function of V_o as shown in Fig. 1, the point of maximum power can be tracked when V_o is controlled such that it is always equal to half of V_{oc}.

Therefore, we propose a technique that attains the maximum power from an energy harvesting device, such as a PEG or TEG, but not a solar cell, which can be modeled as a resistive model. By measuring V_{oc} from the device, the power can be maximized by controlling V_o so that it reaches the maximum power point. Furthermore, the point can be tracked at all times by adaptive control of V_o according to periodic measurement of V_{oc} even when conditions vary, resulting in MPPT.

III. MPPT Algorithm with Energy Management

The proposed algorithm for MPPT by output voltage control is shown in Fig. 2(a). First, the state of charge (SOC) of the battery that supplies power to the system should be checked to determine the load operation of the sensor node and the energy harvesting operations. If there is enough energy in the battery, the system can sustain itself without energy harvesting, whereas if there is little energy, it extends the lifetime through energy harvesting at the maximum power point under intermittent load operations. After one system cycle with the harvesting, it returns to the battery check. When the system requires energy harvesting, the algorithm for the maximum power point runs through the following several steps. Initially, V_{oc} is measured by halting the output voltage control operation. According to the V_{oc}, the reference voltage for controlling the output voltage at the maximum power point is determined to be half of the V_{oc}. Finally, when there is more than one device, the energy source with greater power is selected by comparing power from the predefined profile or measurement of each device.

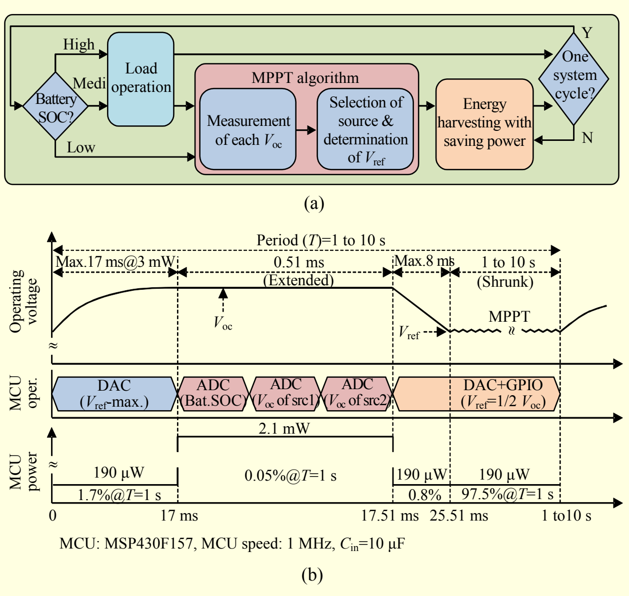

Fig. 2. (a) Algorithm for MPPT tracking and (b) timing diagram and power consumption of microcontroller.

The algorithm is operated by a microcontroller that is composed of a processor and peripheral units such as analog-to-digital converters (ADCs), digital-to-analog converters (DACs), and general-purpose input and output (GPIO) devices. The timing diagram and the power consumption of the microcontroller in the algorithm are shown in Fig. 2(b). When the reference voltage is set to the maximum value by the DAC, harvesting is halted and consequently the operating voltage increases to V_{oc}. The voltage is measured by the ADC and repeated if there are more harvesting sources after the SOC measurement. The reference voltage is then set by the DAC to half the measured V_{oc} for the source with greater power, which is selected by the GPIO device. Finally, by maintaining the reference voltage, maximum power is obtained continuously until the end of the period. The DAC consumes low power while the ADC consumes higher power. However, most of the power consumption is due to the DAC because it has much longer operation time than the ADC. The DAC occupies at least 97.5% of the time, which gets larger as the period becomes longer. Thus, for most of the harvesting time with the MPPT control, power consumption is reduced while maintaining only the essential control of the DAC and curtailing any unnecessary power consumption of other units such as the ADC by powering them down or off. Consequently, the microcontroller achieves low power control by adopting power savings of the sporadically used units. The tracking speed depends highly on the capacitance of the input capacitor because the algorithm in the microcontroller runs in short time under 1 ms. At 10 µF, it takes at most 17 ms to increase the input voltage from minimum to maximum with energy generation by harvesting at 3 mW. It takes at most 8 ms to draw input voltage from maximum to minimum. This represents high speed relative to the period.

Energy transfer from a harvesting device to a battery requires a highly efficient DC-DC conversion integrated circuit (IC) to which the algorithm can be applied. We therefore propose an energy management IC (EMIC). The EMIC is composed of two switches for inputs, four switches for a buck-boost topology with an external inductor, a switch driver controlled by a switch controller, a comparator that allows the input voltage to track the reference, another comparator for reverse current detection, and a bias generator to supply bias current to the comparators. A shutdown block is used to suppress all bias currents controlled by the microcontroller when energy transfer is unnecessary. The supply voltage is 3.3 V for the IO and 1.2 V for the core, where it is preferable to reduce power consumption using the lower voltage for the core. One energy-aware operation is pulse frequency modulation (PFM), that is, reducing power consumption when the input energy is low. Another operation is reference voltage tracking using a comparator that enables regulation of the input voltage to the point of maximum power adaptively according to the conditions. This is an outstanding difference compared to a general DC-DC converter, which regulates output voltage to a fixed value.

The energy harvesting system is shown in Fig. 3. The system transfers energy and sustains itself via management of the stored energy by periodic control and monitoring of the microcontroller. The system consists of two harvesting devices, the EMIC with an external inductor, a battery, a power supply IC, and a microcontroller. The fundamental power source is the battery, which supplies power to the EMIC, the microcontroller, and the power supply IC supplying the other voltage to the EMIC. As the microcontroller and the power supply IC, MSP430F157 [6] and LTC1877 [7] are used with 190 μW for the DAC and 33 μW as measured quiescent power consumptions, respectively.

The system requires a battery capable of recharging without a memory effect, the most appropriate being a lithium-ion battery. Since this type of battery is generally composed of graphite for the anode and $LiCoO_2$ for the cathode, the nominal voltage is 3.7 V. The voltage cannot be supplied directly to the ICs, such as the EMIC or the microcontroller; moreover, the voltage variation depending on the SOC is considerable. Thus, we developed a new lithium-ion battery using $LiFePO_4$ as the cathode material. The characteristics of the battery are adjusted so as to be appropriate for supplying power directly to the ICs with a moderate nominal voltage of 3.3 V. This value must be lower than the maximum supply voltage 3.6 V of the microcontroller and cover the entire EMIC input voltage range with higher voltage than the maximum input 3 V. Furthermore, the voltage variation depending on the SOC diminishes, so the voltage becomes steady around the nominal voltage.

IV. Experimental Results

To evaluate the proposed algorithm, the EMIC was implemented in a 0.18-μm BCDMOS process. It occupies a die area of 4.4 mm^2, as shown in Fig. 4. It is operated at 1 MHz and controlled by a current-mode PFM under 32-mA peak current of an inductor, which has 10-μH inductance and 80-mΩ series resistance, inducing conduction loss at most 12 μW. The EMIC was simulated by the accurate Cadence Spectre simulator in a 0.18-μm process, as shown in Fig. 5. The input

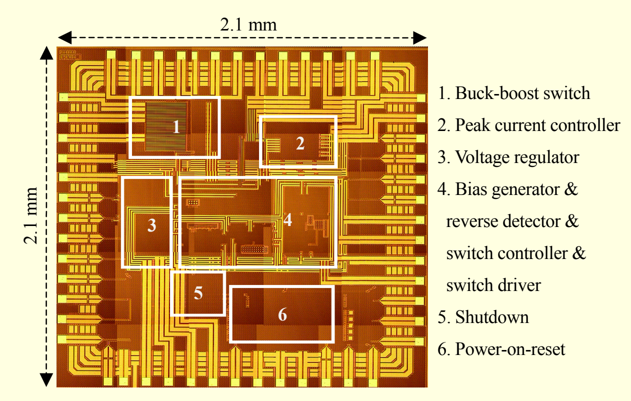

Fig. 4. Chip photograph of EMIC.

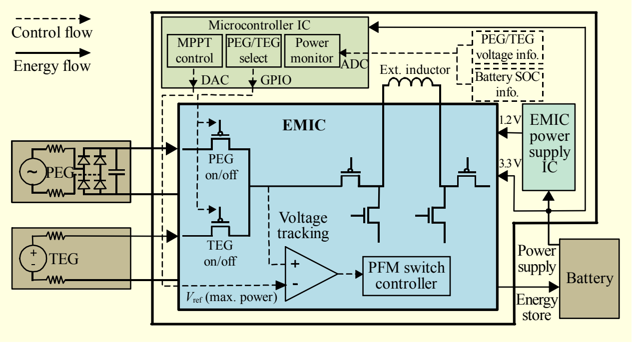

Fig. 3. Energy harvesting system.

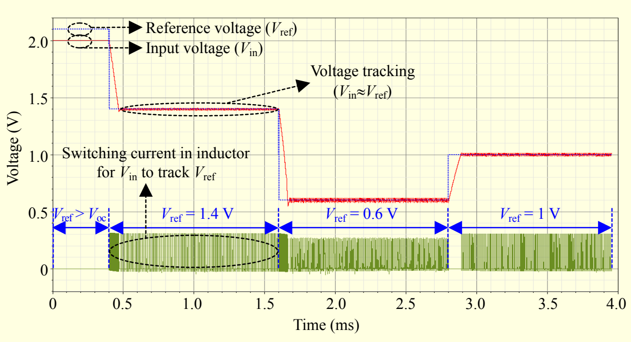

Fig. 5. Voltage tracking to reference voltage via EMIC.

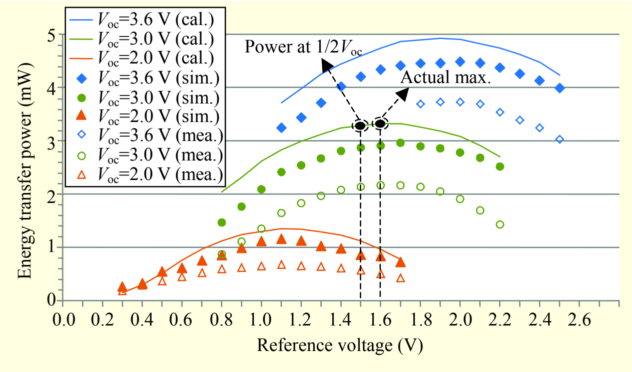

Fig. 6. Variation of energy transfer power by different reference voltages.

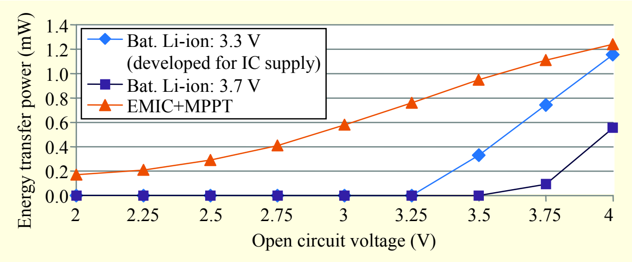

Fig. 7. Effect of MPPT compared to direct transfers.

energy harvesting source was modeled by a 2-V ideal voltage source with an internal resistance of 500 Ω. When the reference voltage (blue line) exceeds the maximum input voltage (red line), the IC does not transfer energy. When the reference voltage becomes lower, however, the IC tries to ensure that the input voltage tracks the reference voltage by transferring input energy via the switching current in the inductor (green line). On the other hand, when the reference voltage becomes higher, it waits until the input voltage increases to the reference voltage and tracks it. The tracking error is less than 20 mV.

The proposed technique of transferring energy at maximum power by tracking the reference voltage was verified with the implemented EMIC (Fig. 6). The energy transfer power varies by different reference voltages and is maximized at half of the V_{oc}. The power is compared by calculation with the parasitic resistance, simulation with the Spectre tool, and measurement with the implemented IC for different V_{oc} values representing different amounts of energy. The input source is modeled by an ideal source with different voltages and an internal resistance of 500 Ω. The line of calculation is not a perfect parabolic form due to different conduction loss. However, there is a small amount of error (0.1 V) between the voltage for the actual maximum power and half of the V_{oc}. The solid dots for the simulation are lower than the calculation line owing to the reverse current loss at zero current sensing while running in the discontinuous conduction mode. The average loss is 10.7%. Although the unfilled dots in the measurement are much lower than the simulation due to the greater reverse current and despite the fact that some of the data are omitted due to the lack of tracking under a high current condition, the power at half of the V_{oc} is almost maximal, with at most 3.7% error. Thus, the concept of energy transfer at maximum power by tracking half of the V_{oc} is verified.

The effect of MPPT is described in Fig. 7, which compares the transfer power with direct transfer to the lithium-ion battery from the input source with 2 kΩ. When V_{oc} is lower than the battery voltage, energy can be transferred by only the EMIC, not by the direct transfer, since the EMIC is designed to enable low voltage transfer over the lowest input voltage, 0.9 V. While the energy transfer power becomes greater as V_{oc} increases, it is still higher with the IC than with the direct transfer, though it shows a quicker increase without conversion loss. Thus, MPPT transfers energy with less influence by variation of V_{oc} due to changes of the harvesting conditions.

V. Conclusion

This letter proposed a technique for transferring harvested energy at maximum power by voltage tracking. Using a microcontroller with a power saving technique, the MPPT algorithm maintains maximum power with low power consumption and high-speed tracking. An experiment verified that the algorithm maximizes the energy transfer power using the implemented EMIC. The power is increased and less affected by variable conditions compared to direct transfer.

References

[1] V. Raghunathan et al., “Energy-Aware Wireless Microsensor Networks,” *IEEE Signal Process. Mag.*, vol. 19, no. 2, Mar. 2002, pp. 40-50.

[2] T. Esram and P.L. Chapman, “Comparison of Photovoltaic Array Maximum Power Point Tracking Techniques,” *IEEE Trans. Energy Conv.*, vol. 22, no. 2, June 2007, pp. 439-449.

[3] G.K. Ottman et al., “Adaptive Piezoelectric Energy Harvesting Circuit for Wireless Remote Power Supply,” *IEEE Trans. Power Electron.*, vol. 17, no. 5, Sept. 2002, pp. 669-676.

[4] S.E. Moon et al., “Sustainable Vibration Energy Harvesting Based on Zr-Doped PMN-PT Piezoelectric Single Crystal Cantilevers,” *ETRI J.*, vol. 31, no. 6, Dec. 2009, pp. 688-694.

[5] H. Nagayoshi, T. Kajikawa, and T. Sugiyama, “Comparison of Maximum Power Point Control Methods for Thermoelectric Power Generator,” *Proc. Thermoelectron.*, 2002, p. 450.

[6] Texas Instruments, MSP430 16-bit Ultra-low Power MCUs. http://www.ti.com

[7] Linear Technology, Switching Reg. http://www.linear.com