Design of Hybrid Energy Harvesting Self-Powered Power Supply for Transmission Line Sensor

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Abstract. In order to realize the self-power supply of the wireless temperature sensor at the tension clamp of the high-voltage transmission line, the environmental energy is harvested and stored, and to power the transmission line sensor nodes. A hybrid environment energy harvesting system for the transmission line is designed, which harvests the solar energy and transmission line vibration energy in the environment and harvests the solar energy and the piezoelectric ceramic through the photovoltaic panel. The output voltage of the photovoltaic cell is low under weak light. A new type of energy harvesting circuit is designed for the low output voltage of the photovoltaic cell, which can efficiently harvest the light energy in the transmission line. However, the vibration frequency of the transmission line is low, the structure of piezoelectric vibration energy harvester is designed by finite element method, the natural frequency is close to the vibration frequency of the excitation source, and the energy utilization ratio is the largest. The two energy collectors are impedance matched respectively in order to increase the energy output power of the whole system. The system is controlled with supercapacitor by energy management mode, which provides stable electric energy for load and realizes the sustainable self-power supply of wireless temperature sensor.

1. Introduction
In recent years, electricity consumption in urban and rural areas has increased with the continuous growth of the national economy. During the peak period, the high-load operation of transmission lines has led to an increase in the temperature of the tensile contact line, and the lighter causes the power loss, and the heavy one causes the power off due to the clamp to fall off. It is usually nec-essary to comprehensively monitor the lead-flow clamps of the high-voltage transmission lines before the peak time to ensure the safety of the power grid [1]. Therefore, wireless detection is performed on the temperature of the tensile strain of the transmission line, which helps the moni-toring personnel to check the safety hazard in advance. However, the power supply of the high-voltage transmission line real-time detection equipment is not easy to obtain, which has become an important issue limiting the wide application of wireless sensors for transmission lines.

At present, the power supply modes of wireless sensors in the transmission line environment are the battery, solar power [2-3], overhead transmission line ground [4], conventional current transformer [5-6]. According to the energy source, it is divided into two categories: power grid energy extraction and environmental energy harvesting. The grid energy-receiving technology has problems such as...
insulation, volume, power, engineering and application range. Therefore, the wireless sensor is powered by a clean, environmentally friendly environmental energy harvesting method. The energy that can be harvested in the transmission line environment mainly includes solar energy, vibration energy, wind energy, and heat energy. Different forms of environmental energy have their own shortcomings, such as low energy density, poor stability, and large environmental factors, which cannot continuously supply power to the sensor. Therefore, in special cases, it is difficult to satisfy the long-term self-power supply of the sensor by a single form of energy harvesting.

At present, the main problems of solar energy and vibration energy harvesting systems in transmission line environments are as follows: 1) Selection and design of appropriate energy harvesters for the transmission line environment. 2) The harvested energy is transmitted at maximum power and efficiently combined. 3) Reduce the power consumption of the entire system. 4) Long-term power supply to the wireless temperature sensor node. Domestic and foreign scholars have carried out corresponding research on the above questions, such as harvesting sustainable and self-powered sensor nodes in the agricultural Internet of Things, harvesting RF energy and vibration energy in the farmland environment, but the article does not study the farmland environment and design the piezoelectric energy harvester [7]. Solar energy/vibration energy / thermal energy in the environment is harvested to continuously power the wireless sensor. This paper mainly studies the influence of the environment on the energy harvester and does not study the subsequent circuits and sustainable power supply [8]. In the document [9], a hybrid energy harvesting system that can harvest vibration energy and wind energy at the same time is designed for the sensor node of bridge health detection. Although the bridge environment is analyzed, the feasibility of power supply to the sensor node is realized. However, reliable continuous power supply is not possible. In the document [10], a self-powered system for substation state detection sensor is designed. A hybrid energy collector that harvests electromagnetic/thermal/vibration energy is proposed. The low-power circuit is mainly used to reduce the power consumption of the whole system. The above research provides a reliable design basis for the design of the hybrid energy harvesting system of transmission lines, but there is no research on the hybrid energy harvesting of solar energy and vibration energy in the transmission line environment at present.

On the basis of the above research, the self-power supply circuit of the wireless temperature sensor at the tension clamp of the high-voltage transmission line is designed, the solar energy and vibration energy of the transmission line environment are harvested, and the energy harvester is selected and designed separately according to the transmission line environment. In order to improve the output power of the energy collector, the respective energy conversion circuits are designed and impedance matched to achieve maximum power tracking. Finally, the energy harvested by the two energy collectors is efficiently combined, and combined with the supercapacitor, the wireless temperature sensor node is continuously self-powered by controlling the discharge of the supercapacitor.

2. Power Demand Analysis of Wireless Temperature Sensor Node

The wireless temperature sensor node system of the transmission line mainly has the components of the sensor module, the controller module, the wireless transceiver module and the power module, as shown in Fig. 1. The selection and power consumption of each module device are shown in Table 1. In order to realize the low power consumption design of the node, the node should be in a sleep state as much as possible.

[Diagram: Figure 1. Structural block diagram of sensor nodes]
Table 1. Power consumption of main components of the sensor node

| Device        | Working voltage (v) | Working current (mA) | typical application |
|---------------|---------------------|----------------------|---------------------|
| Temperature Sensor | 3.5                 | 0.003                | 1                   |
| transceiver   | 2.3                 | 0.0002               | 34                  |
| Controller    | 1.9                 | 0.150                | 400                 |

The data in Table 1 shows, the output voltage of the power module is about 3.3V, and the current is about 450mA during data transmission and reception, and about 150μA under sleep conditions. Therefore, the main component that affects the energy consumption of wireless sensor network nodes is the wireless transceiver module. Due to the non-sustainability of environmental energy, it is impossible to stably supply power to electronic devices during data transmission and reception. It is necessary to cooperate with super capacitors to ensure long-term self-power supply between wireless sensor nodes.

3. Design of hybrid energy harvesting system

The designed hybrid energy harvesting system mainly consists of 8 modules, piezoelectric energy harvester and impedance matching circuit, photovoltaic energy harvester and impedance matching circuit, energy storage device, controller module, output voltage regulator circuit, sensor module, such as Figure 2 shows.

![Figure 2. System overall design Diagram](image)

4. Solar harvester circuit design

This article selects the Imd001-6 model supplied by custom-made Imdsolar Solar Energy. First, according to the output characteristics of the panel, as shown in Fig. 3, according to Table 1, it is not possible to directly supply power to the sensor. In order to improve the energy utilization rate, an energy collecting circuit based on the micro-circuit board of the transmission line is designed, as shown in FIG. 9. The converter can achieve higher voltage gain and stepless adjustment of the output voltage.

![Figure 3. Panel output](image)  ![Figure 4. Capacitor C1 and panel output voltage](image)
The working principle of the circuit is relatively simple. During phase 1, capacitor C1 is linked to
the panel and C1 is charged as shown in Figure 4. During phase 2, capacitor C1 is linked to the panel,
and ideally, the output voltage during phase 2 is twice the panel voltage. Under the condition of
impedance matching between the control photovoltaic output converter and the photovoltaic cell, the
output characteristic curve of the panel is shown in Fig. 5. The 0.5 s front of the photovoltaic cell is
powered by the wireless sensor alone, and then the supercapacitor charging state is shown in Fig.6.

![Figure 5. Panel output under impedance matching](image)

5. Structural optimization design of piezoelectric energy harvester

5.1. Analysis of Environmental Vibration Characteristics of Transmission Lines

Overhead transmission lines have been subjected to environmental impacts such as wind, rain and
lightning for many years, and the vibration phenomenon is more obvious. In this paper, the vibration
characteristics of the newly developed overhead transmission line JL1X1/G2A-1520/125-481 are
analyzed. When the power transmission line re-ceives 0.510m/s and the wind speed is in the direction
of the transmission line, it is easy to generate high-frequency low-amplitude and long-lasting breeze
vibration. Long-term breeze vibration causes the transmission line to vibrate in the vertical direction,
resulting in a cyclically alternating dynamic bending stress. In the open area or when the wind speed is
stable, the vibration can sometimes last for several days. The vibration frequency of the wire is
generally 0 150 Hz, which is mostly in the range of 10 30 Hz, and the maximum amplitude is
generally not more than 12 times the diameter of the wire. Assuming that the wire is a cylindrical rigid
body, when the wind speed is stably blown to the rigid body, Diana and Falco [7] proposed that the
wind input power per unit length of the wire is [7] according to the wind tunnel test:

\[ P_w = \exp[a \ln\left(\frac{y}{D}\right) + b \ln\left(\frac{y}{D}\right) + c]f^3D^4 \]  

(1)

Where: \( y \) is amplitude, \( a, b, c \) is model parameters, generally take \( a = 0.053 \), \( b = 1.41 \),
\( D = 4.12 \times 10^{-3} \), \( c = 2.98 \).

The self-damping power \( P_\zeta \) of the wire is [9]:

\[ P_\zeta = 10^\beta\left(\frac{y}{D}\right)^\alpha \]  

(2)

In the formula, \( \alpha, \beta \) are the model coefficients of experiment. This article is taken in accordance
with the international power grid. \( \alpha = 2, \beta = 4 \).

When the external excitation frequency is equal to the natural vibration frequency of the structure,
the external load is balanced with the damping force. The work done by the load in the same vibration
period is equal to the energy consumed by the damping force. According to the law of conservation of energy, the input wind power is equal to the self-damping power of the wire. Equation (3):

\[ P_w - P_z = 0 \]  

(3)

Bring (1) and (2) into equation (3) to obtain the transcendental equation between \( f \) and \( y \). In the case of known wire diameter, the relationship between the amplitude and frequency of the transmission line is obtained by matlab solution transcendental equation. Shown figure 7.

![Figure 7. Wire vibration](image)

![Figure 8. Piezoelectric output](image)

5.2. **Piezoelectric energy harvester optimization design**

According to the relationship between the vibration frequency and the amplitude of the transmission line as shown in Fig. 7, the natural frequency of the piezoelectric cantilever energy harvester structure is designed to be around 19 Hz. The fixed end is fixed in the base, and in order to reduce the first-order natural frequency of the harvester, the end of the cantilever beam is attached with a mass. In order to subject the cantilever beam to large strain, the substrate is selected as phosphor bronze material, the mass and the base are also phosphor bronze, and the piezoelectric wafer is PZT-5H.

| symbol | Material and geometry | value |
|--------|-----------------------|-------|
| \( C_{33}^E \) /GPa | Piezoelectric modulus | 120 |
| \( C_{33}^p \) /GPa | Substrate elastic modulus | 200 |
| \( \rho_p \) /kg \cdot m\(^{-3}\) | Piezoelectric layer density | 7500 |
| \( \rho_s \) /kg \cdot m\(^{-3}\) | Substrate density | 7850 |
| \( \varepsilon_{33}^T \) /nF \cdot m\(^{-1}\) | Piezoelectric constant | 3200 |
| \( d_{31} \) /pC \cdot N\(^{-1}\) | Piezoelectric constant | 275 |
| \( L_p \) /mm | Piezoelectric layer length | 75 |
| \( L_s \) /mm | Base length | 85 |
| w/mm | width | 20 |
| \( t_p \) /mm | Piezoelectric thickness | 0.15 |
| \( t_s \) /mm | Substrate thick-ness | 0.2 |
| \( R_i / k\Omega \) | External resistor | 12 |
Table 3. Influence of Structural Parameters of Cantilever Beam on Natural Frequency

| Wafer length/mm | Frequency /Hz  | Block thickness/mm | Frequency /Hz  | Substrate thickness/mm | Frequency /Hz |
|-----------------|----------------|--------------------|----------------|------------------------|---------------|
| 10              | 9.835          | 1                  | 25.053         | 0.1                    | 16.274        |
| 20              | 12.251         | 1.5                | 20.456         | 0.15                   | 20.234        |
| 30              | 15.384         | 2                  | 17.707         | 0.2                    | 24.471        |
| 40              | 18.496         | 2.5                | 15.826         | 0.25                   | 28.926        |
| 50              | 20.251         | 3                  | 14.435         | 0.3                    | 33.565        |
| 60              | 20.237         | 3.5                | 13.623         | 0.35                   | 38.354        |

The material parameters used in the energy harvester are shown in Table 2. The finite element analysis software was used to analyze the twin field piezoelectric cantilever beam, and the results shown in Table 3 were obtained. It can be seen from Table 3 that the size of the piezoelectric wafer and the substrate are fixed, the thickness of the mass is changed, and the width and length are kept unchanged. As the mass length increases, the mass of the mass increases, and it is concluded that the quality of the mass can be effectively increased. Reduce the natural frequency of the cantilever beam and increase the output voltage of the energy harvester. The size of the fixed mass is constant, and the length of the piezoelectric wafer is changed, so that the natural frequency increases as the length of the wafer increases. Keeping the other parameters unchanged, changing the thickness of the substrate, the natural frequency increases as the thickness of the substrate increases. In order to collect low frequency vibrations, a higher output power is obtained. The piezoelectric cantilever beam structure should be selected with suitable size masses. Under certain width conditions, long and thin cantilever beams should be selected. The first-order natural frequency is 19.4715 Hz by finite element analysis.

6. hybrid energy harvesting circuit design and Charge / Discharge control

6.1. Design of Hybrid Energy Harvesting Circuit

In this paper, based on the characteristics of solar energy and vibration energy in the transmission line environment, and the output characteristics of the solar panel and piezoelectric vibration energy harvester, the hybrid energy harvesting circuit shown in Figure 9 is designed. In order to improve the transmission efficiency of the energy collector, an impedance matching method is employed. The controller controls the whole system, and according to the output power of the energy harvester, with the super capacitor, the corresponding working mode is selected, and the wireless temperature sensor can be continuously self-powered.

6.2. Charge / discharge control strategy

Because the wire vibration and the solar intensity are unstable in practical applications, the vibration energy and light energy input into the system are also unstable. For the convenience of analysis, the system is divided into 11 working modes. 0 means that the solar panel and the piezoelectric vibration energy harvester have no power output, 1 means that the solar panel and the piezoelectric vibration energy collector have power output, 0 means that the load works in a light load state, and 1 means that the load works in a heavy load state, 0 means the super capacitor stops working, 1 means the super capacitor works in the charging state, and -1 means the super capacitor works in the discharging state. The whole system works in these 11 working modes as shown in Table 4. In actual work, these 11
modes are a dynamic and smooth conversion process, which can be converted to each other at any time.

![Figure 9. Charge / discharge control circuit](image)

6.3. Simulation results
This paper simulates the working mode in which the data is transmitted and the energy collector output cannot supply power to the electronic device. It is necessary to supply the wireless sensor with the super capacitor. In this paper, the pure temperature sensor is used to replace the wireless temperature sensor. The resistance value $R$ is 0.1 kΩ and 10.1 kΩ under light load and heavy load conditions respectively. The super capacitor discharge load voltage is shown in Figure 10. The load current is shown in Figure 11, which satisfies the wireless temperature sensor work requirements.

| Weather situation      | Operating mode | Solar energy | Vibration energy | load | Super capacitor |
|------------------------|----------------|--------------|------------------|------|-----------------|
| Winding and dull       | 0              | 0            | 1                | 1    | -1              |
|                        | 1              | 0            | 1                | 0    | 1               |
| Light and windless     | 2              | 1            | 0                | 1    | 0               |
|                        | 3              | 1            | 0                | 1    | -1              |
| Windy and light        | 4              | 1            | 0                | 0    | 1               |
|                        | 5              | 1            | 1                | 1    | 1               |
|                        | 6              | 1            | 1                | 1    | 0               |
|                        | 7              | 1            | 1                | 1    | -1              |
| No wind and no light   | 8              | 1            | 1                | 0    | 1               |
|                        | 9              | 0            | 0                | 1    | -1              |
|                        | 10             | 0            | 0                | 0    | 0               |

![Figure 10. Super capacitor discharge load voltage](image)
Figure 11. Super capacitor discharge load current

7. Conclusion
The research on vibration energy harvester and photovoltaic energy harvester has gradually matured. Based on the research and design of this, a new hybrid energy harvesting system for transmission lines is proposed. The vibration frequency of the transmission line is analyzed, and the piezoelectric vibration energy collector adapted to the transmission line environment is designed by the finite element. According to the output voltage of the photovoltaic panel, it is not possible to directly supply power to the system electronic equipment, and the power adjustment circuit suitable for the electronic equipment of the system is designed. To improve the output power of the energy harvester, an impedance matching method is employed. Combined with super capacitors, it realizes long-term self-power supply of wireless sensors on transmission lines.

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