Simulation Study on Influencing Factors of Electric and Mechanical Energy Hybrid Harvester for Power Transmission Lines

Liu Cao[1], Yulong Liu[1], Fei Sheng[1], Zufen Wu[2](✉), Dongyang Hu[2], Xiaolong Huang[2], and She Chen[2]

[1] State Grid Wulumuqi Electric Power Supply Company, Wulumuqi 830054, China
[2] College of Electrical and Information Engineering, Hunan University, Changsha 410082, China
{wuzufen,chenshe}@hnu.edu.cn

Abstract. The stable power supply of monitoring devices on the transmission lines has been a practical problem for a long time. In this work, we propose an electric filed and mechanical energy hybrid harvester (EFMEH). With a coaxial rotatory freestanding triboelectric nanogenerator combined with a high-potential electric filed energy harvester as the basic structure, the EFMEH can capture the electric filed energy from the grid transmission line and the mechanical energy such as wind and raindrop energy from the external environment simultaneously. Compared with mechanical energy harvester (MEH), it can significantly improve the power supply reliability of the monitoring devices on the transmission lines. In order to study the output characteristics of the EFMEH and clarify the influence of key parameters on the output, a finite element model has been built. The simulation results show that both the operating voltage and the triboelectric effect cause periodic changes in the potential of the stator electrode. It has been demonstrated show that the output voltage amplitude can reach 810.81 V when the radius of the transmission line is 1 cm, and the total coupling capacitance is 38.79 pF when the number of stator electrodes is 16.

Keywords: Condition monitoring device · electric filed energy harvesting · triboelectric nanogenerators

1 Introduction

With the economic growth, human society's demand for electricity is increasing, and sustainable energy sources has also been developing in order to achieve national carbon peak and carbon neutral goals [1]. In the power system, it is particularly important to monitor working conditions of the equipment or real-time monitoring of power lines status, such as lightning, ice cover, fouling, vibration, etc. [2] Most of the high-voltage lines are in remote areas and it will consume a lot of manpower for daily operation and maintenance. The deployment of monitoring devices can achieve remote monitoring and solve the problem. However, the monitoring device needs to work on or around the high-voltage power lines, how to supply stable power to them is a difficult problem [3].

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In the practical engineering, solar, wind, electric field and other energy harvesting methods are typically used, and other energy are converted into electrical energy through the energy harvester. The obtained electrical energy is stored in the battery and discharge when the monitoring device needs electricity [4]. However, solar energy harvester efficiency is low, and it is vulnerable to weather and time. In rainy weather or night, it cannot be used, resulting in unstable power supply. Although wind energy harvester technology is mature, it still has some disadvantages and is difficult to put into an encapsulated structure. Therefore, its service life is limited and it requires frequent maintenance. Electric filed energy harvester is stable and the structure is simple, but the output is AC small current. The circuit presents high capacitive impedance, and there is a dead zone of power supply [5–7]. In order to overcome this drawback, a composite power supply system combining electric filed energy on the high-voltage side and artificial light source on the low-voltage side have been proposed [8], using artificial light source as a backup power source. This system can solve the problem of dead zone of electric field induction. However, the low-voltage side artificial light source requires external power supply, which is more inconvenient to use, and the energy is not highly efficient to utilize after secondary conversion.

In this work, we take advantage of the fact that the triboelectric nanogenerator can effectively convert the mechanical energy into electrical energy and combine the electric field energy harvester and the triboelectric nanogenerator. Then, we propose a dual-capture energy harvester combining electric field energy and vibration energy. In order to study the output characteristics of the hybrid harvester and clarify the effects of different design parameters on the output, a finite element model of the hybrid harvester was established. The hybrid harvester mode can effectively capture both electric field energy and mechanical energy.

2 Principle of Dual Capture Energy Technology

2.1 Principle of Electric Field Energy Harvester Technology

The basic principle of Electric filed energy harvesting (EFEH) is the basic principle is to charge the capacitor through the displacement current between the high-voltage line and the electrode. After the capacitor acquires enough energy, it then supplies the load through the management circuit [8, 9]. There are stray capacitance C_{ce} between transmission line and metal plate, and coupling capacitance C_{ed} between metal electrode and ground. The equivalent capacitance C_{eq} between transmission line and ground is:

$$C_{eq} = \frac{C_{ce}C_{ed}}{C_{ce} + C_{ed}} \tag{1}$$

The voltage of the transmission line is U_{ac}, then the current I_{ac} between the transmission line and ground is:

$$\dot{I}_{ac} = \frac{\dot{U}_{ac}}{jwC_{eq}} \tag{2}$$

The transmission line voltage U_{ac} is a stable value and the capacitance C_{eq} between the transmission line and ground is a fixed value. So the current I_{ac} is a stable value from Eq. (2). The electric field energy harvester technology is to use this stable current to convert electric field energy into electrical energy and store it with capacitor or directly power the load. In the high potential energy harvester mode, the load is connected in parallel at the capacitor C_{ce}, which can directly power the load. The main influence of the current is the coupling capacitor C_{ed}, and the stray capacitor C_{ce} has little influence on the current (Fig. 1).

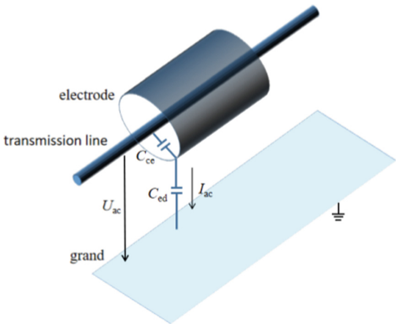


Fig. 1. Schematic diagram of electric field harvester

2.2 Principle of Triboelectric Nanogenerator Energy Harvester Technology

Triboelectric nanogenerator (TENG) is an energy harvester technology that converts mechanical energy into electrical energy, working on the combination of both frictional and electrostatic induction effects. This technology converts mechanical energy into electrical energy by using mechanical movements derived from body movements, wind energy, and environmental vibrations. According to the operating principle, TENG is divided into four main categories: vertical contact separation, lateral sliding, single electrode, and independent frictional electric layer modes [10–12]. In this work, the transverse sliding mode is selected, and the specific process is shown in Fig. 2.

The outer metal electrode rubs against the friction material under the action of external mechanical energy. Due to the different electronegativity of the metal and the friction material, electrons move from the outer metal electrode to the friction material, so the metal electrode is positively charged and the friction material is negatively charged. Because the surface area of the outer metal electrode is the general surface area of the friction material, the charge density of the outer metal electrode is twice the charge density of the friction material. Step 1: The inner left metal electrode is induced as positive potential, and the right electrode is induced as negative potential, so the current direction is from left to right. Step 2: The outer metal electrode gradually moves to the right under the action of external vibration, reaching the middle of the two inner metal electrodes. There is no potential difference between the two pole plates, and the load has no current. Step 3: When the outer metal electrode moves to the top of the right inner electrode, the right electrode induces a positive potential, the left electrode induces a negative potential, and the current direction is from right to left. Change the structure in the figure to a ring shape, then the load can be powered continuously.

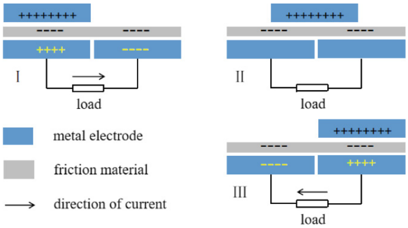
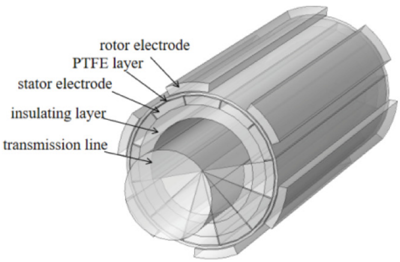


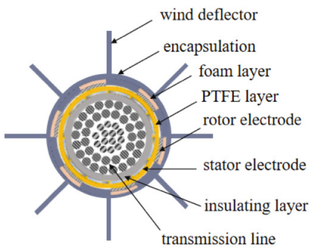
Fig. 2. Principle of energy harvester of triboelectric nanogenerator

3 Hybrid Harvester Model Design and Simulation

A dual-capture simulation model was built using COMSOL Multiphysics as shown in Fig. 3, in which the triboelectric nanogenerator structure is composed of rotor electrode, PTFE and stator electrode together, and the field energy harvester structure is composed of transmission line, insulation layer and stator electrode.



(a)3D schematic diagram



(b)2D schematic diagram

Fig. 3. Schematic diagram of hybrid harvester

3.1 Electric Field Energy Harvester Model Simulation

To investigate the factors affecting the output voltage amplitude of the electric field induction, three main aspects are analyzed: the transmission line radius r_1, the insulation layer thickness d_i, and the dielectric constant ε_i of the insulation layer.

1) The effect of transmission line route radius r_1

The thickness of the insulation layer is 1cm and the relative dielectric constant of the insulation layer is 10. The effect of r_1 on the output voltage amplitude is investigated by changing the wire radius of the transmission line, which is shown in the Fig. 4. The output voltage waveform at $r_1 = 2$ cm is shown in the Fig. 5. As the line radius increases, the output voltage amplitude decreases gradually from 810.81 V to 413.37 V. However, the magnitude of the decrease gradually decreases. When the transmission line radius is 1.03 cm, the voltage amplitude is reduced by about 127.75 V because of an increase of 0.3 cm line radius. When the transmission line radius is 2.37 cm, the voltage amplitude is reduced by about 38.6 V because of an increase of 0.3 cm line radius.

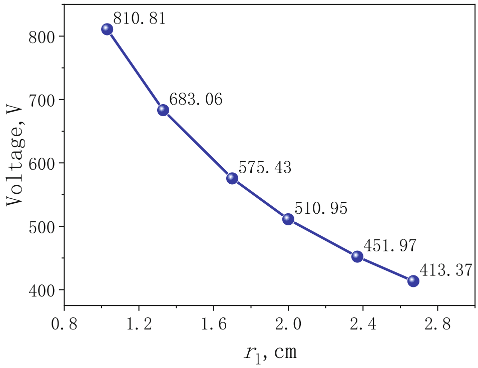


Fig. 4. Effect of r_1 on output voltage amplitude

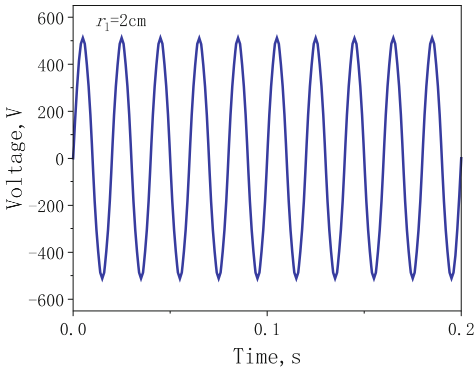


Fig. 5. Output voltage waveform when $r_1 = 2$ cm

2) The effect of insulation layer thickness

The radius of the transmission line is 2 cm and the relative dielectric constant of the insulation layer is 10. The thickness of the insulation layer is varied and the results is shown in Fig. 6. It can be seen that as the thickness of the insulation layer increases, the output voltage amplitude increases accordingly, but the magnitude of the increase decreases. The transmission line is cylindrical, and the electric field in close proximity can be approximated as a uniform electric field with constant voltage. So the increase in insulation thickness makes the potential difference larger, which means the output voltage increases. But the further away from the transmission line, the smaller the field strength, so the amplitude increase is reduced.

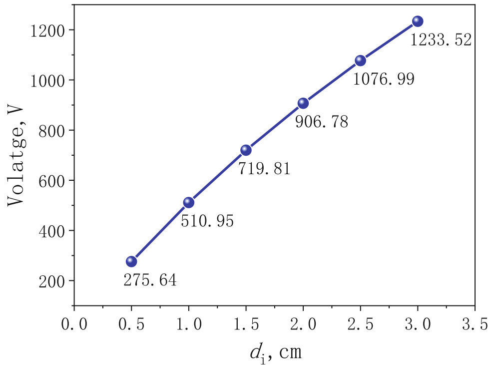


Fig. 6. Effect of insulation thickness on output voltage amplitude

3) The effect of the relative dielectric constant of the insulation layer

The radius of the transmission line is 2 cm and the thickness of the insulation layer is 1 cm. The relative dielectric constant of the insulation layer is changed and the results is obtained in Fig. 7. It can be seen that the output voltage amplitude decreases with the relative dielectric constant of the insulation layer. When the relative dielectric constant of the insulation layer increases from 5 to 10, the voltage amplitude decreases from 1019.01 V to 511.15 V. When the relative dielectric constant increases from 30 to 35, the voltage amplitude decreases from 171.27 V to 146.84 V.

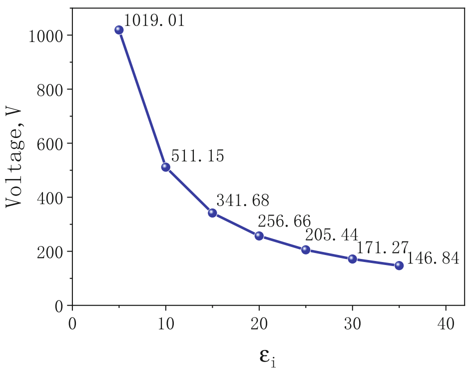


Fig. 7. Effect of relative dielectric constant of the insulation layer on the output voltage amplitude

From the previous analysis, it can be demonstrated that the device can be installed on the transmission line of small radius. If we want to increase the output voltage of the electric field energy harvester, the thickness of the insulation layer can be increased and the relative dielectric constant of the insulation layer can be reduced. However, it is necessary to consider the line insulation and the actual local environment to avoid the impact on the line. In addition, the larger device is more likely to cause damage, so the insulation thickness should not be too large.

3.2 Triboelectric Nanogenerator Model Simulation

To investigate the factors affecting the output voltage amplitude of the triboelectric nanogenerator, two main aspects are analyzed: the PTFE surface charge density σ and the PTFE thickness d_p.

1) The effect of PTFE surface charge density σ

The PTFE thickness is 2 mm, Fig. 8 and Fig. 9 show the effect of PTFE surface charge density on the output voltage amplitude of TENG. With the increase of σ, the output voltage amplitude gradually increases, and the voltage amplitude is linearly related to σ. When σ increases by 2×10^{-6} C/m^2, the output voltage amplitude increased by about 305.69 V.

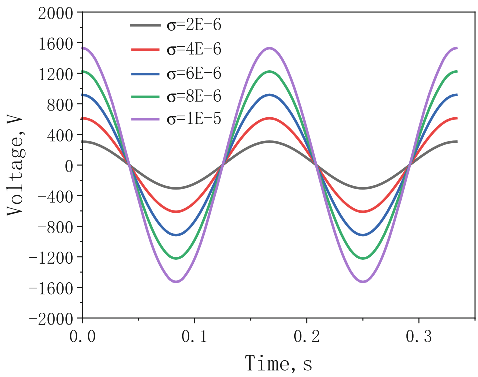


Fig. 8. Output curves of triboelectric nanogenerator

2) Effect of PTFE thickness d_p

The σ is kept at 2×10^{-6} C/m^2, and Fig. 10 shows the effect of PTFE thickness on the output voltage amplitude of TENG. With the increase of PTFE thickness, the output voltage amplitude gradually decreases, and the magnitude of the decrease gradually decreases. When the d_p is 1 mm, the output voltage amplitude can reach 1294.1 V, and when the d_p is 5 mm, the output voltage amplitude is 483.97 V, which is only 37.40% of that at 1 mm.

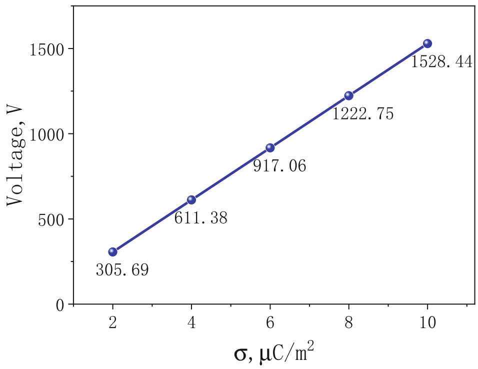


Fig. 9. Effect of σ on output voltage amplitude

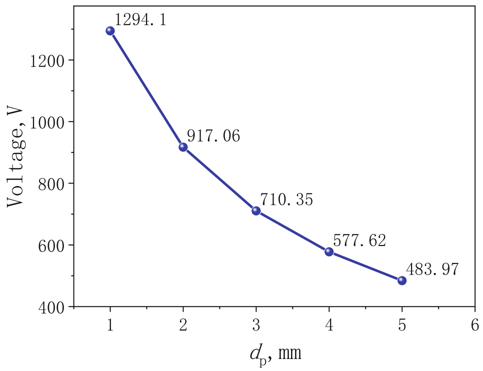


Fig. 10. Effect of d_p on output voltage amplitude

From the above analysis, it can be found that the output voltage amplitude of the triboelectric nanogenerator is positively related to σ and negatively related to d_p. Therefore in order to increase the output voltage, the friction material is suitable for the use of materials that are easy to gain and lose electrons, and the material thickness should be thin.

4 Discussion on Coupling Capacitance

From the working principle of energy harvester by electric field, it is known that when the capacitance of the energy harvester electrode plate to ground is larger, the capacitance impedance is smaller and the current flowing through the load is larger. Due to the small size of the stator electrode, the single electrode capacitance is small, so the coupling capacitance value can be improved by connecting the stator electrodes in parallel. In order to study the influencing factors of coupling capacitance, a simulation model has been established.

The simulation results show that the single capacitance decreases and the coupling capacitance increases as the number of stator electrodes increases. When the number of stator electrodes is 4, the individual capacitance value is 3.54 pF and the coupling capacitance is 14.15 pF. When the number of stator electrodes is 16, the individual capacitance value is 2.42 pF and the coupling capacitance is 38.79 pF. As the number of stator electrodes increases, the width of electrodes decreases, so the size of single capacitance decreases. Due to the small size of the electrodes, the single capacitance decreases, but the reduction is not significant. The magnitude of the coupling capacitance is approximately linearly related to the number of stator electrodes, and the results obtained from the theoretical analysis and simulation are the same (Fig. 11).

Therefore, to make the total coupling capacitance larger, the number of stator electrodes can be increased. But if the number of stator electrodes become greater, it means that the width of the electrodes is thinner and the strength is smaller, which is more likely to cause damage to the stator electrodes. Therefore, it is necessary to choose a suitable number of stator electrodes in the device, which can increase the total coupling capacitance and have a certain strength at the same time.

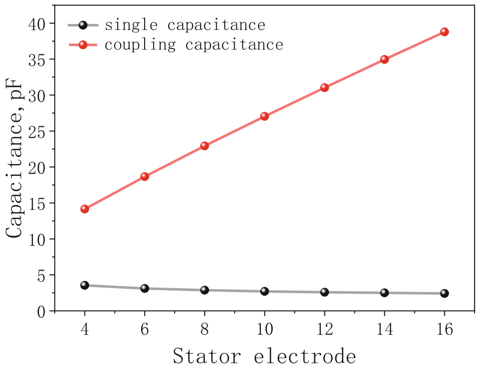


Fig. 11. Effect of the number of stator electrodes on capacitance

5 Conclusions

In this work, a power supply technology has been proposed for condition monitoring devices based on the dual capture method of electric field and vibration energy. A hybrid harvester structure has been established, in which electric field induction and triboelectric nanogenerator are used to capture energy through the same structure. The electric field energy comes from the internal grid and the mechanical vibration energy comes from the external environment, and the energy harvester sources are complementary, which can improve the reliability of power supply.

We have analyzed the influencing factors of the electric field energy harvester module and the triboelectric nanogenerator energy harvester. The transmission line radius, insulation layer thickness, insulation layer relative dielectric constant, PTFE surface charge density and PTFE thickness are investigated. It has been demonstrated show that the EFEH output voltage amplitude can reach 1233.52 V and the TENG output voltage amplitude can reach 1528.44 V. In addition, the single coupling capacitance is 2.42 pF and the total coupling capacitance is 38.79 pF when the number of stator electrodes is 16.

References

1. Xiao, X.Y., Zheng, Z.: New power systems with new energy sources under the "double carbon" target: contributions, key technologies and challenges. Eng. Sci. Technol. **54**(01), 47–59 (2022)
2. Guo, S., Wang, P., Zhang, J., et al.: An overview of electromagnetic energy collection and storage technologies for a high voltage transmission system. Energy Storage Sci. Technol. **8**(01), 32–46 (2019)
3. Zhi, R., Liu, Z., Zhang, L., Lu, W.: Research and application of online monitoring power supply for high-voltage transmission lines. Power Technol. **39**(02), 413–415 (2015)
4. Guo, D., Wang, P., Zhang, J., et al.: A review of electromagnetic energy harvesting and storage technologies for high-voltage transmission systems. Energy Storage Sci. Technol. **8**(01), 32–46 (2019)
5. Kang, R., Lin, H., Yang, M.: Review on power supply technology for on-line monitoring device of middle and high voltage electrical equipment. Electr. Energy Manage. Technol. **06**, 1–7 (2016)
6. Lei, J.: Analysis of key technologies in wind power and photovoltaic power generation. Integr. Circuit Appl. **39**(11), 324–325 (2022). https://doi.org/10.19339/j.issn.1674-2583.2022.11.146
7. Wang, L., Li, Z., Meng, X., et al.: Power supply technology for low power online monitoring sensors based on electric field induction. High Voltage Technol. **46**(02), 538–545 (2020)
8. Luo, Y.P., Zeng, X.J., Lei, Y.P., et al.: High-voltage electric field induction energy harvester technology based on discharge method. Power Syst. Autom. **39**(08), 113–119 (2015)
9. Wang, L., Li, Z., Meng, X., et al.: Optimal design of a wireless energy harvester power supply for AC electric field. High Voltage Electron. **56**(05), 121–127 (2020)
10. Menendez, O., Cheein, F.A.A., Rodriguez, J.: Displacement current-based energy harvesters in power grids: topologies and performance evaluation. IEEE Ind. Electron. Mag. **16**(3), 52–66 (2021)
11. Zeng, Q.X., Wu, Y., Tang, Q., et al.: A high-efficient breeze energy harvester utilizing a full-packaged triboelectric nanogenerator based on flow-induced vibration. Nano Energy **70**, 104524 (2020)
12. Yang, Y., Zhang, H.L., Chen, J., et al.: Single-electrode-based sliding triboelectric nanogenerator for self-powered displacement vector sensor system. ACS Nano **7**(8), 7342–7351 (2013)