Hindawi Publishing Corporation
International Journal of Distributed Sensor Networks
Volume 2012, Article ID 603709, 6 pages
doi:10.1155/2012/603709

Research Article

An Energy Supply System for Wireless Sensor Network Nodes

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Received 26 November 2011; Revised 25 March 2012; Accepted 25 March 2012

Academic Editor: Sabah Mohammed

The power source is a critical obstacle for wireless sensor network nodes. In order to prolong the lifetime of wireless sensor networks, this paper presents an energy supply system that uses a specially designed broadband piezoelectric energy harvesting technology for sustaining the operation of wireless sensor network nodes. The proposed energy supply circuit can apply an optimal control voltage to the piezoelectric element to ensure impedance matching between the vibration source and the energy supply system in nonresonance frequencies. As compared to the conventional piezoelectric energy harvesting circuit, it is shown that the efficiency has been increased 4 times. In this work, the overall system structure, the function modules design, and the performance testing analysis are illuminated in detail. Experimental results reveal that this energy supply system can significantly improve power within the wide bands by the active piezoelectric energy harvesting technology and enable wireless sensor network nodes to operate normally.

1. Introduction

Wireless sensor networks have been of great interests over the last few decades. Wireless sensor networks are the integration of sensor technology, embedded computing technology, modern network and wireless communication technology, distributed information processing technology, and so on. They can be used to monitor, sense, and collect the information on the environment or objects by microsensors and transmit these information to the users. Therefore, they have gained numerous applications such as military defense, industry and agriculture, city management, biological and medical treatment, and environmental monitoring [1–3].

However, wireless sensor networks are not rapid commercialization as people have expected. One of the most critical bottlenecks is the energy supply problem for wireless sensor network nodes. At present, the wireless sensor network node generally uses traditional chemical battery. Because of the large numbers of devices and their small size, changing the battery is unpractical or simply not feasible. It cannot fully meet the development requirements of wireless sensor networks. Therefore, more and more attention has been attracted to harvest energy from the surrounding environment to achieve the self-power for wireless sensor networks [4–6]. The combination of an energy harvester with a small-sized rechargeable battery (or with another energy storage system like a thin-film rechargeable battery or a supercapacitor) is the best approach to enable energy autonomy of the network over the entire lifetime. Some possible ambient energy sources are, for instance, photonic energy, thermal energy, or mechanical energy. Because of fast response, low cost, simple structure, no electromagnetic interference, easy manufacture, and so forth, piezoelectric energy harvesters are suitable for wireless sensor networks [7].

Piezoelectric energy harvesters convert mechanical strain energy into electricity. When the resonance frequency of the harvester matches with the input frequency of vibration, the harvester can output the maximum electric power. In practical applications, there are two important problems in piezoelectric energy harvesters. Firstly, the bandwidth of the piezoelectric device is relatively narrow. The vibration status is often unsteady and varies from applications to applications

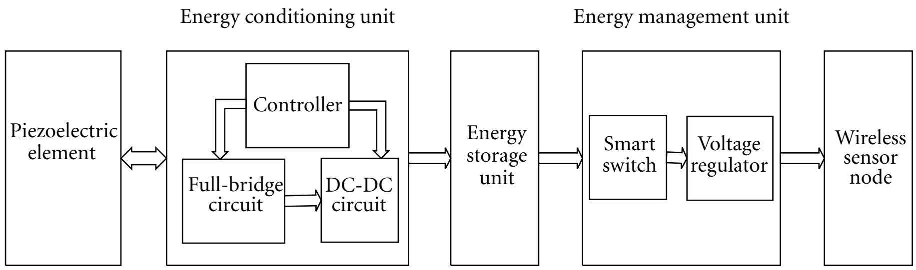

Figure 1: Schematic of the energy supply system.

and from time to time. If the vibration frequency is slightly away from the resonance frequency, the output electricity will significantly decrease. To enhance the harvested power, we need to track the vibration status dynamically and adjust the piezoelectric energy harvester for best load matching. Secondly, the energy harvesting efficiency is small, and the harvested energy is very little.

The purpose of this paper is placed on resolving the two aforementioned challenges by using the designed ultra-low-power energy supply circuit to harvest maximal energy for wireless sensor network nodes. The energy supply system can run an adaptive active piezoelectric harvesting technology to generate an optimal control voltage and improve harvested energy in the broadband. The remainder of this paper is organized as follows. The related work in the literature is presented in Section 2. Section 3 gives an overall design scheme of the energy supply system. Section 4 details the energy conversion unit and the active piezoelectric energy harvesting technology. The energy management unit is given in Section 5. Section 6 gives the system simulation, results, and discussion. Finally, we draw the conclusions of this paper in Section 7.

2. Related Work

A great amount of researches has been conducted about the energy harvesting technology as a self-power source for wireless sensor network nodes. Shwe et al. exploited a temperature sensing system which harvested the power energy from surrounding machinery vibration by the piezoelectric generator [8]. The approach is very useful in real-time remote monitoring of the machine temperature by sensor network in industries. Tan et al. presented an energy harvesting circuit design of piezoelectric pushbutton generator for wireless radiofrequency (RF) transmitter [9]. When the piezoelectric push button is depressed, 67.61 mW of electrical energy is scavenged and it is sufficient to transmit 12-bit digital word information.

As described above, the harvested energy by the piezoelectric energy harvester is very small. At the same time, it is greatly affected by the vibration status (i.e., magnitude and frequency). Therefore, previous research works have addressed the issue of maximizing the harvested electrical power. Several optimization schemes have been proposed in the literature [10, 11]. They are based on one of these principles: reducing the power loss in rectifying diodes [12], improving the extracted power by using an adaptive circuit [13, 14], adaptive control of the rectified DC voltage [15], or adjusting the natural frequency of piezoelectric energy harvesters [16]. At present, there are three predominant energy harvesting circuits: the passive diode-rectifier circuit [17], the semiactive circuit [18–20], and the active circuit [21]. The passive diode-rectifier circuit is the simplest technology, and its efficiency is the lowest. In the semiactive circuit, the output voltage can be processed nonlinearly by switched control circuit to increase its magnitude and change its phase so that the harvested electrical energy is maximized. In the active circuit, appropriate electrical boundary conditions applied to the piezoelectric element can push the harvested energy to the limits of the piezoelectric harvester. To improve the adaptability of the energy supply system, we propose an adaptive active piezoelectric technology in this paper with the natural frequency of the energy supply system easily adjusted by changing the amplitude and phase of its control voltage.

3. Energy Supply System

The energy supply system that can be used to convert the energy of ambient mechanical vibrations to electricity is used to power the wireless sensor node. In order to increase the generated power and convert more mechanical energy effectively, an energy supply system must be employed. Figure 1 presents a schematic of the proposed system. It contains a piezoelectric element, an energy conditioning unit, an energy storage unit, and an energy management unit.

The piezoelectric element converts the external vibration mechanical energy to alternating power and outputs electrical energy to the energy storage unit through the energy conditioning unit. In the energy conditioning unit, the controller runs an active piezoelectric energy harvesting technology which will be discussed in the next chapter. It outputs an optimal control voltage applied to the full-bridge circuit and the DC-DC circuit. The energy storage unit which is used to store the generated electrical energy is commonly a rechargeable battery or a supercapacitor. The energy management unit contains two parts, a smart switch and a voltage regulator, and monitors the voltage of the energy storage unit. When the voltage of the energy storage unit is in the setting range, the energy management unit can output a constant voltage to power the wireless sensor node.

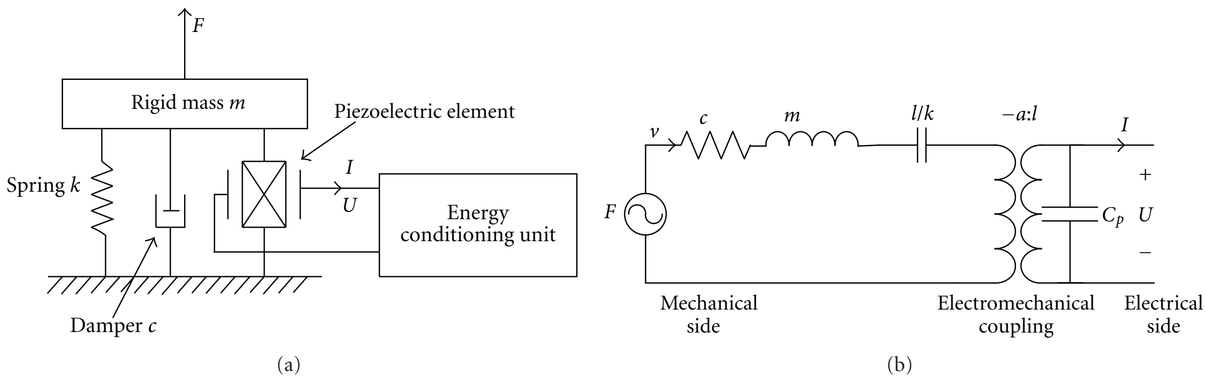

Figure 2: Electromechanical coupling model and equivalent circuit model.

4. Energy Conditioning Unit

The energy conditioning unit is the most important part of this energy supply system. It determines the harvesting power of the energy supply system and affects the lifetime of the wireless sensor node. An active piezoelectric energy harvesting technology is used to this energy conditioning unit. When the frequency of the external exciting force changes, it can adaptively generate an optimal control voltage applied to the piezoelectric element. Therefore, this system can be in resonant state and realizes impedance matching. Figure 2 presents the electromechanical coupling model and the equivalent circuit model of the piezoelectric energy harvester [22].

In this basic approach, v is the exciting velocity, m is the rigid mass, c represents the damping coefficient, the spring k corresponds to the stiffness of the mechanical structure, α is the force factor, and C_P corresponds to the plate capacitance of piezoelectric element. U is the output voltage, and I is the output current of the piezoelectric element.

Assuming that the external exciting force F is sinusoidal, the impedance of the mechanical side is given by

$$\vec{Z}_m = c + j\left(\omega m - \frac{k}{\omega}\right), \tag{1}$$

where $\omega = 2\pi/v$. When the impedance of the electrical part corresponds to the mechanical part, the maximum energy can be harvested. The optimal matching impedance of the mechanical side is

$$\vec{Z}_m = c + j\left(\frac{k}{\omega} - \omega m\right). \tag{2}$$

Therefore, the optimal impedance of the electrical part can be expressed as

$$\vec{Z}_m = \frac{\omega^2 m - k + j\omega c}{\omega^2 c_p - j\omega\left(\omega^2 c_p m - ck\right)}. \tag{3}$$

Starting from (3), the optimal impedance is difficult to be achieved. We propose an active piezoelectric harvesting technology and apply a control voltage to piezoelectric element for generating the equivalent impedance.

The optimal control voltage can be found out

$$\vec{U}_{\text{opt}} = \frac{-\omega c - j\left(k - \omega^2 m\right)}{2\alpha\omega c}\vec{F} \tag{4}$$

The optimal magnitude of the control voltage can be expressed by

$$U_{\text{mag}} = \sqrt{\omega^2 c^2 + \left(k - \omega^2 m\right)^2}\frac{F_m}{2\alpha\omega c}. \tag{5}$$

The optimal phase angle between the control voltage and the excitation force can be written as

$$\theta = 180 - \arctan\left(\frac{k - \omega^2 m}{\omega c}\right). \tag{6}$$

To achieve the active piezoelectric energy harvesting technology, a circuit of the energy conditioning unit is shown in Figure 3. When in the external environment vibration occurs, piezoelectric element converts mechanical energy into electrical energy. Because the output energy of the piezoelectric element is alternating, a full-bridge rectifier is essential to transform the AC to the DC. A step-down converter is mainly used to regulate the rectified voltage, so the system can output the maximum power by setting the duty cycle of the DC-DC converter. The power detector detects the power which flows into a constant voltage rechargeable battery and inputs the value of the power to the MSP430F169 controller. The MSP430F169 controller can give the optimal amplitude and phase angle of a control voltage. If we use the excitation force as the reference, the phase generator will generate a square-wave drive signal of the optimal phase angle between the control voltage and the excitation force to control the four MOSFETs of the full-bridge converter which can apply the optimal control voltage to the piezoelectric element.

The full-bridge rectifier adopts a diode rectifier and four N-channel ZVN3320 MOSFETs which are controlled by the phase angle between the control voltage and the vibration force. Firstly, it can convert AC power to the DC power. Secondly, it can apply the optimal control voltage to the piezoelectric element.

Because the power levels associated with the piezoelectric energy harvester are very low in the practical application, a

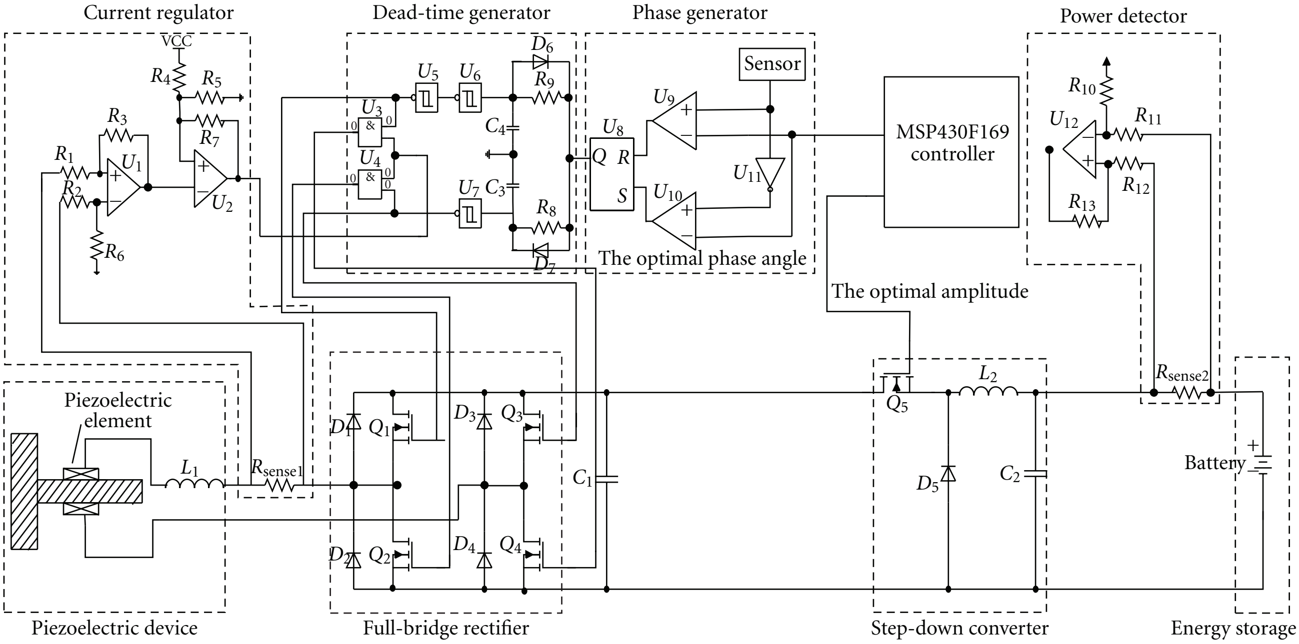

Figure 3: Energy conditioning unit circuit.

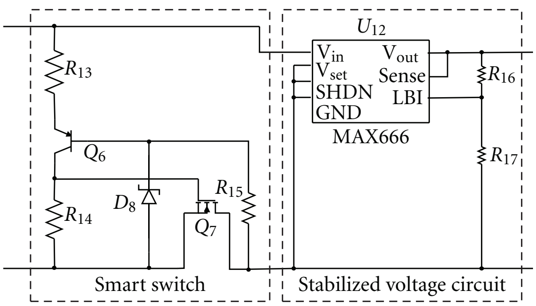

Figure 4: Circuit of the energy management unit.

step-down converter is designed to adjust the rectifier voltage for maximizing the output power. In the implementation, the IRF7853 was chosen as the transistor for its high speed and low power consumption. The optimal magnitude of the control voltage is used to control the transistor to get the optimal rectifier voltage.

In the phase generator, a TS862 by ST is chosen as the comparator for its ultra-low-power consumption. It compares the vibration force signal detected by the accelerometer to the optimal control voltage and generates two pulse signals that are 180° out of phase. Finally, RS trigger transforms the pulse signals to a square-wave phase signal.

To avoid the simultaneous turn-on of the two switches in the same bridge arm, a dead-time generator is essential. SN74LVC3G14 and SN74AHCT08 by TI are chosen as the Schmitt-trigger inverter and the AND gate.

During the voltage transition periods of the piezoelectric element, there may be a large charging/discharging current resulting in large I^2R loss, so a current regulator is developed. It can monitor the output current and output pulse signals to reduce the power loss. At the same time, a power detector is necessary and can be simply built by a differential amplifier with a sense resistance to measure the output power.

5. Energy Management Unit

The energy management unit detects the voltage of the energy storage unit and controls the output power to drive the operation of wireless sense nodes. It contains two parts: a smart switch and a stabilized voltage circuit. Figure 4 presents the circuit of the energy management unit.

When the external vibration occurs, the rechargeable battery of the energy storage unit is charged. If the voltage of the rechargeable battery increases to the threshold voltage which is determined by the voltage stabilizing diode D_8, the transistor Q_6 turns on. At the same time, the resistor R_{14} divides the voltage of the rechargeable battery and makes the MOSFET Q_7 conduct. The rechargeable battery begins to discharge, and the power is transferred to the stabilized voltage circuit. When the voltage of the resistor R_{14} is too low to make the MOSFET conduct, the energy management unit disconnects. The rechargeable battery continues to be charged.

6. Experimental Results and Discussions

Experimental results are taken to validate the energy supply system presented in this paper and to demonstrate the operation of the energy supply system. A sinusoidal exciting force generated by the shaker is applied to the piezoelectric element. First of all, we test the performance of the energy conditioning unit. Under the active piezoelectric energy harvesting technology, the voltage and current of the piezoelectric element are shown in Figure 5. It can be seen that when the vibration force happensat a maximum or minimum value, the voltage of the piezoelectric element will turn in the short time, and the current will be well regulated. Because of the current regulator, the out current is very small among −10 mA to 10 mA.

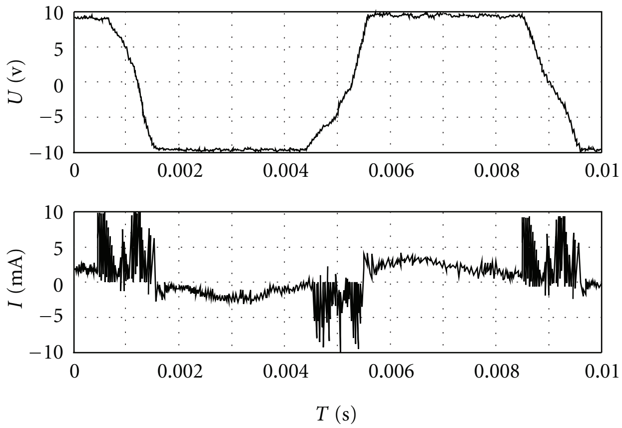

FIGURE 5: Voltage and current of the piezoelectric element.

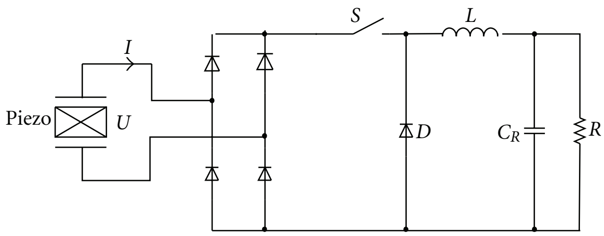

FIGURE 6: Classic energy harvesting technology.

Ottman et al. design a classic energy harvesting technology for wireless remote power supply, as shown in Figure 6 [23]. It consists of an AC–DC rectifier with an output capacitor, an electrochemical battery, and a switch-mode DC–DC converter that controls the energy flow into the battery.

Compared to the classic energy harvesting technology, Figure 7 presents the experimental and theoretical power of the energy conversion unit. Because of the circuit efficiency, the harvested power is no longer a constant for different excitation frequencies. The maximum power harvested by the active circuit is 9.8 mW at the resonance frequency 85 Hz. In the nonresonant frequencies, the experimental power regulated by the active piezoelectric energy harvesting technology does not quickly reduce. The output power is up to 4 times larger than the power by the classic energy harvesting technology in nonresonance frequencies.

Assuming the input of the energy management unit is a sinusoidal wave, the output voltage of the smart switch is presented in Figure 8. When the input voltage is lower than 3.6 V, the output voltage is 0. When the input voltage is higher than 3.6 V, the output voltage equals to the input value and the smart switch is equivalent to a voltage follower.

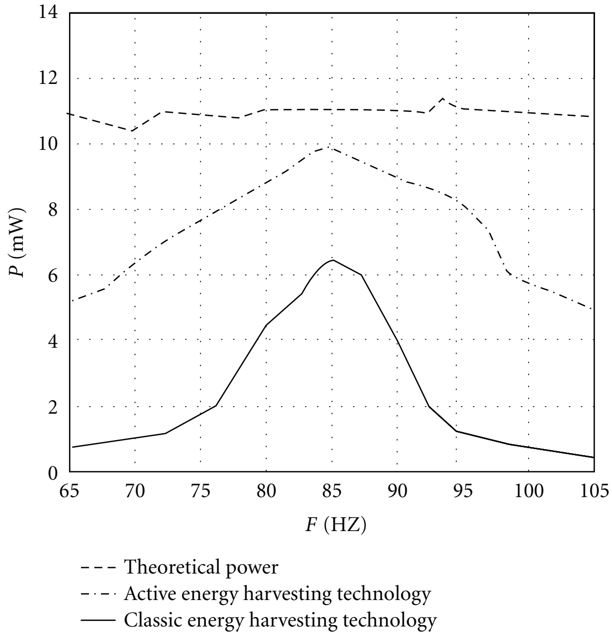

FIGURE 7: Experimental and theoretical power of the energy conditioning unit.

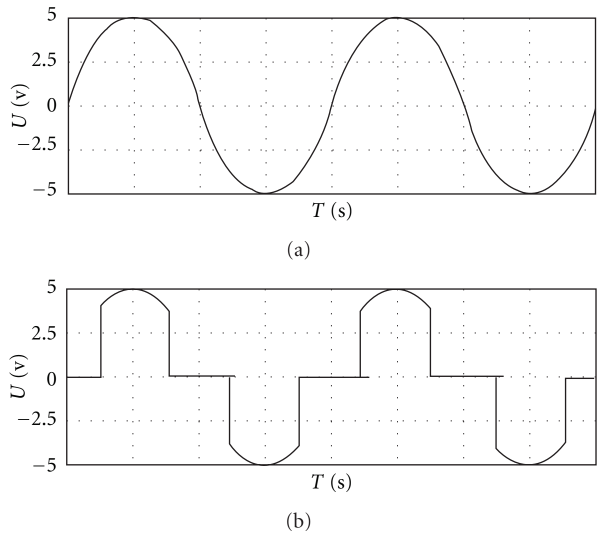

FIGURE 8: Input and output voltage of the smart switch.

7. Conclusions

In this paper, a new energy supply system based on the mechanical vibrations for the wireless sensor node is discussed. An active piezoelectric energy harvesting technology is proposed to make the impedance of the electromechanical coupling system matching. Therefore, the energy supply system can improve the harvested power within the wide bands. At last, the energy supply system can output the constant voltage through the energy management unit to power the wireless sensor node.

Acknowledgments

This research is supported by the National Hi-Tech Research Development Program (863 Program) (no. 2009AA044902), the Key Scientific and Technological Project of Henan Province (91100210300), the Henan University of Science and Technology Scientific Research Start-up Foundation for

Dr. (no. 09001550), the National Defense Project (JPPT-ZCGX1-1), the Major Project of Basic and Advanced Technology Research of Henan Province (No. 112300413205), the Henan University of Science and Technology Innovation Fund Project for Postgraduates (CXJJ-YJS-Z011), and the Education Department of Henan Province Key Science and Technology Research Project (12B510010).

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