Micro-Energy Testing Method for Output Power and Experimental Research

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Abstract. This paper proposes a testing method for measuring the output of micro-energy harvesters, deriving the specialized testing formula for output power due to the complexity and uniqueness in the test of micro-energy system. A set of micro-energy testing system based on ARM9 was designed to verify the result and the output of the voltage and power parameters from the micro-energy harvesters were tested and analyzed, including wind-induced vibration micro-energy harvester and solar collector. Experimental results show that the relative error of the testing system is less than 10%, and the measurement accuracy meets the practical measurement requirements.

Introduction

The MEMS micro-energy harvester is widely used in various wireless sensor networks [1-2], embedded systems, or microelectronic interactive systems due to the characteristic that it can power electronic devices by collecting vibration energy [3], solar energy, wind energy [4], and the like from the environment. However, most micro-energy harvesters at this stage have the limitations of low output power, poor load capacity and inability to continue power supply. This drawback not only limits the field of its application, but also causes total difference of testing method between micro-energy and ordinary energy in terms of output power.

In recent years, researchers all over the world have begun to take up theses and researches on micro-energy system, but the measurement of output power remains the traditional method with the aid of oscilloscopes. Qiaochu Tang and other researchers at the Shanghai Institute of Microsystems and Information Technology in 2015 designed a piezoelectric-based vibration energy harvester and used an oscilloscope to test its performance [5]. University College Cork and Paderborn University in Germany also proposed a similar testing scheme about the load characteristic of piezoelectric micro-generator [6-7].

Such traditional methods are no longer suitable for the modern testing requirements of micro-energy since manual operations make the analysis results have the disadvantages of large uncertainty, low
This paper aims to propose a general output power testing method for micro-energy, based on the analysis of micro-energy output characteristics and the actual demand of micro-energy supply. On the one hand, the paper derived the micro-energy testing formula using Nyquist Theorem. On the other hand, an ARM9-based micro-energy testing system was designed to measure output power from various common micro-energy harvesters. Finally, the testing experiment system was set up and implemented and analysis results of the signal were provided.

Analysis of Output Power in Micro-Energy

Most of micro-energy harvesters rely on solar, wind or vibration energy in the environment to generate electricity. Generally, they can only produce small-scale power (units between microwatt and milliwatt) and due to the weak driving ability, most harvesters need energy storage device to achieve instantaneous high-power supply through the accumulation of electric charge, unlike traditional energy supply. Regarding of the characteristics of instantaneous power supply, systems powered by micro-energy (such as wireless micro-sensors and automatic navigation detonators) generally have two states which are low-power sleep and high-power operation.

The test of micro-energy output power needs to simultaneously consider the two modes of operation: the power consumed by the load circuit in the sleep state should be less than the output power of the micro-energy harvester and the energy storage device is charged. In high-power operation state, the energy storage device discharges and provides high-power output instantaneously.

The testing method of the output power is considered under the two working modes, namely, the charging and discharging process of the energy storage device. When the output of the micro energy system changes, it is assumed that the energy stored in the capacitor is $W$ and the capacitance is $C$. The voltage across the capacitor is $U$. $\Delta t$ and $\Delta W$ represent the time interval between $t_1$ and $t_2$ and the change in energy during that time, respectively. The calculation formula of the output power can be written by the conservation of energy as:

$$W = \frac{1}{2} \times C \times U^2. \tag{1}$$

$$P = \frac{\Delta W}{\Delta t} = \frac{W_2 - W_1}{t_2 - t_1} = \frac{1}{2} \frac{C(U_2^2 - U_1^2)}{t_2 - t_1} \tag{2}$$

In sampling systems, the sampling theorem is generally used to capture all information from a discrete sample sequence. Testing system commonly uses analog-to-digital converters to collect voltage values across the load. In this way, output power can be written as:
\[ P = \frac{\sum_{n=1}^{n} P_i}{n} = \frac{C(U_1^2 - U_1^2)}{2t} + \frac{C(U_2^2 - U_2^2)}{2t} + \ldots + \frac{C(U_n^2 - U_n^2)}{2t} = \frac{1}{2} \times \frac{C(U_n^2 - U_1^2)}{nt} \]  

(3)

where, \( U_1 \) to \( U_n \) respectively denote as the voltage values at the energy storage device, \( t \) represents the sampling time interval, \( n \) is the number of sampling points.

Therefore, in low-power sleep state when the energy storage unit is charged, the instantaneous output power of the harvester can be calculated by measuring the changes of the voltage across the load. Similarly, in high-power operation state, we can also calculate the instantaneous output power. As shown in Figure 1.

![Charging and discharging process of harvester](image)

Fig 1. Charging and discharging process of harvester.

**Micro-Energy Testing System Design**

According to the theoretical analysis of the output power described in the previous section, a micro-energy testing system was designed and implemented, which can directly test and measure the output power of multiple types of micro energy including wind energy, electromagnetic piezoelectric energy, electrostatic piezoelectric energy and solar energy. In addition, in order to simulate the hybrid power supply by multi-energy in practical applications, the system can set the micro-energy supply modes (multiple series or parallel supply), capacity of energy storage, size of load resistance and other parameters.

The framework of the proposed testing system is illustrated in Fig. 2(a). mainly including: (a) embedded system; (b) multichannel rectifiers; (c) energy storage devices; (d) electric relay group; (e) load loop. MEMS micro-energy harvesters are driven by energy from the environment, including wind energy, solar energy, vibration energy, etc. The sine wave signal is rectified by rectifiers and charges energy storages. The energy storage device and load loop are controlled by the embedded system using the relay group. Users can select the power supply mode of the energy storage device and the resistance value of the load loop. Voltage values across load are measured by sampling circuit to calculate the output power. Power supply modes of the energy storage device includes single supercapacitor and a plurality of supercapacitors in series or parallel mode. Fig. 2(b) is the picture of micro-energy testing system.
The integrated micro-energy system already includes the rectifiers and energy storage. The testing process is similar except that the output does not pass through the rectifier bridge or energy storage devices, but directly connects the relay group.

![Micro-energy system diagram](image)

Fig 2. (a) Framework of the testing system; (b) the picture of the testing.

**Experimental results and analysis**

According to the basic characteristics of the micro-energy harvesters and devices in the micro-energy testing system (as shown in Table 1), the output power of the harvester in different working states was tested, and experimental results were analyzed.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temperature/$t_a$</td>
<td>298[K]</td>
</tr>
<tr>
<td>Working voltage/$V_s$</td>
<td>3.0[V]</td>
</tr>
<tr>
<td>Storage self-discharge rate/$\eta_s$</td>
<td>0.8</td>
</tr>
<tr>
<td>Diode on-voltage drop/$V_d$</td>
<td>0.5[V]</td>
</tr>
<tr>
<td>System natural frequency/$\omega_n$</td>
<td>23.4[Hz]</td>
</tr>
<tr>
<td>Energy storage capacity/C</td>
<td>12[mF]</td>
</tr>
<tr>
<td>Frequency of sampling/f</td>
<td>1M[HZ]</td>
</tr>
</tbody>
</table>

**Measurement of output voltage in various micro-energy sources**

In the first set of experiments, vibration micro energy harvester and solar energy collector supplied the testing system respectively. Single supercapacitor was set as the energy storage device and Load impedance was 500Ω, 1000Ω and 2000Ω. The output voltage value of the testing system was collected by the A/D conversion module and dynamically displayed on the display module. Fig. 3(a) and Fig. 3(b) showed the results.

Fig. 3 showed that testing system had experienced three stages: storage energy, energy saturation and energy release. Using Eq. 1, the output power of the system in the charging phase and the discharging phase can be calculated. The error is within 10%, compared with the rated output power of the micro-energy harvesters. The results is shown in Table 2.
According to Thevenin’s theorem, any power source can be equivalent to a series connection of voltage source and impedance, where the impedance is equal to the input impedance when all power supplies are set to zero. In the case where the voltage source is externally connected to the load resistor, the voltage source has the maximum output power when the load impedance is equal to the conjugate complex of the input impedance. Therefore, in this experiment, the output voltage and output power were measured with the change of load resistor in 1Ω, 10Ω, 100Ω, 1KΩ, 10KΩ, and 100KΩ to calculate the matching impedance of the micro energy harvester. Fig 4 shows that the system output voltage gradually reaches the peak voltage of 3.6V while the output power undergoes a process of rising first and then decreasing as the load resistance value increases. Therefore, it can be concluded that the matching impedance of this micro-energy harvester is around 800Ω.
Conclusion

In this paper, a general output power testing method for micro-energy is proposed and a testing system is designed and verified. Experimental results show that the error of micro-energy testing system is less than 10% and can be used in some occasions where the accuracy is not high. In addition, analysis also shows the testing system can measure the matching impedance of harvesters. The testing system makes a meaningful exploration in the auto-testing field of micro-energy.

References


Fig 4. Output voltage and power curve with the change of load resistor.