Multi-Source Energy Harvesting for Wireless Sensor Nodes

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Abstract

The past few years have seen an increasing interest in the development of wireless sensor networks. But the unsatisfactory or limited available energy source is one of the major bottlenecks which are limiting the wireless sensor technology from mass deployment. Ambient energy harvesting is the most promising solution towards autonomous sensor nodes by providing low cost, permanent, and maintenance-free energy source to wireless sensor nodes. In this paper, we first invested available energy source such as solar, vibration, thermal and other potential energy sources, and described the mathematical model of each energy source. Secondly, a novel adaptive topology maximum point power tracking method is proposed. This method is that changes the solar cells array from series to parallel or series-parallel mixed way to find out a best array that output the maximum power. This method also can be used in other energy source. At last, we purchased the matured energy generator: vibration, thermal, and solar panels to measure and verify the output power of each energy source. The experimental result showed that the conversion efficiency of this novel MPPT method can reach 60%-80% in outdoor and it is able to supply sufficient power to wireless sensor nodes.
Contents

Abstract........................................................................................................................................1

1. Introduction and Background......................................................................................................4
   1.1. System Architecture..............................................................................................................5
   1.2. History...................................................................................................................................6
   1.3. Energy Harvesting Sources....................................................................................................6

2. Photovoltaic (Solar Cell).............................................................................................................9
   2.1. Photovoltaic Model................................................................................................................9
   2.2. Maximum Power Point Tracking Methods ..........................................................................12
       2.2.1. Constant Voltage Method...............................................................................................13
       2.2.2. Short-Current Pulse Method..........................................................................................13
       2.2.3. Fractional Open-Circuit Voltage (FOCV)......................................................................13
       2.2.4. Perturb and Observe Methods (P&O)............................................................................15
       2.2.5. Incremental Conductance Method (IncCond).................................................................15
       2.2.6. Comparison of MPPT Methods.......................................................................................15

3. Thermoelectric Generator ..........................................................................................................18
   3.1. Thermoelectric Effect............................................................................................................18
   3.2. MPPT Method.......................................................................................................................20

4. Vibration ....................................................................................................................................23
   4.1. Methods of Converting Vibrations to Electricity.................................................................23
       4.1.1. Electromagnetic...............................................................................................................24
       4.1.2. Electrostatic....................................................................................................................25
       4.1.3. Piezoelectric...................................................................................................................26
       4.1.4. Comparison of Conversion Methods...............................................................................26
   4.2. Piezoelectric Model...............................................................................................................28

5. Other Energy Source ..................................................................................................................31
   5.1. Human Power.......................................................................................................................31
   5.2. Wind/Air Flow.......................................................................................................................31
   5.3. Electromagnetic....................................................................................................................32
6. Energy Storage ........................................................................................................... 33
   6.1. Super Capacitor ................................................................................................. 33
   6.2. Batteries ........................................................................................................... 34
7. Adaptive-Topology MPPT Method ........................................................................... 35
   7.1. Solar Cell Output Characteristics .................................................................... 35
   7.2. MPPT Method and Model ............................................................................... 37
   7.3. System and Control Flow ................................................................................ 39
8. Experimental Result ............................................................................................... 41
   8.1. Thermal Generator Result ............................................................................... 41
   8.2. Vibration Result ............................................................................................... 46
   8.3. Solar Cells Array Result .................................................................................. 48
   8.4. Power Supply to MCU .................................................................................... 57
9. Conclusion and Future Work .................................................................................. 59
References ..................................................................................................................... 60
1. Introduction and Background

The past few years have seen an increasing interest in the development of wireless sensor networks. It is obviously that more and more wireless sensor nodes will be deployed around our environment, such as the monitoring of human living condition, environment, animals and plants, health monitoring of civil structures, industry control etc. In many applications, for example, an ECG sensor is taken by a patient to monitor his heart, and a light sensor embedded in a light to adjust light illumination.

In order to operate these sensors, some of them are able to be powered by common power such as 220V AC power which connects to power grid or other high-power source. But under most of circumstances, wireless sensor nodes or sensors which can hardly have physical connections to the outside world, they must be powered by themselves or batteries. Unfortunately, batteries have many disadvantages, included bulk size, finite energy, limited off-shelf life, and chemical that could course environment pollution [1]. These disadvantages will increase wireless sensor network maintain cost. Batteries must be replaced by new batteries every one or two years because of its life. Especially in wilderness, replace new batteries is a complex task. To overcome these disadvantages of battery, a self power, scavenging energy from ambient environment and long life low cost power system is required in wireless sensor networks.

Owing to the limiting factor of batteries on the above disadvantages, few kinds of available ambient energy sources such solar and vibration have been developed to supply power to wireless sensor node. The purpose of this paper is to review existing and potential power source for wireless sensor network and design a multi-source energy harvesting management system. This power management system includes energy scavenging module, control module and energy storage module.

In this paper, we would introduce the power system architecture, history of energy harvesting in chapter 1. From chapter 2-6, we would detail study available ambient energy source, energy reservoir, and charger. In chapter 7, we propose a novel MPPT method to optimize solar cell, this method also can be used in other ambient source. The experimental results we be exhibited in chapter 8. At last in chapter, we would like to conclude this paper and propose some future tasks.
1.1. System Architecture

In order to supply ambient environment energy to wireless sensor nodes, the power system architecture should consist of at least three modules: an energy source, an energy reservoir, and charge controller. As shown in Fig. 1.1, this is the fundamental power system architecture. It includes an ambient energy source, an energy reservoir module (battery and buffer), and charge controller (MCU and switch).

Ambient energy source, typically defined as power generator. This module consists of some power generators and a maximal power point tracking (MPPT) circuits. The generator converts ambient energy source such as solar, mechanical energy, air flow, thermal etc. to electrical energy. The conversion ability depends on the ambient energy source density, the generator size and production technology. In order to maximize conversion, a MPPT circuit is necessary and controlled by charging controller or MCU. The MPPT method varies from different ambient energy source.

Buffer and battery are two important parts of energy reservoir module. Buffers are typically capacitor, super capacitor. These buffers collect energy from power generator and supply power to charging controller. They also charge the battery if the collected power is larger than consumed power. Battery supply energy to system when collected power is less than consumed power.

Charge controller is always a micro controller unit (MCU) which is powered by buffer or
battery, it controls the MPPT circuit to maximize the conversion efficiency of power generator and switch between buffers and battery.

1.2. History

The first observation of energy harvesting in form of current from ambient natural source was in 1826 when Thomas Johann Seebeck found that it occur a current flow in a closed circuit made of two different metals when the temperature is different in these two metals [2][3]. In the following decade years, thermoelectric effects were explored and power generation, and refrigeration was recognized [4].

In 1831, Joseph Henry and Michael Faraday discovered electromagnetic induction that produced electricity from magnetism [7]. In October of this year, the first direct-current generator which consisting of a copper plate rotating between magnetic poles was invented by Michael Faraday [8].

Edmund Becquerel discovered the photovoltaic effect in 1839 [5], and Charles Fritts coated a layer of selenium with a thin layer of gold and constructed the first large area solar cell in 1894 [6]. It had a higher efficiency while after developing the quantum theory of light and solid state physics in the early 1900s [5].

Pieere and Jacques Curie predicted and proved experimentally piezoelectricity in 1880, which is a phenomenon that certain crystals would exhibit a surface charge when subject to mechanical stress [2].

1.3. Energy Harvesting Sources

Ambient environment exist a large number of energy, such as solar, air flow, thermal energy and so on, but these are unlike to fossil fuel or nuclear fuel, the density of these energy source is lower than fossil fuel and nuclear fuel. Due to this reason, the cost is too high to afford if generate macro power while scavenging energy from ambient environment. With development of wireless sensor network, it requires quantity of wireless sensor nodes around ambient environment; it is usually that most of nodes are not able to connect to power grid to supply power, so long-life
ambient environment power supply is sufficient to wireless sensor networks. Owing to the different characteristics of ambient power sources, it is important to investigate characteristics of common source.

Table 1.1 Comparison of power scavenging and energy source

<table>
<thead>
<tr>
<th>Power source</th>
<th>Power density (μW/cm³)</th>
<th>Conversion efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>—Outdoor</td>
<td>15,000 (direct sun)</td>
<td>17%</td>
</tr>
<tr>
<td>—Indoor</td>
<td>150 (cloudy)</td>
<td></td>
</tr>
<tr>
<td>Vibration [12]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>—Piezoelectric</td>
<td>335</td>
<td>5%</td>
</tr>
<tr>
<td>—Electrostatic</td>
<td>44</td>
<td>9%</td>
</tr>
<tr>
<td>—Electromagnetic</td>
<td>400</td>
<td>1%</td>
</tr>
<tr>
<td>Acoustic noise [11]</td>
<td>0.003 at 75 dB</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.96 at 100 dB</td>
<td></td>
</tr>
<tr>
<td>Temperature gradient</td>
<td>15 at 10°C [11]</td>
<td>7% at 100°C</td>
</tr>
<tr>
<td>Human power [10]</td>
<td>330</td>
<td></td>
</tr>
<tr>
<td>Air flow [10]</td>
<td>7,600 at 5 m/s</td>
<td>5%-30%</td>
</tr>
<tr>
<td>Pressure variation [10]</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>

Lots of researchers have identified several micro-energy harvesting sources [6-10]:

—Solar and light.
—Thermal or temperature gradient.
—Mechanical energy, including vibrating and motion.
—Human power.
—Acoustic noise.
—Pressure variation.
—Electromagnetic.
— Air flow or wind.
— Water flow.

Table 1.1 shows the power density of variety ambient source. It is obviously that solar, vibrations and thermal source will convert decade micro Watt if an energy block have a size of several cm$^3$. 
2. Photovoltaic (Solar Cell)

The conversion of solar energy into electricity has so far focused on two approaches [14]. One is solar cell (also called photovoltaic cell or photoelectric cell), this is a device that converts the light energy into electricity by the photovoltaic directly. The other is solar-thermal that convert light energy into thermal and uses mechanical heat engines to generate electricity [15][16]. Solar-thermal achieve about maximal 5% conversion efficiency [17], which is much lower than the conversion efficiency of solar cell. The solar cell usually convert 17% of solar energy into electricity, this value could reach 35.8% in lab [18]. So this paper will focus on solar cell rather than solar-thermal.

Typically, materials used for solar cells includes poly-crystalline silicon, mono-crystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenide/sulfide [19]. Different material has different advantageous and disadvantageous, for example, poly-crystalline silicon solar cells has high efficiency but high cost, mono-crystalline silicon solar cells is cheaper and longer life than poly-crystalline silicon solar cells, but its efficiency is only about 12%, which is lower than poly-crystalline silicon solar cells 15%-24%, amorphous silicon solar cells is not stable enough.

2.1. Photovoltaic Model

A solar cell can be modeled as a current source parallel with a diode in theory, but as show in Fig.2.1, this circuit includes a series resistance \( R_s \) and a diode \( I_0 \) in parallel with a shunt resistance \( R_{sh} \) [20]. \( R_s \) is solar cell material resistance at the surface and back of solar cells, \( R_{sh} \) is the resistance from short of photovoltaic edge leakage current. Actually, \( R_s \) is a very small value, so this circuit can be simplified as Fig.2.2 in practice, in this paper, we assume \( R \) is 0.1Ω.
The PV module current \( I_{\text{panel}} \) is given by [20]:

\[
I_{\text{panel}} = I_L - I_0 \left( e^{\frac{V_{\text{panel}} + I_{\text{panel}} R_s}{a}} - 1 \right) - \frac{V_{\text{panel}} + I_{\text{panel}} R_s}{R_{sh}}
\] (2-1)

\( I_L \) is the current that generated by current source IAC, \( I_0 \) is the reverse saturation current through the diode. \( V_{\text{panel}} \) is the output voltage of solar panel. \( a \) is the modified panel ideal factor, which is defined by

\[
a = \frac{N_s \gamma k T_c}{q}
\] (2-2)

\( N_s \) is the number of cells in series, \( \gamma \) is the usual PV signal-cell ideal factor, this value is typically from 1 to 2. \( k \) is Boltzmann’s constant \((1.38 \times 10^{-23} \text{J/K})\) and \( T_c \) is panel temperature.

In above equation (2-1) and (2-2), the technology-dependant parameters such as \( R_s \) and \( R_{sh} \), they are determined by experimental voltage-current curves rather than irradiance [20]. Other
parameters depend on environment, i.e., panel surface temperature and irradiance.

In particular, different types of solar cell panel shows different voltage-current curve: mono-crystalline silicon cells exhibits a shape knee voltage-current curves and poly-crystalline and amorphous silicon cells exhibit a voltage-current slopes with a smooth knee which spanning over a large voltage range [21]. Here we derive some environment determined parameter in equation (2-1).

Assuming that the short circuit current \( I_{sc} \) is equal to \( I_L \) [22], it is obviously that we have a relationship between \( I_{sc} \) and \( V_{oc} \) [20]

\[
I_{sc} = I_0 \left( e^{\frac{qV_{oc}}{kT}} - 1 \right) + \frac{V_{oc}}{R_{sh}}
\]

\( V_{oc} \) can be written as (2-4), because of \( R_{sc} \gg V_{oc} \)

\[
V_{oc} = \left( \frac{kT}{q} \right) \ln \left( \frac{I_{sc}}{I_0} + 1 \right)
\]

\( I_0 \) and \( I_L \) is determined by irradiance and temperature [23][24]:

\[
I_0 = I_{0,STC} \left( \frac{T_c}{T_{ref}} \right)^\gamma e^{\left( \frac{qE_G}{kT_c} \right) \left( \frac{1}{T_{ref}} - \frac{1}{T_c} \right)}
\]

\[
I_L = I_{L,STC} S + \alpha I_{sc} \left( \frac{1}{T_{ref}} - \frac{1}{T_c} \right)
\]

\( I_{0,STC} \) is diode reverse saturation current under \( T_{ref} \), \( I_{L,STC} \) is the output current that the output voltage is zero, so \( I_L \) is equal to \( I_{sc} \), \( S \) is the solar irradiance expressed in W/m\(^2\)[K], \( E_G \) is band gap energy:

\[
E_G = 1.16 - 7.02 \times 10^{-4} \frac{T_c^2}{T_c - 1108}
\]

Fig. 2.3 and Fig 2.4 shows the voltage-current (V-I) curve and voltage-power (V-P) curve of solar cell under three kind of different solar irradiance, the red triple has the highest solar irradiance and green round has the lowest solar irradiance. As shown in these two figures, the output current and output power increase with the rise of solar irradiance.
2.2. Maximum Power Point Tracking Methods

There is a probable mismatch between the load characteristics and the maximal power points (MPP) of the solar cell array [25]. So in most solar cell application, maximal power point tracking (MPPT) is essential to match the load and solar cell array as possible. As shown in Fig. 2.4, the maximal power point load is different in different solar irradiances.

There are several methods to track the MPP voltage. In medium-high power photovoltaic
system, power feedback method is wildly used, Perturbation and Observation Method (P&O) [26], the Incremental Conductance Method (IncCond) [27], and the Hill Climbing Method (HC) [28] are three popular tracking methods based on power feedback method. Fractional Open-Circuit Voltage (FOCV) is widely adopted in small scale solar cell system [29]. This paper will give a brief instruction of popular MPPT methods [30].

2.2.1. **Constant Voltage Method**

Constant Voltage Method is a simple method to track solar cell MPP. In this method, the output voltage $V_{out}$ is equal to a constant voltage $V_{ref}$, which is a MPPT voltage of solar cell. $V_{PV}$ is the solar cell voltage, If $V_{PV} > V_{ref}$, the DC/DC bucks $V_{PV}$ to $V_{ref}$, otherwise, the DC/DC boost $V_{PV}$ into $V_{ref}$ to match the maximal power point voltage. This method is used in the condition that the solar cell panel is in low insulation condition [31] or insulation is constant while temperature varies.

2.2.2. **Short-Current Pulse Method**

In fact, the MPP current is proportional to the short current $I_{sc}$ under various conditions of insulation, so this method is that giving a reference current $I_{ref}$ to convert to track and convert $I_{PV}$ into $I_{ref}$. In order to obtain this measurement, it should introduce a static switch in parallel with the solar cell panel to create the short circuit condition.

2.2.3. **Fractional Open-Circuit Voltage (FOCV)**

There is nearly linear relationship between the operating voltage at MPP $V_{mpp}$ of a solar cell module and open-circuit voltage $V_{oc}$,

$$V_{FOCV} = kV_{oc}$$  \hspace{1cm} (2-8)

$k$ is a constant that always ranging from 0.6 to 0.8, which depends on environment and solar
insulation levels. In this method, $V_{FOCV}$ approaches 0%-5% error of $V_{mpp}$. It requires measurements of the voltage $V_{oc}$ when the circuit is open.

As shown in Table. 2.1, we measured six conditions of environment, the experimental results show the constant $k$ is ranging from about 60% to 70%. In Table. 2.2, assume $V_{FOCV} = 0.6$ and $V_{FOCV} = 0.65$ respectively, the power tolerance is ranging from 93.08% to 100% and 94.69% to 99.52% respectively.

<table>
<thead>
<tr>
<th>Table 2.1 Maximal Point Power and Constant $k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Circuit Voltage ($V_{OC}$)</td>
</tr>
<tr>
<td>---------------------------------</td>
</tr>
<tr>
<td>6.36</td>
</tr>
<tr>
<td>12.49</td>
</tr>
<tr>
<td>3.14</td>
</tr>
<tr>
<td>6.20</td>
</tr>
<tr>
<td>3.10</td>
</tr>
<tr>
<td>12.43</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Table. 2.2 Power Tolerance of Different Constant $k$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximal Point Power(mW)</td>
</tr>
<tr>
<td>--------------------------</td>
</tr>
<tr>
<td>4.17</td>
</tr>
<tr>
<td>4.33</td>
</tr>
<tr>
<td>4.26</td>
</tr>
<tr>
<td>2.56</td>
</tr>
<tr>
<td>2.60</td>
</tr>
<tr>
<td>2.55</td>
</tr>
</tbody>
</table>
2.2.4. Perturb and Observe Methods (P&O)

Perturb and Observe method is a method that operates by periodically perturbing (decrementing or incrementing) the panel voltage and comparing the solar cell output power with the previous perturbation cycle. If the panel output voltage changes and power increases, the control system moves the solar cell output operating point in that direction, otherwise the output operating point moves into opposite direction. There is a disadvantage that when the solar cell panel reach the maximal power point, the system still perturbs and oscillates around the maximal power point periodically, which reducing the output power [30].

2.2.5. Incremental Conductance Method (IncCond)

IncCond is an improvement method of P&O. This method is based on the observation that the following equation holds at the MPP [28]:

\[
\frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} = 0
\]  \hspace{1cm} (2-8)

Where \( V_{pv} \) and \( I_{pv} \) are the output solar cell voltage and current respectively. If \( \frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} < 0 \), the operating point in the P-V curve is on the right side of MPP, whereas when \( \frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}} > 0 \), it is on the left side of MPP. In practice, it is necessary to define a threshold value \( \varepsilon \), if \( |\frac{dI_{pv}}{dV_{pv}} + \frac{I_{pv}}{V_{pv}}| < \varepsilon \), which means that the operating point reaches the MPP and the control system stop to perturb until a change of \( dI_{pv} \).

This method requires the measurement of the solar cell voltage \( V_{pv} \) and current \( I_{pv} \) to determine the correct perturbation direction.

2.2.6. Comparison of MPPT Methods

The purpose of maximum power point tracking is increasing the efficiency of energy conversion. Hence, we compare the conversion efficiency of above maximum power point tracking methods. In [30], the author took into account two different irradiance cases. Case 1 is
characterized by 441 W/m$^2$ and 587 W/m$^2$; case 2 is 0W/m$^2$, 272 W/m$^2$, 441 W/m$^2$ and 587 W/m$^2$ with a time of 160s, see Fig. 2.5 and Fig. 2.6 [30].

![Fig. 2.5 Case 1 of Solar MPPT Comparison](image1)

![Fig. 2.6 Case 2 of Solar MPPT Comparison](image2)

Table 2.3 shows the comparison result of above mentioned maximum power point tracking methods. In case 1, the average power in 180s is $\frac{4493}{180}=25$W, and in case 2, this average power is about 20.6W. As shown in Table 2.3, Perturb and Observe Methods has the highest efficiency in both cases, which will reach more than 96%. The efficiency of Incremental Conductance Method, Constant voltage method and Fractional Open-Circuit Voltage are from 93.5% to 93.8% in case 1.
and from 94.1% to 94.5% in case 2. These three methods efficiency are nearly the same. Compared with above four methods, Short-Current Pulse Method has the lowest efficiency which is only 91% and 89.2% respectively in both cases. But Fractional Open-Circuit Voltage is widely adopted in small scale solar cell system than other methods [29].

Table 2.3 Efficiency Comparison of Different MPPT [30]

<table>
<thead>
<tr>
<th>Method</th>
<th>Case1</th>
<th>Case2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ideal</td>
<td>4493 J</td>
<td>3298 J</td>
</tr>
<tr>
<td>Perturb and Observe Methods</td>
<td>4346 J</td>
<td>3212 J</td>
</tr>
<tr>
<td>Incremental Conductance Method</td>
<td>4215 J</td>
<td>3117 J</td>
</tr>
<tr>
<td>Constant voltage method</td>
<td>4201 J</td>
<td>3100 J</td>
</tr>
<tr>
<td>Fractional Open-Circuit Voltage</td>
<td>4200 J</td>
<td>3104 J</td>
</tr>
<tr>
<td>Short-Current Pulse Method</td>
<td>4088 J</td>
<td>2942 J</td>
</tr>
</tbody>
</table>
3. Thermoelectric Generator

In recent years, there have been some developments in materials and structures for use in highly efficiency thermal energy system. Thermoelectric generator is a device that converts the temperature difference between two sides of conductor or semi-conductor into electricity. This phenomenon is called thermoelectric effect or Seebeck effect. There typical efficiency is always as much as 14% [32][35].

3.1. Thermoelectric Effect

A temperature difference between two points in a conductor or semiconductor results in a voltage difference between these two points is called Seebeck effect [33]. Vice versa, when a current is made to flow through a junction composed of materials A and B, heat is generated at one side and absorbed at other side.

![Fig. 3.1 the Seebeck Effect](image)

Considering Fig 3.1, this diagram is conductor that heated one side and cold at other side. The electrons in the hot side are more energetic and therefore have greater velocities than the
colder side. Therefore, there is a net diffusion of electrons from the hot side toward the cold side which leaves behind exposed positive metal iron in the hot side and accumulates electrons in the cold side. This situation prevails until the electric field developed between the positive ions in the hot side and the excess electrons in the cold side prevents further electron motion from the hot and cold end [33]. Thus a voltage develops between the hot and cold ends with the cold end at negative potential.

The potential difference \( \Delta T \) form cold side to hot side can be presented as:

\[
\Delta T = \int_{T_0}^{T} SdT
\]  

(3-1)

\( S \) is Seebeck coefficient (thermopower) of hot and cold side as a function of temperature and \( T \) and \( T_0 \) are temperature of these two sides. This coefficient depends on the material’s temperature and crystal structure. In practice, the Seebeck effect is fruitfully utilized in the thermocouple (TC), hot side and cold side made by different materials. As shown is Fig 3.2, material A is cold side and material B is hot side, these two materials are connected by wire C. So formula (3-1) is presented by

\[
\Delta T = \int_{T_0}^{T} (S_A - S_B) dT
\]  

(3-2)

\( S_A \) and \( S_B \) are Seebeck coefficient of material A and B respectively.

![Fig 3.2 Thermocouple](image)

The efficiency of a thermoelectric device is defined as \( \eta \) [34]:

\[
\eta = \frac{E_{\text{Load}}}{E_T}
\]  

(3-3)

Where \( E_{\text{Load}} \) is the energy that provided to the load and \( E_T \) is heat energy absorbed at hot
junction. The maximal efficiency $\eta_{\text{max}}$ is defined as:

$$\eta_{\text{max}} = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_C}{T_H}}$$  \hspace{1cm} (3-4)$$

Where $T_H$ is the temperature at the hot junction and $T_C$ is the temperature at the cold junction. $ZT$ is the modified dimensionless figure of merit, which takes into consideration the thermoelectric capacity of both thermoelectric materials being used in the device and is defined as [36]:

$$ZT = \frac{(S_p - S_n)^2 \bar{T}}{[(\rho_n \kappa_n)^2 + (\rho_p \kappa_p)^2]^{1/2}}$$  \hspace{1cm} (3-5)$$

Where $\rho$ is the electrical resistivity, $\bar{T}$ is the average temperature between the hot and cold surface, the subscript n and p denote properties related to the n- and p-type semiconducting thermoelectric materials respectively.

### 3.2. MPPT Method

The voltage generated by thermoelectric generator changes dynamically over a wide range as function of temperature [37], which showed in Fig.3.3 Fig.3.4, the output power characteristics of thermoelectric generator. In both figures, it have the temperature gradient C>B>A.

As shown in Fig 3.5, the equivalent circuit of thermoelectric generator can be modeled as a voltage source [38]. $V_{oc}$ is open circuit voltage, which is proportional to the Seebeck coefficient and the temperature gradient, $R_s$ is internal resistance and $R_{load}$ is load resistance. $R_s$ can be calculated by $\frac{V_s}{I_{sc}}$, where $I_{sc}$ is the short circuit current of thermoelectric generator.
The maximum power point transfer condition is that $R_S = R_{Load}$ [38], assume that output voltage and output current is $I_{out}$. The output power $P$ can be expressed as [39]:

$$ P = I_{out} V_{out} = \left( \frac{V_{oc} - V_{out}}{R_s} \right) $$

(3-6)

The maximum power point is determined by the following differential relationship:
\[
\frac{\partial P}{\partial V_{out}}_{\text{max}} = \left( \frac{V_{OC} - 2V_{out}}{R_s} \right) = 0 \quad (3-7)
\]

It is obviously that while \( V_{OC} = 2V_{out} \), the output power at the maximum power point. In this case, the voltage at maximum power point is \( V_{max} \) that can be expressed by:

\[
V_{max} = \frac{V_{OC}}{2} \quad (3-8)
\]

And output power at the maximum power point \( P_{max} \) is:

\[
P_{\text{max}} = \frac{V_{OC}^2}{4R_s} \quad (3-9)
\]
4. Vibration

Vibration-to-electricity conversion is a potential source for self-sustaining wireless sensor network in many environment. Low level vibrations occur in many environments including: large commercial building, industrial environments, automobiles, aircraft, ships, trains, and household appliances [12]. Low level vibration source could generate about 300-800μW/cm³ in such environment [40]. Vibrations from a range of different source have been measured in Table 4.1 [12].

Table 4.1 List of Vibration Source with their maximum acceleration magnitude and frequency of peak acceleration [12]

<table>
<thead>
<tr>
<th>Vibration Source</th>
<th>Peak Acceleration (m/s²)</th>
<th>Frequency of Peak (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base of a 5 HP 3-axis machine tool</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>Kitchen blender casing</td>
<td>6.4</td>
<td>120</td>
</tr>
<tr>
<td>Clothes dryer</td>
<td>3.5</td>
<td>120</td>
</tr>
<tr>
<td>Door frame just after door closes</td>
<td>3</td>
<td>125</td>
</tr>
<tr>
<td>Small microwave oven</td>
<td>2.25</td>
<td>120</td>
</tr>
<tr>
<td>HVAC vents in office building</td>
<td>0.2-1.5</td>
<td>60</td>
</tr>
<tr>
<td>Wooden deck with people walking</td>
<td>1.3</td>
<td>385</td>
</tr>
<tr>
<td>Bread maker</td>
<td>1.03</td>
<td>120</td>
</tr>
<tr>
<td>Window next to busy street</td>
<td>0.7</td>
<td>100</td>
</tr>
<tr>
<td>Notebook computer while CD is being read</td>
<td>0.6</td>
<td>75</td>
</tr>
<tr>
<td>Washing machine</td>
<td>0.5</td>
<td>109</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>0.1</td>
<td>240</td>
</tr>
</tbody>
</table>

4.1. Methods of Converting Vibrations to Electricity

There are three typical methods to convert mechanical movement to electricity power [41]:
electromagnetic (inductive), electrostatic (capacitive), and piezoelectric. These three methods have their own advantageous and disadvantageous which will be discussed in following.

4.1.1. Electromagnetic

This method results from the relative motion of an electrical conductor in a magnetic field. As shown in Fig. 4.1, the basic electromagnetic generator consists of a mass mounted on a spring which vibration relative to housing when subjected to an external vibration force [42]. The relation motion between the coil and magnetic field causes a current to flow in the coil. The voltage on the coil is determined by Faraday's Law given in equation 4.1.

![Fig. 4.1 Schematic of Generic Vibration Convert][42]

\[
\varepsilon = -\frac{d\Phi_B}{dt}
\]

(4-1)

Then the maximum open circuit voltage across the coil is given by:

\[
V_{oc} = NB \frac{dy}{dt}
\]

(4-2)

Where \( N \) is the number of turns in the coil and \( B \) is the strength of the magnetic field, \( l \) is the length of on coil (\( 2\pi r \)), and \( y \) is the distance of the coil moves through the magnetic field.

This mass consists of the magnet or the coil. As shown in fig. 4.3, this system can be
reasonably described by a second-order mass \( (m) \)-spring \( (k) \) –damper \( (D_p) \) system. The equation of motion of the mass relative to the housing when driven by a sinusoidal vibration force \( F \) is given by [43]:

\[
m\frac{d^2x}{dt^2} + D_p \frac{dx}{dt} + kx = F_o \sin \omega t - F_{em}
\]

(4-3)

where \( F \) is the movement between mass and housing (or between magnet and coil). \( D_p \) is the parasitic damping force due to air resistance and material loss, \( F_{em} \) is the electromagnetic force due to the force between the current in the coil and magnet. \( \omega_r = \sqrt{k/m} \) is a mechanical resonant frequency. So it is important to have the frequency of the driving force equal to the mechanical resonant frequency to maximize displacement. When \( D_{em} = D_p \), the output power will reach the maximal electrical power, the average generated electrical power can be obtained from [42]:

\[
P_{avg} = \frac{1}{T} \int_0^T D_{em} \left( \frac{dx}{dt} \right)^2 dt = D_{em} \frac{F_o^2}{2(D_p + D_{em})^2}
\]

(4-4)

In order to harvest the maximal power, there are two aspects should be taken into account: for one thing, a strong magnet has to be attach to the generator. For another hand, how much this magnet and its motion would affect electronics is another challenge.

### 4.1.2. Electrostatic

The basic of electrostatic energy conversion is a variable capacitor [11]. Electrostatic generators are mechanical devices that produce electricity by using manual power [44][45], which consists of two conductors separated by a dielectric such as capacitor. As the conductor moves, the energy stored in the capacitor changes, that providing the mechanism for mechanical to electrical energy conversion. An electrostatic generator is always illustrated by a simple rectangular parallel plate capacitor. There are three types of electrostatic generator [11]: in-phase overlap convert, in-phase gap closing convert and out-of-plane gap closing convert.

The voltage generated by the generator is expressed by equation (4-5) [12]:
\[ V = \frac{Q}{C} = \frac{Qd}{\varepsilon_0lw} \]  

(4-5)

where \( Q \) is the charge of capacitor, \( d \) is the distance between two plates, \( l \) is the length of the plates, \( w \) is the width of the plate, and \( \varepsilon_0 \) is the dielectric constant of free space. The voltage can be increased by decrease the capacitance [46]. Then the energy converted by generator can be expressed by (4-6):

\[ E = \frac{1}{2} QV = \frac{1}{2} CV^2 = \frac{Q^2}{2C} \]  

(4-6)

### 4.1.3. Piezoelectric

Piezoelectric materials are materials that convert mechanical energy from vibrations, force and pressure into electricity. At present, polycrystalline ceramic is the most common piezoelectric material. Typically, the constitutive equations for a piezoelectric material are given by following equation [12]:

\[ \delta = \frac{\sigma}{V} + dE \]  

(4-7)

\[ D = \varepsilon E + d\sigma \]  

(4-8)

where \( \delta \) is mechanical strain, \( \sigma \) is the mechanical stress, \( Y \) is the modules of elasticity (Young’s Modules), \( d \) is the piezoelectric strain coefficient, \( E \) is the electric field, \( D \) is the electrical displacement (charge density), \( \varepsilon \) is the dielectric constant of the piezoelectric material. The open circuit which means that the electrical displacement (\( D \)) is zero is defined as:

\[ V_{oc} = \frac{-dt}{\varepsilon} \sigma \]  

(4-9)

where \( t \) is thickness of the piezoelectric material.

### 4.1.4. Comparison of Conversion Methods

It is important to discuss both of the qualitative and quantitative comparison of the above
three methods of power conversions. We present the power density to illustrate the qualitative comparison of these methods, as shown in Table 4.2.

<table>
<thead>
<tr>
<th>Type</th>
<th>Power Equation</th>
<th>Practical Maximum</th>
<th>Theoretical Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>$E = \frac{B^2}{2\mu_0}$</td>
<td>4mJ/cm³</td>
<td>400mJ/cm³</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>$E = \frac{1}{2}eE^2$</td>
<td>4mJ/cm³</td>
<td>44mJ/cm³</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>$E = \frac{\sigma^2 k^2}{2Y}$</td>
<td>17.7mJ/cm³</td>
<td>335mJ/cm³</td>
</tr>
</tbody>
</table>

In this table, the theoretical energy of piezoelectric is 335mJ/cm³ compared with the theoretical energy of electromagnetic 400mJ/cm³. But piezoelectric has the higher conversion efficiency, the practical energy density is 17.7mJ/cm³, which is more than four times of other two methods.

Besides power density, for piezoelectric method, its advantageous is supply high voltage from 2 to 10 volts, which is the direct generation of appropriate voltages. Another advantageous is that no separate voltage source is required to initiate the conversion process and no need for mechanical limit stops. But this method is difficult to implement to microelectronics system.

For electromagnetic method, it is no need separate voltage source and no mechanical stops too. But the output voltage of this method is low, which can only reach 0.1 volt, and it is also difficult to integrate with the electronics and Microsystems.

The most significant advantageous of electrostatic converter is that it is potential for integration with microelectronics. Unfortunately, it requires a separate voltage source to initiate the conversion process because the capacitor must be charged up to initial voltage for the conversion process to begin. Requiring a mechanical stop to ensure the capacitor electrodes do not come into contact and short the circuit is another disadvantageous. Table 4.3 shows the summary quantitative comparison of these three methods.

Currently, because piezoelectric material has high energy density, high conversion efficiency
and other excellent advantageous, this method has been widely used in ambient energy harvesting. So we would discuss this method detail in following.

Table 4.3 Summary Quantitative Comparison of Three Methods [12]

<table>
<thead>
<tr>
<th>Type</th>
<th>Advantageous</th>
<th>Disadvantageous</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic</td>
<td>No separate voltage source and no mechanical stops.</td>
<td>Low output voltage (0.1 volts); Hard to integrate to micro electric system.</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>Easy to integrate to micro electric system.</td>
<td>Need separate voltage source to start and mechanical stops to prevent from short circuit.</td>
</tr>
<tr>
<td>Piezoelectric</td>
<td>High output voltage (2-10volts); No separate voltage source and no mechanical stops.</td>
<td>Generator size is too big to integrate to micro electric systems.</td>
</tr>
</tbody>
</table>

4.2. Piezoelectric Model

Fig. 4.2 is the mechanical model of piezoelectric. The piezoelectric beam shakes vertically, and conversion the mechanical energy to AC current. Thus the electromechanical energy conversion mechanism of the beam can be modeled with a current source in parallel with a capacitor, this current source also can be replaced by a voltage source series with a capacitor, as shown in Fig. 4.3 and Fig. 4.4.[47][48][49]. In Fig. 4.4, the \( V_{th}(t) \) can be calculated by:

\[
V_{th}(t) = \frac{1}{C_p} \int i_p(t) dt
\]  

(4-10)
In order to rectify the AC current to DC current, typically, a full-bridge diode rectifier is used to connect to generator, as shown in Fig. 4.5. $C_p$ is a filter capacitor which connect to the load. In this case, the maximum rectified voltage occurs when $R_{load} = 0$. This is also called open circuit voltage, this value is [48]:
\[ V_{OC} = \frac{I_P}{2\omega C_p} \]  \hspace{1cm} (4-11)

Fig. 4.5 Piezoelectric Model with Full-Bridge Rectifier

Where \( \omega \) is the frequency of vibration. When it connects to load, the piezoelectric maximum voltage is limited by filter voltage: \( v_p(t) < V_F \), and if filter voltage is half of open circuit voltage:

\[ V_F = \frac{V_\omega}{2} \]  \hspace{1cm} (4-12)

The output power will reach the maximum power, this maximum average power is [49]:

\[ P_{\text{max}} = \frac{C_p \omega V_{OC}^2}{2\pi} \]  \hspace{1cm} (4-13)
5. Other Energy Source

Besides mentioned energy source above, other energy sources are available to supply power to microelectric system, such as human power, wind (air flow) and electromagnetic field [10][50].

5.1. Human Power

Human power is passive power source in that the human does not need to do anything other than that they would normally do to generate power. The average human body burns about 10.5MJ of energy per day [10]. There are some projects has proposed tapping into some of this energy to power wearable electronics such as watches. [51]. MIT has developed a piezoelectric shoe that produces an average of 330μW/cm² while a person is walking [51].

5.2. Wind/Air Flow

Wind power has been used as a large scale power source for a long time, it is common today still. This paper focuses on the small scale of wind power. The power from moving air can be calculated as follow [10]:

\[ P = \frac{1}{2} \rho A v^3 \]  (5-1)

Where \( \rho \) is the density of air, this is approximately 1.22kg/m³ normally. \( A \) is the cross sectional area and \( v \) is the air velocity.

In large scale wind system, the maximum efficiency is about 40% which depends on the air velocity and average efficiency is 20% normally. A low air velocity leads to the efficiency low than 20%. Fig. 5.1 shows the power density from air flow [10], the output power is about 0.2mW/cm² if the efficiency is 5% when air velocity is 5m/s. It is reasonable that convert the air flow to electrical power at small scale.
Recently, ambient electromagnetic especially RF energy is a possible energy source for energy harvesting. RF energy means available through public telecommunication service such as GSM and WLAN frequencies [50]. But this energy is limited by the power density and need large area to collect usable energy, the ideal collected power can be expressed as:

\[ P = P_t \frac{A_r}{4\pi r^2} \]  

(5-2)

Where \( P_t \) is the transmission power from source, \( A_r \) is the receive area, \( r \) is the distance. When harvesting in the GSM or WLAN band, the distance ranging from 25m to 100m from a GSM base station, power density ranging from 0.1 to 1.0 mW/m² which is expected by single frequencies [51]. Alternatively, a total antenna surface can be minimized if one uses a dedicated RF source, which can be positioned close to the sensor node, thereby limiting the transmission power to levels accepted by international regulations [50].

Powercast Company has developed a universal chip for the purpose of replace the battery charger. The frequency is 906MHz and the power is 2-3W, and 15mW of power is received at 30cm distance.
6. Energy Storage

There are two choices available for energy storage: super capacitor and batteries. Generally speaking, batteries are mature technology. Super capacitors have higher power density and high life time than batteries. It has been used to handle short duration power surges [54].

6.1. Super Capacitor

Compared with batteries, super capacitors have virtually infinite recharge cycles and are ideal for frequent pulsing applications. Unfortunately, super capacitors have higher leakage current, large size and cost [53]. Super capacitor can be modeled as a power source:

$$ E_{\text{t}}(t) = \max(\int (P_{\text{in}}(t) - P_{\text{out}}(t) - P_{\text{leak}}(t))dt, E_{\text{max}}) $$  \hspace{1cm} (6-1)

Where $P_{\text{in}}$ is the power from environmental energy sources, $P_{\text{out}}$ is output power and $P_{\text{leak}}$ is the leakage power caused by leakage current. The totally energy in capacitor is expressed by:

$$ E = \frac{1}{2} CV^2 $$  \hspace{1cm} (6-2)

Where $C$ is the capacitance of capacitor, $V$ is capacitor voltage. For example, if two capacitors with 22F and 50F, there storage energy are 68.75J and 156.25J respectively. The leakage current of super capacitor increases with the decreases of their capacitance and the rated voltage decreases with the increases of their capacitance, a capacitor with 22F has 0.049mA leakage current and 2.5V rated voltage, a capacitor with 50F has 0.073mA leakage current and 2.3V rated voltage. Fig. 6.1 shows the super capacitor leakage in 24 hours.

Configuration of super capacitor also plays an important role in choosing a suitable super capacitor in a system [55]. It means series or parallel with two or more super capacitors. For one hand, series lower the leakage current, but it results half the total capacitance. For another hand, parallel two super capacitors can increase the capacitance and increase the leakage current.
6.2. Batteries

Batteries are used in the condition that when the energy in super capacitor is exhausted. It needs to hold energy for a long period of time and low leakage current [55]. There are three types of rechargeable batteries are commonly used at present: Nickel Cadmium (NiCd), Nickel Metal Hydride (NiMH) and Lithium based (Li+). Lithium rechargeable battery has the lowest leakage current, highest density, high recharge cycle and high voltage for one cell. But it needs a complex charging circuit to protect battery. The NiCd battery is less used because of its low energy density. The NiMH battery has memory effect and limited by the leakage current.
7. Adaptive-Topology MPPT Method

As discussed in above chapters, solar cell is able to scavenge more energy than other energy source. Here we present a novel maximum power point tracking method on solar cells: adaptive topology MPPT method, this method also can be implemented in other energy source such as vibration and thermal.

7.1. Solar Cell Output Characteristics

The core of maximum power point tracking is impedance matching. The output impedance of solar cell is affected by many factors such as environment temperature and irradiance. It is not a constant value and varies from time to time. The solar cell array with different connection methods also occur the change of output impedance, it requires different resistors to connect to the output of solar cell to match the output impedance.

Here we model a solar cell component as one current source series with a resistor, which is mentioned in Fig. 2.2. Assume the current is 0.2mA and resistance is 0.1Ω. Fig. 7.1 and Fig. 7.2 are four solar cells series and parallel respectively.

![Fig. 7.1.Four Solar Cells Series](image)
Though Fig. 7.1 and Fig. 7.2 have different array, they have the same maximum output power if they are under the same environment. Differently, when the output power reaches maximum
output power, the loads is different. The matching load is about 8KΩ while all cells are series as shown in Fig.7.3 and the matching load is about 1KΩ while all cells are parallel which is described in Fig. 7.4.

### 7.2. MPPT Method and Model

According to above analysis, we present a novel MPPT method: for one thing, we change the solar cell array as series, parallel or series-parallel mixed array. Under the same environment, these arrays has the same maximum output power theoretically but requiring different load to match the impedance. For another thing, there are many load resistors with different resistances could be choice to connect to the solar cell array in order to choose a load to maximize the output power.

If four solar cells are used in this system, as shown if Fig. 7.5 there are three arrays are able to choose. Similarly, 2” solar cells could convert to $n + 1$ arrays.

![Available Arrays of Four Solar Cells](image)

For the purpose of conversion the solar cells array automatically, a solar cells variation diagram has been designed, as shown in Fig. 7.6. In this diagram, the cathode of Solar cell P1 connects to ground. If switch S1, S2 and S3 are on, S4-S9 are off, the array convert to array 1 as shown in Fig.7.7, all solar cells are series in this case, which is like array 1 as shown in Fig. 7.5; when S1-S3 are off, and S4-S9 are on, as shown in Fig. 7.7, Array 2, all solar cells are parallel, this is described as array 2 in Fig.7.5; if S1, S3, and S5,S6 are off, S4,S5, S8, S9 and S3 are on, the solar cells array is like array 3 shown in Fig. 7.7. This array is equal to Array 3 in Fig. 7.5. These
three types of array have the same output maximum power but required different matching loads.

![Diagram of Solar Cell Control](image)

**Fig. 7.6 Solar Cell Control Diagram**

![Diagram of Conversion of Solar Cell Array](image)

**Fig. 7.7 Conversion of Solar Cell Array**

In order to match the impedance of solar cells array, there are many resistors with different resistance and switches can be connected to the solar cell array, as shown in Fig. 7.8. The entire resistance can be calculated by:

$$ R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \ldots + \frac{1}{R_n}} \quad (7-1) $$

All switches are controlled by a MCU, the total resistance range from the minimum resistance to the maximum resistance. The number of available resistance is determined by the number of resistors. For example, if there are $n$ resistors, the available resistance is $2^n$, and if available solar cells array is $m$, there are $m \times 2^n$ combination modes.
7.3. System and Control Flow

Our system architecture is presented in Fig. 7.9, it consists five parts: solar cells, matching resistors, DC/DC, super capacitor and MCU. Solar cells and matching resistors are controlled by the MCU to output the maximum power as possible. Then the DC/DC converts the output voltage of matching resistor to working voltage such as 3.3V, 2.5V or 1.7V. The super capacitor reserves the power to supply to MCU. Fig. 7.12 is the block diagram with m solar cells and n matching resistors.

Assuming there are m available solar cell arrays in solar cells block and n available resistors in matching resistor block, so there are $m \times n$ possible combination modes in this system. Fig. 7.10 is the flow chart of MCU in energy harvesting system. In this chart, Solar(i) means the $i$ th solar cells array and Resis(j) is the $j$ th matching resistor. At the beginning, it iterates all possible combination modes of solar cells and matching resistors and measure the output voltage of solar cells array, store it in the memory of MCU. Then according to equation (2-8) to calculate the constant $k$, compare the constant $k$ with $k_{ref}$, $k_{ref}$ is a reference which is raging from 0.60 to
0.70 in this paper. The array corresponding to $k$ which is closest to $k_{ref}$ is the maximum power point array (MPP array). The environment such as irradiance and temperature changes frequently, so the system works under this array for a period and start to search a new MPP array.

![Flow Chart of MCU in Energy Harvesting System](image)

Fig 7.10 Flow Chart of flow chart of MCU in Energy Harvesting System
8. Experimental Result

In this chapter, we have measured thermal generator, vibration piezoelectric generator and variable array solar cells and compare these experimental results.

8.1. Thermal Generator Result

ECT 310 Perpetuum Module is a thermoelectric generator module developed by EnOcean [56], which is used in this paper. This module includes a DC/DC convertor, which enable to use heat as their power source. Typically, this module connects an external low cost peltier element TEC2L-15-15-5.6/73. Fig. 8.1 and Fig. 8.2 is a picture of this module and element. The size of this module and component is 14.0×14.0×5.0mm and 15.0×15.0×4.0mm respectively.

Fig. 8.1 ECT-310 DC/DC Convertor
As shown in Table. 8.1 [57], the start-up input voltage of ECT is 20mV, and maximal input voltage is 500mV. Fig. 8.3 is the Vin-Vout Characteristics of ECT-310, the input voltage is unloaded input voltage.

**Table. 8.1 Technical Data of ECT 310 [57]**

<table>
<thead>
<tr>
<th>Peltier Element Characterizes</th>
<th>TEC2L-15-15-5.6/73CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature coefficient</td>
<td>12.5mV/K</td>
</tr>
<tr>
<td>Internal resistance</td>
<td>1.44Ω</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>0.046 W/K</td>
</tr>
</tbody>
</table>

ECT 310 DC/DC Convertor

<table>
<thead>
<tr>
<th></th>
<th>Typical Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{in}$ input voltage start-up</td>
<td>20 mV</td>
</tr>
<tr>
<td>$V_{in}$ input voltage max.</td>
<td>500mv</td>
</tr>
<tr>
<td>$V_{out}$ output voltage @ $V_{in}$=20…50 mV</td>
<td>3…4V</td>
</tr>
<tr>
<td>$V_{out}$ output voltage @ $V_{in}$=20…500mV</td>
<td>3…5V($R_{load}$&lt;10MΩ)</td>
</tr>
</tbody>
</table>
The open circuit output voltage ($V_{OC}$) of peltier element is proportion to the temperature gradient between two sides of peltier element TEC2L-15-15-5.6/73. As shown in Fig. 8.4, it exists a linear relationship between open circuit output voltage and temperature gradient in two sides of peltier elements. This open circuit voltage is the maximal output voltage of element, as mentioned above, the maximal power point voltage is half of open circuit voltage. This voltage could reach several mW typically, which need connect a boost DC/DC to boost the voltage to a typical reference voltage such 3.3V etc. This is the reason why we use a boost DC/DC here.
Fig. 8.5 and Fig. 8.6 show the output characteristics of the element used in this experiment, which has the same result as described in Fig. 3.3 and Fig. 3.4. A variable resistance was used as a load and measured in three temperature gradients: 10°C, 18°C, and 33°C. The output current (I_out) linearly decreased with the output voltage in the same temperature gradient and the output voltage and current increase with the raise of temperature gradient. As shown in Fig. 8.6, the maximal output power is nearly the half of the maximal output voltage, this maximal output voltage is equal to the open circuit output mentioned above, which verified the theoretical formula (3-8).

![Fig. 8.5 Experimental Thermoelectric Generator Output Current-Voltage Curve](image1)

![Fig. 8.6 Experimental Thermoelectric Generator Output Power-Voltage Curve](image2)
Fig. 8.7 shows the output power of thermoelectric element and DC/DC convertor. The blue star is the output power of TEC2L-15-15-5.6/73CS Peltier element. This output power increased by the growing of temperature gradient. When the temperature gradient is 5°C, the output power is about 0.1mW, at 10°C temperature gradient, this power is 0.45mW. By the temperature gradient reaching to 15°C, this power will reach to 1mW. Meanwhile, if the element connects to ECT 310 DC/DC convertor directly, the transfer efficiency can be calculated by:

\[
\eta = \frac{P_{\text{max element output power}}}{P_{\text{max DC/DC output power}}}
\]  

(8-1)

This efficiency is more than 95% when temperature gradient is less than 15°C. Table 8.2 is the experimental data. It is clear that the transfer efficiency decrease with the increase of temperature gradient. Though the transfer efficiency decline, the output power of DC/DC convertor raise smoothly compared with the increase of output power of element.
Table 8.2 Experimental Data of Thermal Generator

<table>
<thead>
<tr>
<th>Temperature gradient (°C)</th>
<th>Output power of element (mW)</th>
<th>Output power of DC/DC convertor(mW)</th>
<th>Transfer efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>0.080</td>
<td>0.078</td>
<td>98.97</td>
</tr>
<tr>
<td>9.8</td>
<td>0.451</td>
<td>0.395</td>
<td>97.33</td>
</tr>
<tr>
<td>14.2</td>
<td>0.896</td>
<td>0.872</td>
<td>93.38</td>
</tr>
<tr>
<td>17.8</td>
<td>1.364</td>
<td>1.274</td>
<td>87.65</td>
</tr>
<tr>
<td>22.5</td>
<td>2.259</td>
<td>1.555</td>
<td>71.51</td>
</tr>
<tr>
<td>27.5</td>
<td>3.152</td>
<td>2.254</td>
<td>68.84</td>
</tr>
<tr>
<td>30.2</td>
<td>3.682</td>
<td>2.513</td>
<td>68.25</td>
</tr>
<tr>
<td>33.0</td>
<td>4.484</td>
<td>2.700</td>
<td>60.21</td>
</tr>
<tr>
<td>37.2</td>
<td>5.832</td>
<td>3.210</td>
<td>55.04</td>
</tr>
<tr>
<td>40.5</td>
<td>7.250</td>
<td>3.475</td>
<td>47.93</td>
</tr>
</tbody>
</table>

8.2. Vibration Result

In this paper, we use the Volture vibration energy harvesters which are developed by Mide Technology. There are six alternative standard size of Volture, which corresponds to different working frequents. Fig. 8.8 is a Volture vibration energy harvester V20W [58], all Volture vibration energy harvesters have the same shape like this picture. Table 8.3 lists main characters of these six harvesters: the working frequent is ranging from 30Hz to 275Hz, and the maximum output power can reach 9.231mW if amplitude is 1g. To ensure the most efficient harvesting, it is essential to tune the Volture’s natural frequency to match that of the vibration source. Tuning is performed by adding a tuning mass to the end of the cantilevered Volture until the natural frequency of the piezo beam is the same as the vibration source. The larger the tuning mass the lower the natural frequency of the Volture. Typically, the weight of tuning mass is ranging from 0 kilogram to decade kilogram, the detail data can be found in the data sheet of Volture.
Table. 8.3 characters of Volture Harvesters [59]

<table>
<thead>
<tr>
<th>Types</th>
<th>Recommended Working Frequency</th>
<th>Maximum Output Power (Amplitude is 1g)</th>
<th>Size(inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V20W</td>
<td>75-180</td>
<td>5.860mW on 75Hz</td>
<td>3.19×1.5×0.034</td>
</tr>
<tr>
<td>V25W</td>
<td>40-120</td>
<td>9.231mW on 40Hz</td>
<td>3.19×1.5×0.024</td>
</tr>
<tr>
<td>V21B</td>
<td>105-275</td>
<td>2.252mW on 105Hz</td>
<td>2.72×0.66×0.031</td>
</tr>
<tr>
<td>V21BL</td>
<td>40-110</td>
<td>2.662mW on 40Hz</td>
<td>3.56×0.66×0.031</td>
</tr>
<tr>
<td>V22B</td>
<td>80-240</td>
<td>0.59mW on 80Hz</td>
<td>2.553×0.6×0.031</td>
</tr>
<tr>
<td>V22BL</td>
<td>30-110</td>
<td>1.84mW on 30Hz</td>
<td>3.633×0.6×0.031</td>
</tr>
</tbody>
</table>

In my experiment, because of the lack of experimental equipments, so I only measure the V20W and connected it to a full bridge directly (Fig. 8.9). Also I did not tune the mass of Volture.
The out power frequency is 100Hz, there are three amplitudes: 3g, 4.5g and 6.5g. It is clear that the maximum output power is 0.12mW, 0.3mW and 0.66mW when amplitudes are 3g, 4.5g and 6.5g respective and the output power is proportion to the square of the amplitude.

Fig. 8.10 the Output Power of V20W without Tuning

8.3. Solar Cells Array Result

In this experiment, we have developed a solar cell array including 4 solar cells, the open voltage of one solar cell is from 2.8V to 3.2V, the size is 3.5cm×1.4cm for one solar cell. Thus there are three available solar cell arrays as mentioned in Fig. 7.5: four series (4-S), four parallel (4-P) and two parallel with two series (P-S).

As mentioned in chapter 2, the characteristic of solar cells is presented by voltage-current curve. In this experiment, first we have measured the solar cell array under low, medium and high irradiance with three different arrays: 4-S, 4-P, and S-P. These solar cells are connected with wire directly. There is no other component such as transistor or resistor to consume any energy. The voltage-current curve is shown from Fig. 8.11 to Fig. 8.13 under low, medium and high irradiance conditions. It is clear from this diagram that the 4-S has the highest open voltage and lowest short current, 4-P has the lowest open voltage and highest short current and S-P is in between. Fig. 8.14 to Fig. 8.16 is their voltage-power curve respectively. Their maximum power is 2.57mW, 4.25mW and 7.73mW under low, medium and high irradiance conditions respectively.
Fig. 8.11 the Voltage-Current curve of Solar Cell Array under low irradiance condition

Fig. 8.12 the Voltage-Current curve of Solar Cell Array under medium irradiance condition

Fig. 8.13 the Voltage-Current curve of Solar Cell Array under high irradiance condition
Fig. 8.14 the Voltage-Power curve of Solar Cell Array under low irradiance condition

Fig. 8.15 the Voltage-Power curve of Solar Cell Array under medium irradiance condition

Fig. 8.16 the Voltage-Power curve of Solar Cell Array under high irradiance condition
The above mentioned data are ideal maximum power point. In practice, according to Fig. 7.9, the novel MPPT method should connect several transistors and resistors into circuits. These components have leakage current and consume power which reduce the collected power and change the voltage-current characteristics. The following figures from Fig. 8.17 to Fig. 8.19 are voltage-current curve with MPPT circuit under low, medium and high irradiance conditions. Fig. 8.20 to Fig. 8.22 is respective voltage-power curve. Their maximum power is 1.88mW, 3.88mW and 6.50mW under low, medium and high irradiance conditions respectively. As shown in Table. 8.4, the MPPT efficiency is 73.15%, 91.29% and 84.09% respectively under low, medium and high irradiance.

| Table 8.4 Comparison of Solar Cells Array Efficiency |
|---------------------------------|-----------------|-----------------|-----------------|
|                                | Low Irradiance  | Medium Irradiance | High Irradiance |
| Ideal Power (mW)               | 2.57            | 4.25             | 7.73            |
| Practical Power (mW)           | 1.88            | 3.88             | 6.50            |
| Efficiency                     | 73.15%          | 91.29%           | 84.09%          |

① The solar cells connect with wire directly.

② MPPT circuit with electrical components.

Fig. 8.17 the Voltage-Current curve of Solar Cell Array under low irradiance condition
Fig. 8.18 the Voltage-Current curve of Solar Cell Array under medium irradiance condition

Fig. 8.19 the Voltage-Current curve of Solar Cell Array under high irradiance condition

Fig. 8.20 the Voltage-Power curve of Solar Cell Array under low irradiance condition
In this experiment, we choose four resistors as the load matching resistors, as shown in Fig. 8.23. There are four resistance values can be chosen to match the output of solar cells array. The maximum load resistance is \( \max[(R_1 + R_4), R_2, R_3] \), and the minimum load resistance is less than \( \min[(R_1 + R_4), R_2, R_3] \), as shown in Table. 8.4, this is available load resistance. Here we choose four resistances: \( R_1 = 58k\Omega, R_2 = 31k\Omega, R_3 = 14.2k\Omega, R_4 = 17k\Omega \), then the actual load resistance are: 75\(\Omega\), 12\(\Omega\), 22\(\Omega\) and 8.6\(\Omega\) respectively. The maximum output voltage of solar cells array can reach about 12V in this experiment and the sample range of ADC is from 0-2.5V in MCU, so we series a resistor with R1, the actual output voltage of solar cell array \( V_{\text{out}} \) which is used in chapter 7.3 can be expressed by:
\[ V_{OUT} = V_R \frac{V_{R1} + V_{R4}}{V_{R4}} \]  

\[(8-2)\]

\[ \begin{array}{ccc}
R1 & R4 \\
R2 & S1 \\
R3 & S2 \\
\end{array} \]

Fig. 8.23 Load Matching Resistors

Table 8.4 Load Resistance Values

<table>
<thead>
<tr>
<th>Load Resistance</th>
<th>Status of S1</th>
<th>Status of S2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R1 + R4 )</td>
<td>Off</td>
<td>Off</td>
</tr>
<tr>
<td>( \frac{(R1 + R4)R2}{(R1 + R4) + R2} )</td>
<td>On</td>
<td>Off</td>
</tr>
<tr>
<td>( \frac{(R1 + R4)R3}{(R1 + R4) + R3} )</td>
<td>Off</td>
<td>On</td>
</tr>
<tr>
<td>( \frac{(R1 + R4)R2R3}{(R1 + R4) + R2 + R3} )</td>
<td>On</td>
<td>On</td>
</tr>
</tbody>
</table>

As mentioned above, there are 3 solar cells arrays and 4 resistances can be choose to optimize the output of solar cells, so there are 12 connections. When we connect a MCU to solar cells array, the system starts to switch all available choices, then according to FOSV method, the system can calculate the maximum output voltage and switch to corresponding solar cell array and resistor itself. Table 8.5 shows the voltage and current we measured in different connection. We have set the switching time is 1.6s. At beginning of start, there is a about 1,100ms start time to start switching. Between the switching of two solar cells array, it exists approximate 33ms of switching delay as shown in Fig. 8.24, which is caused by the charging of transistor capacitor.
Table 8.5 the Voltage-Current of Switching

<table>
<thead>
<tr>
<th>Connections</th>
<th>Voltage (Volt)</th>
<th>Current (mA)</th>
<th>Power (mW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Series</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance 1</td>
<td>6.33</td>
<td>0.50</td>
<td>3.165</td>
</tr>
<tr>
<td>Resistance 2</td>
<td>10.49</td>
<td>0.11</td>
<td>1.154</td>
</tr>
<tr>
<td>Resistance 3</td>
<td>8.71</td>
<td>0.35</td>
<td>3.049</td>
</tr>
<tr>
<td>Resistance 4</td>
<td>6.37</td>
<td>0.49</td>
<td>3.121</td>
</tr>
<tr>
<td>All parallel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance 1</td>
<td>2.75</td>
<td>0.41</td>
<td>1.128</td>
</tr>
<tr>
<td>Resistance 2</td>
<td>2.95</td>
<td>0.02</td>
<td>0.059</td>
</tr>
<tr>
<td>Resistance 3</td>
<td>2.91</td>
<td>0.10</td>
<td>0.290</td>
</tr>
<tr>
<td>Resistance 4</td>
<td>2.85</td>
<td>0.21</td>
<td>0.599</td>
</tr>
<tr>
<td>Two Series with two parallel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Resistance 1</td>
<td>4.82</td>
<td>0.51</td>
<td>2.458</td>
</tr>
<tr>
<td>Resistance 2</td>
<td>5.75</td>
<td>0.05</td>
<td>0.287</td>
</tr>
<tr>
<td>Resistance 3</td>
<td>5.41</td>
<td>0.21</td>
<td>1.136</td>
</tr>
<tr>
<td>Resistance 4</td>
<td>5.06</td>
<td>0.38</td>
<td>1.923</td>
</tr>
</tbody>
</table>

Table 8.6 lists the ideal maximum power under different irradiances and the maximum output power using this MPPT method. The ideal output maximum power in the shadow in outdoor ranges from 3mW to 6mW, and it is more than 6mW which under direct sun in outdoor. If we put
the solar cells array next to the window indoor or in the dusk, the maximum power is less than 3mW. As shown in Table. 8.6, this MPPT efficiency can reach 60% to more than 82.4% in outdoor in daytime. But the efficiency is less than 40% in door or in the dusk.

<table>
<thead>
<tr>
<th>Ideal Maximum Power (mW)</th>
<th>2.06</th>
<th>2.75</th>
<th>3.56</th>
<th>4.47</th>
<th>4.68</th>
<th>5.05</th>
<th>5.88</th>
<th>9.78</th>
<th>10.29</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actual power (mW)</td>
<td>0.41</td>
<td>0.88</td>
<td>2.11</td>
<td>3.44</td>
<td>3.48</td>
<td>4.16</td>
<td>4.94</td>
<td>6.87</td>
<td>7.81</td>
</tr>
<tr>
<td>MPPT Efficiency</td>
<td>20.1%</td>
<td>32%</td>
<td>59.2%</td>
<td>77.1%</td>
<td>74.3%</td>
<td>82.4%</td>
<td>84.0%</td>
<td>70.3%</td>
<td>76.0%</td>
</tr>
</tbody>
</table>

Since the capacitor is seen as a short to the solar cell when the connect together, the traditional voltage regulator such as PWM DC-DC converter and linear regulator would not function properly because $V_{solar}$ would fall to $V_{cap}$ and deviate from $V_{mpp}$, a PFM regulator is designed in literature [60] to resolve this problem.

In this thesis, we connected a super capacitor with the capacitance of 22F to the DC/DC, as shown in Fig. 8.25, this is the DC/DC circuit diagram, the capacitor rating voltage is 2.5V. The DC/DC output voltage is 2.8V, this is larger than the rating voltage of capacitor, so it fulfills the charging requirement. Here we compared four different solar cells array connection: MPPT method, all series without MPPT (All Series Mode), all parallel without MPPT (All Parallel Mode), and two parallel with two series without MPPT (Series-Parallel Mode). The experimental result shows in Table. 8.7. The voltage is 2.3V which is able to drive the MCU and wireless sensor nodes. It is clear that this MPPT method has higher current than all series mode and all parallel modes, but it performs not good compared with series-parallel mode sometimes.

![Fig. 8.25 DC/DC Circuit](image-url)
<table>
<thead>
<tr>
<th></th>
<th>Maximum Power(mW)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4.39</td>
<td>5.21</td>
<td>6.89</td>
<td>7.51</td>
<td>10.02</td>
</tr>
<tr>
<td>MPPT</td>
<td>0.812</td>
<td>0.897</td>
<td>1.114</td>
<td>1.360</td>
<td>1.857</td>
</tr>
<tr>
<td>All Series</td>
<td>0.622</td>
<td>0.542</td>
<td>0.505</td>
<td>0.982</td>
<td>1.829</td>
</tr>
<tr>
<td>All Parallel</td>
<td>0.064</td>
<td>0.259</td>
<td>0.595</td>
<td>0.337</td>
<td>0.440</td>
</tr>
<tr>
<td>Series-Parallel</td>
<td>1.204</td>
<td>0.862</td>
<td>1.028</td>
<td>1.641</td>
<td>2.609</td>
</tr>
</tbody>
</table>

**Charging efficiency**

<table>
<thead>
<tr>
<th></th>
<th>MPPT 42.4%</th>
<th>39.6%</th>
<th>37.1%</th>
<th>41.7%</th>
<th>42.6%</th>
</tr>
</thead>
<tbody>
<tr>
<td>All series</td>
<td>32.5%</td>
<td>23.9%</td>
<td>16.8%</td>
<td>30.1%</td>
<td>42.0%</td>
</tr>
<tr>
<td>All parallel</td>
<td>3.3%</td>
<td>11.4%</td>
<td>19.8%</td>
<td>10.3%</td>
<td>10.1%</td>
</tr>
<tr>
<td>Series-Parallel</td>
<td>63.0%</td>
<td>38.0%</td>
<td>34.2%</td>
<td>50.0%</td>
<td>60.0%</td>
</tr>
</tbody>
</table>

### 8.4. Power Supply to MCU

In order to drive a wireless sensor node, here we assume our sensor node has three modes: sleep mode, start mode and active mode. The active mode is that the sensor node transmits data to other nodes, it consumes 25mA current, the start mode is that the node prepares to send data, it consumes 5mA current, and sleep mode as the name means the node do nothing which only consumes 2μA.

We use MSP430-5379 as our MCU, this is a low power microcontroller; it only consumes 6μA in sleep mode. The average consuming current of MCU can be calculated by equation 8-3,

\[
i_{MCU} = \frac{t_{switch}i_{switch} + t_{MCU/\text{sleep}}i_{MCU/\text{sleep}}}{t_{switch} + t_{MCU/\text{sleep}}} \tag{8-3}
\]

For example, assume the switching time \( t_{\text{switch}} \) is 10s, and MCU track the maximum power point every 10 minutes, then sleep time \( t_{\text{MCU/\text{sleep}}} \) is 600s. The sleep current is ideal 6μA, the switching current \( i_{\text{switch}} \) is 558μA as we measured, then the average MCU current \( i_{MCU} \) is 15.05μA.
According to the following equation:

$$n(t_{active}i_{active} + t_{start}i_{start} + \frac{1}{n} - 0.002)i_{sleep}) = i_{charging} - i_{MCU}$$  \hspace{1cm} (8-4)$$

Where \(n\) is the maximum working frequency in one second of sensor node. We are able to calculate the minimum duration time of sensor node with different charging current, as shown in Table 8.7.

<table>
<thead>
<tr>
<th>Charging Current(μA)</th>
<th>100</th>
<th>300</th>
<th>500</th>
<th>800</th>
<th>1000</th>
<th>1500</th>
<th>2000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duration Time(ms)</td>
<td>362</td>
<td>106</td>
<td>62.1</td>
<td>38.3</td>
<td>30.5</td>
<td>20.2</td>
<td>15.1</td>
</tr>
</tbody>
</table>
9. Conclusion and Future Work

In this thesis, my thesis focuses on the following tasks:

1. We have studied the most matured ambient energy source: vibration, thermal and solar; and other potential energy source such as human power, wind and air flow, electromagnetic by literature review.

2. Setup basic analytical models for these ambient energy sources, and list available and exiting MPPT methods.

3. Present a novel MPPT method of solar cells, build the mathematic model and design the analog circuits of it; besides solar, this MPPT method also is available to help thermal and vibration to track the MPP.

4. According to mathematical models of vibration, thermal and solar, we have measured the output power data and verify their characteristic. Also, we give the efficiency of this novel MPPT method, the experimental result shows that its efficiency is 60%-80% in micro system.

5. Calculate the theoretical working time of sensor node by using this MPPT method.

This novel MPPT method has high energy conversion efficiency which reach 60%-80% commonly in micro system while connect to load directly; A small size of 1.4cm×14cm for four solar cells is able to drive the sensor nodes for a duration time of decades micro seconds which depends on irradiance.

In the future, there are also following aspects should take into account to improve this work:

For one thing, in order to optimize the output efficiency, it is better to product PCB board and chooses low power consumption components; this will decrease the leakage current. Besides, it also need optimize MUC to decrease the power consumption.

For another thing, it is necessary to verify this novel MMPT method on vibration and thermal sources. It should measure and calculate the experimental conversion efficiency.

At last, PFM regulator or charging circuit should implement in this design to charge a supercapacitor or battery.
References


[37] H. Nagayoshi, “Comparison of Maximal Power Point Control Methods for Thermoelectric


