

Designs of Energy Harvester for Wireless Sensor Networks

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Abstract. An essential part of the IoT architecture are wireless sensor networks. There has been extensive study done to identify alternative methods of powering wireless sensor networks because the nodes of wireless sensor networks are mostly power constrained. This study mainly introduces three energy collector solutions that can power wireless sensors. They are an electromagnetic vibration energy harvesting system that powers the light source of the fiber Bragg grating sensor, a solar energy collection system that uses ambient photovoltaic energy, and a wind energy harvester that uses gas elastic vibration to convert wind energy into electrical energy. The solar energy collection system is based on maximum power point tracking, in which the solar panels can provide 3W of power with a high efficiency of up to 96%; the wind energy harvester is composed of a wind generator and a power management unit, capable of operating at wind speeds of 2-9m/s, providing 70mW of power. Besides, the electromagnetic vibration energy harvesting system provides an average power output of approximately 40mW when subjected to acceleration levels greater than 0.05g. These results can serve as solutions for sustainable power output.

Keywords: Vibration energy harvesting, maximum power point tracking (MPPT), solar energy harvesting, sensor network, wind energy harvesting.

1. Introduction

The Internet of Things (IoT) is the process of connecting regular physical objects to the internet. This includes everything from common household items like lightbulbs to medical equipment like medical gadgets, wearable technology, smart devices, and even smart cities. IoT devices embedded in physical things are broadly classified into two types, one is the switch (used to send commands to other objects), the other is the sensor (used to collect data and send it out). With the advancement of communication technology and various discoveries in the field of materials, wireless sensor networks and portable devices have achieved huge development opportunities in recent years [1]. These wireless and portable devices require smaller batteries or capacitors to maintain normal working conditions for a long time. However, the service life of these devices, batteries, and capacitors is ultimately limited, and inspection and maintenance are required to keep them working properly.

In commercial applications and experiments, primary batteries have always occupied an important position and are the first choice for sensor energy supply in most scenarios [2]. Non-rechargeable batteries greatly reduce the difficulty of sensor design and simplify the programming steps of the control circuit. The popularization of the IoT has allowed sensors to be spread across various scenes in the city, supporting applications, e.g., automation, light control, and industrial monitoring. Large-scale sensors perform poorly in terms of adaptability and cannot continue to provide services in complex environments. Frequent replacement of batteries increases the number of labor costs. Therefore, sensors are developing towards miniaturization, intelligence, and ultra-long service life.

Current wireless and portable devices can use energy harvesters, which can reduce the size of the device so that it can be placed in locations that are difficult to access, have harsh environments, and are inconvenient to maintain. Additionally, they are able to absorb many forms of environmental energy and transform it into electrical energy. Thus, the sensor is available for a long time, supply it. From a cost perspective, the energy harvester completely replaces the primary battery, saving the labor cost of manually replacing the primary battery. After a period of use, the material cost of producing the sensor can be recovered, and it is easy to achieve positive benefits. Therefore, these energy harvesters can be used in various wireless sensor networks to promote the development of

environmental monitoring, integrated biology, structural monitoring, biomedical equipment, aerospace, and military applications [3].

Electrical energy can be created from a variety of sources, including mechanical energy, solar energy, chemical energy, thermal energy, etc. [2]. For mechanical energy power generation, this article mainly discusses the impact of mechanical energy and wind power generation on energy harvesting sensors and the results in recent years. The two most common methods for converting wind energy into electrical energy are described in the current literature as follows. One used turbines to collect wind energy, followed by the conversion of rotational motion into electrical energy using piezoelectric materials; others used turbines to collect wind energy but electromagnetic induction as the method of conversion [3]. The piezoelectric material undergoes strain and generates electricity as the turbine rotates. In order to achieve the goal of stable operation, non-collapse, and long service life of the sensor, the generator must take into account the average daily wind strength and the rotational kinetic energy required to drive the baffle. Since the daily wind intensity is weak and difficult to maintain, the design of the generator can be done by increasing the torque to make the engine work under weak wind intensity. Therefore, magnets are introduced into the generator, and the repulsive effect of the magnets is used to squeeze the baffle to force the piezoelectric material and vibrate at its resonant frequency to generate maximum power. The use of electromagnetic induction is similar to piezoelectric wind energy harvesters. The weight of the magnets in the electromagnetic induction device is too heavy, causing the turbine to be unable to operate. Therefore, the wind energy harvester cannot work normally under weak wind [4]. However, the power of piezoelectric wind energy harvesters is significantly higher than that of electromagnetic induction generators.

A necessary condition for solar energy collection wireless sensor networks is an efficient solar energy collection system [5]. Photovoltaic cells are utilized by the harvester to turn solar energy into electrical energy, which is subsequently used to recharge rechargeable batteries in the sensor network. [5]. Solar energy harvesting sensors also face similar problems as wind harvesting sensors environmental impact. In locations with insufficient light, such as indoor places, the energy that solar energy harvesting sensors can collect is very limited, which is not enough to supply the power consumption of wireless sensor networks. In addition, the solar collector cannot collect energy at night. The sensor only relies on the electric energy collected during the day and stored in the capacitor or rechargeable battery to work at night. Therefore, the solar energy collection sensor may need a larger capacity rechargeable battery to store electric energy, but it will also increase the size of the sensor to a certain extent.

Environmental vibration can also provide stable and continuous energy to the sensor [5]. Environmental vibration refers to vibrations with small amplitudes caused by natural and man-made causes, such as waves, wind, traffic interference, mechanical vibration, etc., which are often used to determine the dynamic characteristics of sites and engineering structures. The amplitude of environmental vibration is generally below 100Hz, and the typical acceleration level is very low (less than 1.0g), making energy harvesting through environmental vibration one of the feasible methods to power microelectronic devices [6].

The wireless sensor network works in two modes: active mode and sleep mode. It only works in the main mode for 5 seconds every 15 minutes. The power of the wireless sensor network in active mode is 3.6mW, and it consumes basically no power in sleep mode [4, 5]. The wireless sensor network works at 3V DC voltage, which comes from the power control management module including converters, boosters and bucklers, rechargeable batteries or capacitors. Scholars introduced two commonly used types of solar collector systems, pulse width modulation control and MPPT control [5]. The solar energy collection system was simulated and modelled using MATLAB/SIMULINK, and an MPPT tracking-based system with up to 96.26% system efficiency was the result. The designed circuit includes solar panels, DC-DC converters, rechargeable batteries, MTTP control, as well as wireless sensor network nodes, which proves the feasibility of MPPT-controlled solar energy collection system to dynamically increase battery charging time. Researchers designed and manufactured a wind collector, using it to power a wireless sensor network [4]. The

wind turbine can operate at a wind speed of 2-9m/s, providing 70W power for the wireless sensor network, increasing the lifespan of wireless sensor network. Others proposed an electromagnetic energy collection design to power the wide-spectrum light source of fiber optic sensors, which can operate at low environmental vibration frequencies, provide sufficient output power for fiber optic sensors, and be used for environmental monitoring in remote areas [6]. The first section of this article outlines the operation methods of the three energy harvesting sensors of wind energy, solar energy, and environmental vibration. The second section introduces the principles of the three schemes respectively. The third section discusses the implementation methods and simulation results of the three schemes. The fourth section gives conclusions.

2. Energy Harvesting Schemes

2.1. A Wind Energy Harvester

An energy management system and a wind generator were combined to create the author's wind energy harvester [4]. A membrane, a transducer, and a frame make up the wind engine. It transforms wind energy into electrical energy using gas elastic oscillation. The power management unit wasn't designed with a maximum power point tracking algorithm in mind because the aero-elastic flutter generator doesn't need one [7]. It can produce 3.6 mW of power with a maximum output voltage of 6 v at 4 m/s of wind speed without a transformer. Four materials were tested in a setting with a wind speed of 4 m/s, and their vibration frequencies were measured. The materials were a 30 cm long and 2 cm broad satin ribbon, mylar-coated taffeta, camera film, and duct tape. They were 8 Hz, 15 Hz, 10 Hz, and 9 Hz respectively. Finally, polyester-coated taffeta was selected as the material of the membrane. Due to limitations of power conditions and environmental conditions in the simulation, the thickness of the film is specified to be 0.2mm, and the length can be obtained through formula:

$$P_{wind} = 0.5\rho lTV^3 \quad (1)$$

Here, P_{wind} is the amount of usable wind energy, ρ is the air density, l is the membrane's length, T is its thickness, and V is the ambient wind speed in Eq. (1). As a result, the membrane's length can be determined to be 49 cm. In the section on energy conversion, the authors explain how wind energy produced by turbines can be transformed into electrical energy using piezoelectric materials. In order to increase the torque, this patch is placed on the piezoelectric material and the generator stator. The magnet's weight must be relatively light to allow the film to vibrate and have a strong magnetic field density. After modelling and computer analysis, the author selected a 1.3T rare earth magnet with a 12mm diameter and 7mm height. The generator coil has a 6V peak output voltage, and Eq. (2) can be used to determine the number of turns:

$$EMF = -N \frac{\partial \varphi}{\partial t} \quad (2)$$

N is the coil's number of turns and φ is the magnetic flux in Eq. (2), φ may be formulated using Eq. (3):

$$\varphi = BA \sin \theta \quad (3)$$

In the Eq. (3), A is the area exposed to the magnetic field, B is the average magnetic density on the coil, and θ is the magnetic field's angle. According to calculations, the coil needs 6241 turns and is subjected to a 0.045T magnetic field.

2.2. A Solar Energy Harvesting System

A solar battery charging solution for wireless sensor network nodes was proposed by the author based on maximum power point tracking in the literature [4]. Solar panels, DC-DC buck converters, rechargeable batteries, maximum power point controllers, and wireless sensor network nodes make up the overall system. The solar panels obtain energy from the surrounding sunlight and convert light energy into DC power. The DC-DC converter then modifies the magnitude of the acquired voltage before charging the rechargeable battery. The duty cycle of the MOSFET utilised in the DC-DC converter is monitored and managed by the MTTP controller, together with the voltage and current flowing from the solar panel. Wireless sensor networks complete sensing, computing and communication functions. The solar energy collection system won't be able to continuously supply current and voltage to the sensor network and charge the battery if its efficiency is low. Therefore, the solar energy collection system is very important for the sensor network and determines whether the sensor network can continue to work stably. The article simulates that under a constant temperature of 25 degrees Celsius, 1000W/cm² of solar radiation illuminates the solar panel. The solar panel can only extract solar energy with an efficiency of 15%, and the energy is converted to 15mW/cm². To mimic the whole solar radiation, set the solar panel's output to 6V, 500mA, and 3W. A rechargeable battery powers the wireless sensor network node, from which the voltage of the solar cells is output after being enhanced by a DC-DC converter. In this scenario, the wireless sensor network's DC load resistance is 100 ohms.

2.3. A Vibration Energy Harvesting System

For a Fiber Bragg grating sensor's broadband propagation light source, a power source based on a vibration energy harvester was created by the author [6]. The energy harvesting part consists of six identical cantilevered electromagnetic vibration energy harvesters. When the magnet vibrates on the coil, it will cause electromagnetic induction and generate electrical energy. Six beams are produced by the light source and are split into three groups; each group is tuned to a distinct frequency by increasing mass to the magnet. An optical sensor called a fiber Bragg grating operates by periodically perturbing the fibre core's refractive index [6]. In the sensor, the grating serves as a filter, allowing optical fibres that do not fulfil the Bragg equation to pass through while reflecting light that does. The strain acting on the grating at a fixed period will cause a wavelength shift, and the wavelength shift corresponds to the measured change. In terms of temperature sensing, according to the optical fiber's thermal expansion coefficient, at different temperatures, the fiber experiences different axial strains that alter the reflected light's spectrum and change its reflection wavelength [6].

3. Results

Fig. 1, Fig. 2, Fig. 3 and Fig. 4 show the experimental results in [4]. As can be seen from the results, the wind turbine can provide energy for the continuous operation of the wireless sensor network. Fig. 1 shows the operating conditions and maximum power supply voltage of the wind turbine in the wind speed range of 1-9m/s. When the wind speed is greater than 2 m/s, the wind turbine begins to run. The power supply voltage rises as the wind speed does in the 2–7 m/s wind speed range. The maximum power supply voltage reaches a peak value of 8V when the wind speed is 7m/s. After the wind speed exceeds 7m/s, the power supply voltage decreases to 4V and remains stable. Fig. 2 shows the no-load power provided by the wind turbine at various wind speeds. It can be seen from Fig. 2 that after the wind turbine starts operating, the no-load power provided also increases with the increase of wind speed. Likewise, when the wind speed reaches 7m/s, the no-load power reaches a peak value of 70mW. The generator produced four times the expected power at a wind speed of 4 m/s because of the slight slope of the membrane in the upright position, which increased the thickness of the membrane exposed to the wind. From both Fig. 1 and Fig. 2, it can be easily seen that when the wind force is greater than 7m/s, the power and power supply voltage decrease rapidly and finally stabilize. The reason is that the wind engine re-tensions the film when operating at a wind speed

above 7m/s. According to Fig. 3, the gadget can power the load for 166 seconds at 3.6 mW, which is equivalent to 8 hours of electricity for the wireless sensor network. Fig. 4 shows how the wind turbine can store 946mJ of energy by charging a 0.07F capacitor to 5.2V in ten minutes. The power management unit imposes a lifetime limit on the sensor network depicted in [4]. The voltage regulator uses the bulk of the generated power as a result of poor power management because it cannot reduce the input current and offers a consistent current at different voltages. The voltage converter cannot continuously control the regulator duty cycle, so the regulator has a high supply voltage. Another source of inefficiency in power management units is component selection. Select the MOSFET according to its gate voltage. The MOSFET needs to be turned on at a low voltage, so a boost converter is utilized to raise the low input voltage. The output voltage fluctuates between 2.97V and 3.03V due to the voltage regulator's 1% tolerance on the output voltage, but this variation has no impact on the system's ability to function normally.

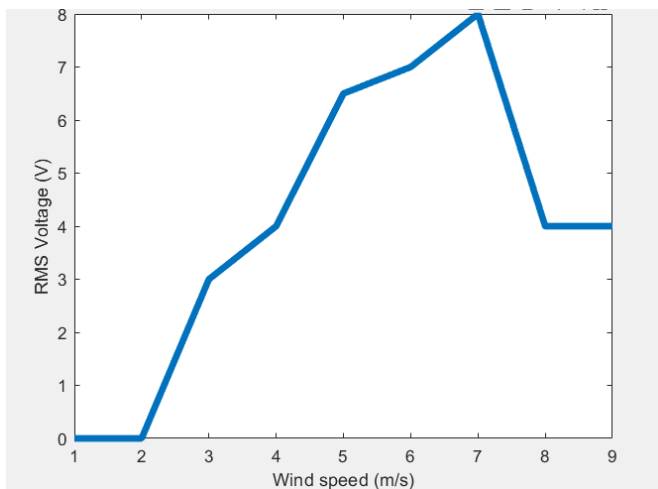


Figure 1. Generator output voltage in relation to wind speed.

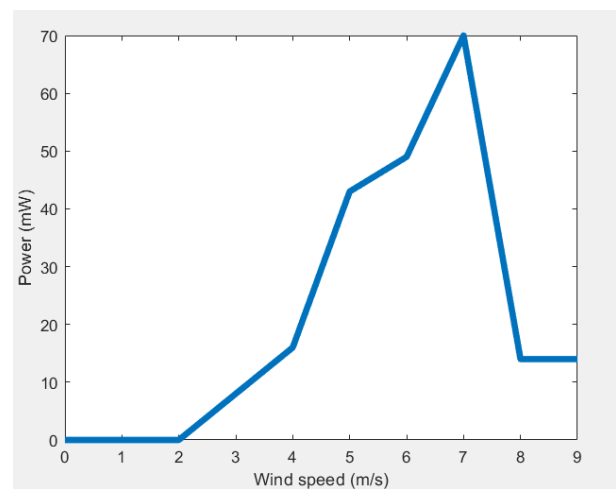


Figure 2. Generator's output power under no load, according to the wind.

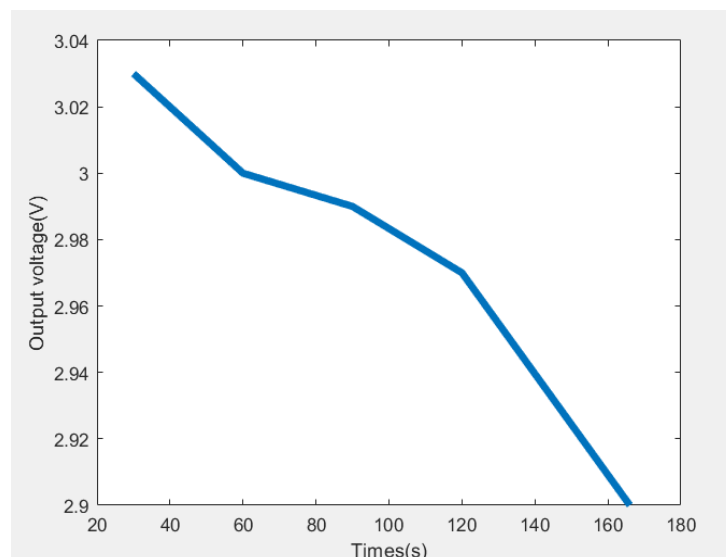


Figure 3. Time-dependent output voltage when the super capacitor is being discharged from 6.3V with a 3.6mW load connected to the output.

In the study's simulation results [5], Fig. 5, Fig. 6 and Fig. 7 depict the variations in battery current (IB), voltage (VB), and state of charge (SoC) over time (s). Fig. 5 shows the solar energy collection system controlled by MPPT. There are three variables: battery voltage, current, and state of charge (SoC). Ten seconds are spent on the simulation. Seen from Fig. 6, the SoC reaches 50% after 100 seconds of simulation time. As shown in Fig. 7, after 200 simulation seconds, the battery charge level

reaches 95%. The result demonstrates how the MPPT-controlled solar energy collection system can dynamically extend the battery charging time. For the MPPT control strategy, the efficiency of the energy harvesting system is computed. According to Table 2, the solar panel's available power is 2.8 watts, and the formula for figuring MPPT efficiency is [8]:

$$MTTP\ Efficiency(\eta_{MPP}) = \frac{P_{MPP}}{P_m} \quad (4)$$

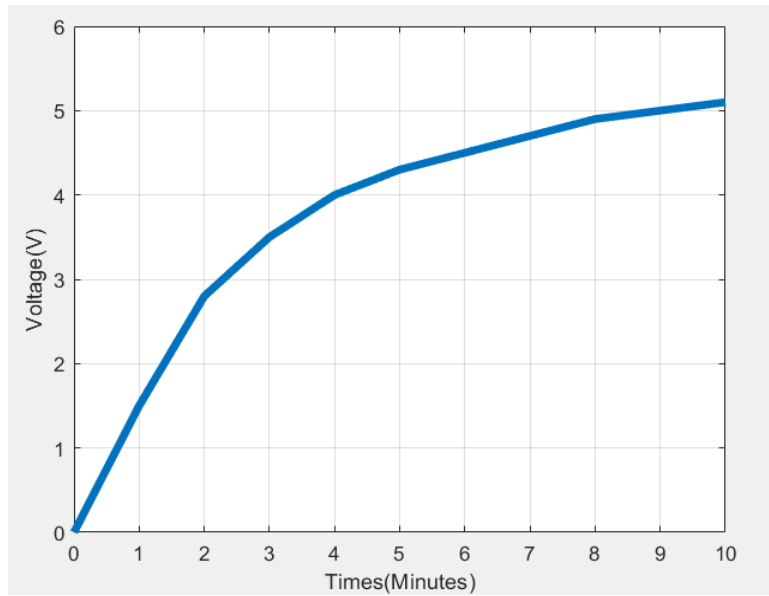


Figure 4. Voltage of a capacitor plotted against time.

The highest theoretical power P_m , according to simulation parameter table 1, is 3 watts. Therefore, the MTTP efficiency is 2.8watts/3watts, which is equal to 93.33%. MTTP causes changes in P_{loss} in the DC-DC buck converter. P_{loss} is the total of the inductor conduction loss (P_L) and the MOSFET switching loss (P_{sw}). The P_o is 1.8W, the P_{sw} is 2mW, and the inductor loss is 20mW, as can be seen from the simulation parameter table. The DC-DC buck converter's efficiency is $(1.8W - 0.022W)/1.8W = 98.79\%$. The energy harvesting circuit's overall efficiency is calculated as the average of the Maximum Power Point Tracking efficiency and the Buck converter efficiency.

$$Harvester\ System\ Efficiency(\eta_{sys}) = \frac{\eta_{Buck} + \eta_{MPP}}{2} \quad (5)$$

The energy harvesting system's overall efficiency is computed using Eq. 5 as follows:

$$\eta_{sys} = (98.79\% + 93.33\%) / 2 = 96.28\% \quad (6)$$

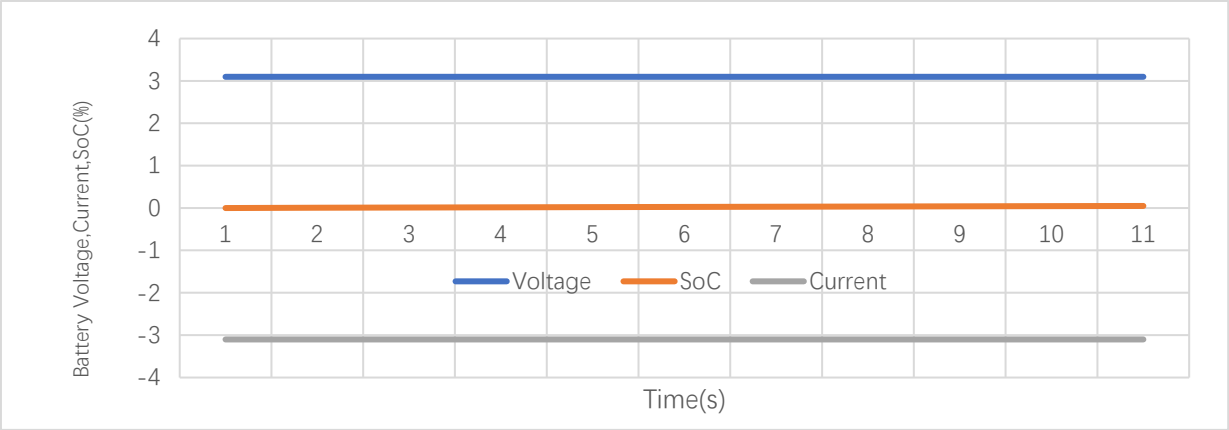


Figure 5. Simulation results of MPPT controlled SEH system for 10 s.

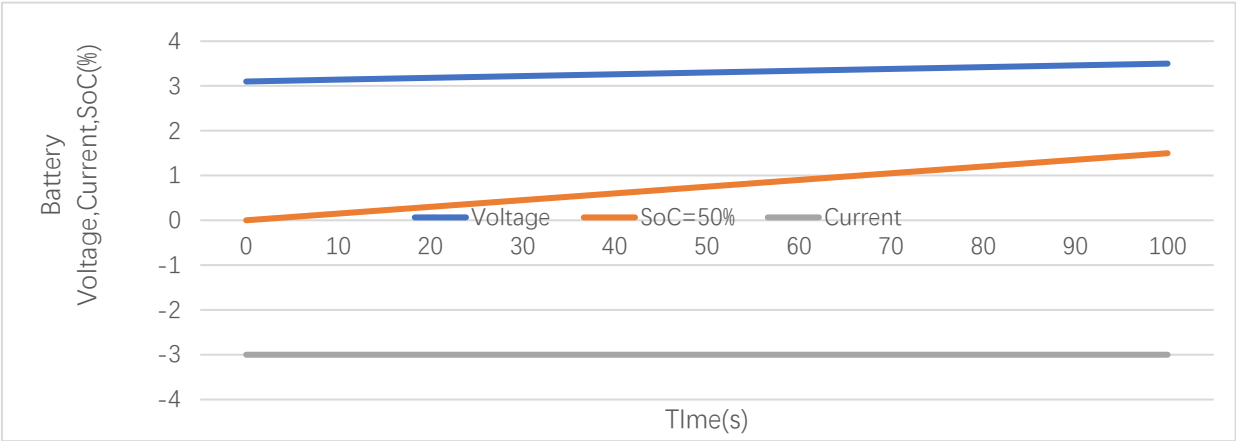


Figure 6. Simulation results of MPPT controlled SEH system for 100 s.

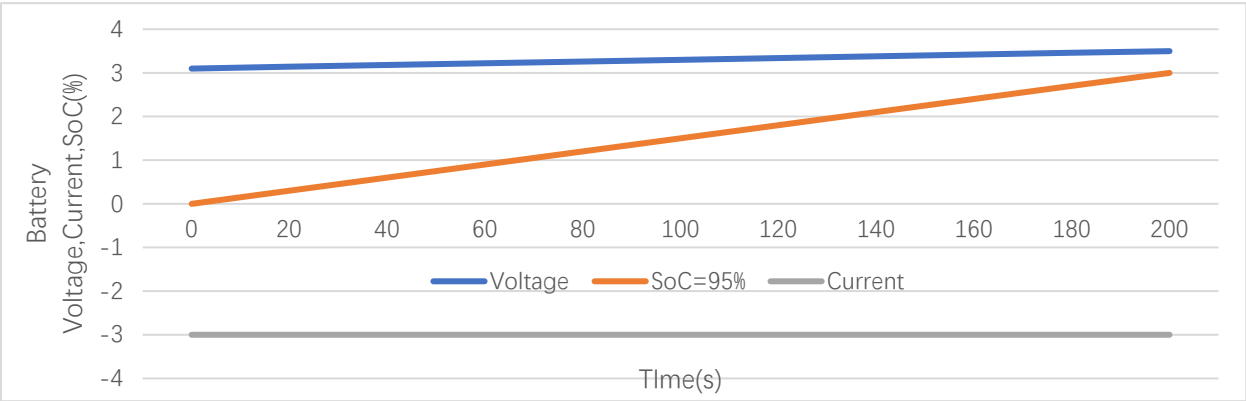


Figure 7. Simulation results of MPPT controlled SEH system for 200 s.

Table 1. Simulation Parameters

Parameters	Value	Parameters	Value
Irradiance (W/m ²)	1000 Watts/m ²	Capacitor (C)	100uF
Temperature (T)	25°C	Inductor (L)	200uH
DC-DC Converter	Boost Converter	MOSFET Switching Frequency (f)	5KHz
Max. Solar Panel output voltage (Vm)	6 volts	Initial duty Cycle	0.5
Max. Solar Panel output current (Im)	500mA	MOSFET Switching Power Losses (Psw)	0.5mW
Max. Power from Solar Cell (Pm)	3 watts	Switching Voltage Loss (Vsw)	0.2 volts
Rechargeable Battery Type	NiCd	WSN Load Model	10-ohm Resistor
Battery Voltage	3.6 volts	Inductor conduction Power Loss (PL)	50 mW

Table 2. Simulation Results for Mppt Control She System

Energy Harvester Parameters	Value
Max. Solar Panel output Power (Pm)	2.8watts
Average Buck Converter Output Voltage (Vm)	3.6volts
Average Buck Converter Output Current (Im)	500mA
Buck Converter Output Power	1.8watts
Inductor Loss	20mW
MOSFET Switching Loss	2mW
Harvester System Efficiency (η_{sys})	96 %

A simulation circuit diagram for an environmental vibration energy harvester is shown in Fig. 8, Table 1 and Table 2. Three pairs of clamp-free cantilever beams with various natural frequencies are represented by the cantilever arms 1 and 2, 3 and 4, and 5 and 6 in Fig. 5. According to Faraday's law of electromagnetism, each electromagnetic vibration energy harvester's voltage's root mean square (RMS) is

$$V_i = \frac{1}{\sqrt{2}} NBL_C f v_i \quad (7)$$

Where L_C is the effective length, R_C is the resistance, and N is the number of turns in the coil. f is the filling factor, The vibrating magnet's speed is given by v_i , the average magnetic flux intensity is given by B , and the number of cantilever beams is given by the subscript i . The velocity of each magnet in the primary vibration mode at time can be determined using the Euler-Bernoulli beam theory [9]:

$$v_i = \frac{Y e^{i\omega t} F \omega^3}{\omega_n^2 - \omega^2 + i2\zeta \omega_n \omega} [\varphi_l + x \varphi_l'] \quad (8)$$

Where Y is the magnitude of the harmonic basic excitation, φ and φ' are the cantilever beam's free end eigenfunctions and the locations of its derivatives along the length of the beam, The fundamental beam's natural and driving frequencies are ω and ω_n , respectively, and x is the distance between the magnet and the beam's free end, ζ is the beam's damping ratio, and F is the forcing term created by the magnet, added mass, and the beam's inertial characteristics. A cantilever beam's mechanical and electromagnetic contributions are included in its damping [10]. In the absence of losses, through Kirchhoff's voltage law and Ohm's law, the average output power P is

$$P = \frac{R_L}{(R_C + R_L)^2} (\sum_{i=1}^6 V_i - 6V_C)^2 \quad (9)$$

Three cantilever beam pairs are tuned to their respective natural frequencies of 7.1Hz, 7.5Hz, and 7.8Hz. Fig. 9 shows that when the collector is subject to an acceleration greater than 0.5g, it can provide sufficient power for the fiber grating sensor. By increasing the natural frequency gap between the three beam groups, the harvester's working frequency bandwidth, which is now about 0.7 Hz, can be enlarged. However, doing so will reduce average output power.

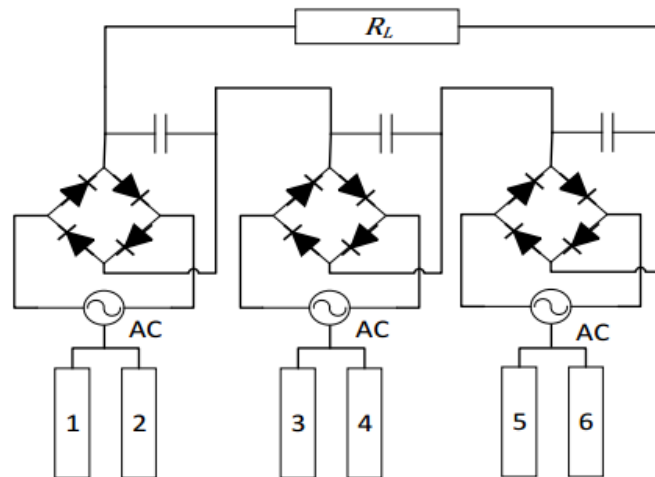


Figure 8. Schematic for the planned harvester's AC to DC circuit.

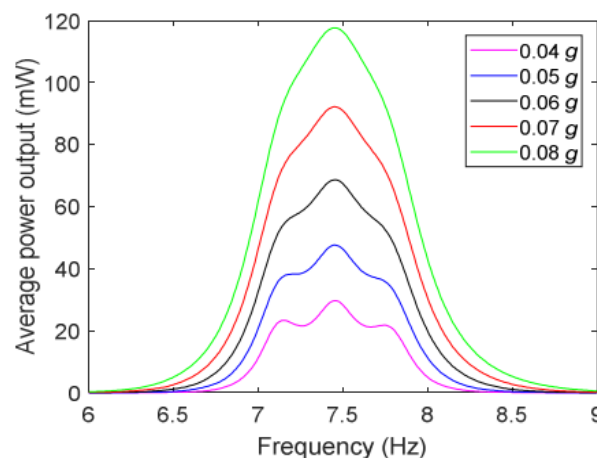


Figure 9. The harvester's average power production at various acceleration levels

4. Conclusion

This study describes three energy harvesting systems that power wireless sensors. The wind energy collection system can provide power for wireless sensor networks for eight hours when the 0.07F capacitor is fully charged and can generate more power than other small wind turbines, but it wastes power in the voltage regulator part and reduces the cost. System efficiency, in subsequent research, the service life of the wireless sensor network can be increased by changing the material and thickness of the membrane or rationally selecting the original components of the boost converter and using MTTP to optimize the power management unit. The solar collector can charge the battery of the wireless sensor network in a short time. It can charge the 100uF capacitor to 95% in 200 seconds, and the efficiency reaches 96.28%. In subsequent research, the battery capacity can be increased to cope with night or Scenarios such as cloudy days that are not suitable for solar energy collection are used to ensure the reliability of wireless sensor networks. The environmental vibration acquisition system

can provide sufficient power for the fiber Bragg grating sensor when the acceleration input exceeds 0.05g to achieve a sustainable fiber Bragg grating sensor. The ambient vibration acquisition system's working frequency bandwidth is, however, somewhat narrow. By altering the natural frequency difference, the operational frequency bandwidth can be increased in the future. Research Its relationship with the average output power determines the best parameters that can balance the operating frequency bandwidth and average output power.

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