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An electromagnetic energy harvesting device based on high efficiency windmill structure for wireless forest fire monitoring application

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ABSTRACT

In this paper, we introduce a miniature windmill-structured energy harvester for wireless monitoring of forest fires. The proposed energy harvester design can effectively scavenge the energy from ambient air flow using electromagnetism, thereby self-powering the wireless sensing nodes for fire alarming. To find an optimal structure with the highest aerodynamic efficiency and sensitivity to wind flow, miniature energy harvesters with various windmill structures were designed, simulated, 3D printed and experimentally characterized. In the performance test, with the optimized windmill structure, a peak output voltage of 5.2 V and a peak output power of 60 mW were achieved by the energy harvester with a load resistance of 150 Ω. Moreover, a wireless transmission module was designed and connected to the windmill-structured energy harvester to constitute a wireless fire monitoring system. This module successfully transmitted an alarm signal upon detection of a fire in the feasibility test.

1. Introduction

Forest fires, also known as wildfires, are uncontrolled fires occurring in the countryside or wilderness, which result in enormous damage to natural and human resources [1,2]. Wildfires eradicate forests, destroy the ecosystem, and may lead to severe casualties if they are not extinguished timely. The damage caused by accidental wildfires to public safety and natural resources is tremendous and intolerable. For instance, in the United States, typically 40,000–250,000 wildfires occur each year, burning 3 million to 10 million acres of land depending on the year [3]. The black forest fire, which happened in Colorado, June 2013, destroyed 509 homes, and forced the evacuation of 38,000 residents. The estimates of damage are expected to exceed $90 million [4]. Due to dry conditions, high heat and restless winds, fast-spreading forest fires can easily become devastating disasters to the human beings nearby. Therefore, the early detection and suppression of fires are crucial for minimizing the damage and casualties.

Considering the fast-spread characteristic of a forest fire, real-time surveillance of the forest area is desired to minimize the range of the danger zone. Moreover, owing to the vast area of a forest, conventional sensor networks with long-wire bundles incur a huge installation and long-term maintenance cost, limiting the number of sensors that can be installed and thereby reducing the overall quality and reliability of the real-time data reported [5]. For these reasons, the wireless sensors network (WSN) is an appropriate choice for solving these problems. Regarded as one of the most significant technologies in the 21st century, WSNs can realize continuous detection and information monitoring [6,7]. Unfortunately, the battery is one of the most common means to power a widely spread wireless sensor installed in a commercial WSN [8]. Its limited electrical power will result in a high maintenance cost [9]. Moreover, the energy-saving strategy employed in the power management module of each node will reduce the sampling rate and the signal transmission rate as well as the accuracy of the real-time data [10]. To solve these problems, researchers have carried out extensive studies on various energy harvesters to substitute the batteries used in WSN applications [11,12].

Energy harvesters are used to convert the ambient energy into electricity to power small autonomous sensors [13]. Many types of energy sources are available for energy harvesting, such as solar, hydraulic, vibration and wind [14–17]. However, vibration is not available in the forest environment. And, due to the shading by the lush leaves on the trees in a forest, it is difficult to harvest sufficient solar energy in the forest; furthermore, a large solar panel will have various installation constraints. On the other hand, wind energy, except that from natural wind in normal conditions, would be viable even in a forest fire condition because of the large amounts of air convections that exist during a forest fire from the temperature difference between the fire zone and its surroundings. Based

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on the above considerations, wind is a more effective and reliable source of energy for this application. Therefore, considering the abundance of natural wind and air convection in a forest environment, the use of wind flow as the energy source for the energy harvesting system is reasonable.

Most conventional energy harvesters use piezoelectric materials for power generation [18]. For instance, Bibo et al. [19] proposed a concurrent piezoelectric energy harvester for both ambient wind power and vibrations. Li et al. [20] reported a polymer piezoelectric energy harvester for low-speed wind. However, the high resistances (~kΩ/MΩ or even more) of piezoelectric materials result in very low output currents and powers, which cannot satisfy the minimum power requirement of a small sensor [21]. On the contrary, the electromagnetic method, having low internal resistance (~Ω), can realize much higher output currents and powers than piezoelectric methods [22]. For example,Tang et al. [23] developed a wide frequency-range energy harvester using non-contact, magnetic repulsive-force excitation based on electromagnetism, which can generate a peak power of 4.42 mW (much more than that based on piezoelectric materials, normally only ~μW). Galchev et al. [24] also presented a micro electromagnetic energy harvesting device for low-frequency and nonperiodic vibrations. Therefore, in order to provide high output currents and powers for the sensor nodes in the practical application, the electromagnetic method is utilized in our design.

In this paper, we proposed a unique windmill-structured electromagnetic energy harvester that can convert ambient wind energy into electricity to supply high output current and power for sensing and signal transmission in forest fire monitoring application. Different blades were designed and manufactured utilizing 3D printing technology. A finite element method (FEM) simulation was conducted to determine the blade design with the highest efficiency. Based on this design, a miniature energy harvester prototype was successfully fabricated and experimentally characterized. A preliminary forest fire wireless monitoring system was also realized and demonstrated.

2. Design and modeling

In a forest environment, natural wind is one of the most reliable and sufficient sources of energy. Moreover, once a forest fire occurs, due to the air temperature difference between the fire spot and the area nearby, a large amount of air convection occurs around the fire area [25]. Both of these types of air flow can be utilized by the energy harvester to generate power. Therefore, the design of the energy harvester should be wind-sensitive and should effectively convert wind energy into electricity. A windmill is a machine that converts the energy of wind into rotational energy by means of blades/vanes. This kind of structure can effectively scavenge the wind energy with low noise and high reliability during its long service life. Therefore, we apply the windmill structure to our harvester design to collect the wind energy.

Schematically shown in Fig. 1, a windmill structure is mounted on a frame with a highly lubricated axis. The streamlined frame can selectively allow the wind to pass through the energy harvester in a particular area, as well as reduce the resistance of the wind input. Four identical magnets, protected by the frame, are attached to the ends of the blade in the same pole arrangement, respectively. A copper coil is installed on the frame just below the magnets. When the airflow produced by the environment passes through the windmill-structured energy harvester, the airflow force pushes the blades to rotate about the pivoting axis. Thereby, the alternate magnet-and-no magnet passing condition over the coils will vary the magnetic flux through the loop of copper coils. In this way, according to Faraday's law of induction, electrical energy will be generated when this energy harvester is placed in a wind field [26].

However, the aerodynamic profiles of blades have a crucial influence on the rotating efficiency of the whole windmill structure [27]. Therefore, aiming for high aerodynamic efficiency, 7 types of windmill structures with various types of blades are designed, shown in Fig. 1. The characteristics of these blades are listed in Table 1. It should be noted that compared with the curvature of the type 2 blade, that of the type 3 blade is expected to concentrate the wind more on the blade end to produce a higher rotating moment. The type 4 blade is designed with a concave/convex angle to produce a high rotating torque. The convex side of the blade features pores/indentations can break up the even airflow pattern on the surface. A layer of air will be created directly over the blade surface of this side, which can reduce the resistance and friction as the blade moves through the air [28]. The dimple patterns will increase the strength of the blade. The parallel arranged slots capture and channel the air flow. The slots near the center axis are wider and deeper than those near the outer edge of the blade. The air flow is guided to the blade end and hence, the moment of rotation is enhanced. Type 5 combines the end-concentrated circular arc shape with pores and slots. In type 6, the direction of the slots is changed, which means that the slots near center axis are narrower and shallower than those near the outer edge of the blade. To determine which structure can reduce resistance more during blade rotation, we replace the pores with half spheres on the convex side of the blade surface in the type 7 design.

The number of blade also affects to the performance of the energy harvester. Considering the inherent torque ripple existed in the blades, which influences to the fatigue life of the device as well as the output power quality, three or more blades in the windmill structure are desirable to reduce the torque ripple [29]. In addition, proper number of blades is another important issue to keep a high performance of the energy harvester. In order to avoid the decrease in power generation ability caused by the counteraction of magnetic flux between permanent magnets, a certain distance should be ensured between each magnet in the windmill structure. This leads a limited number of blades as less than five in the present dimension. Based on above considerations, four blades are adopted for each type of windmill structures.

To determine the windmill structure with the highest efficiency, the FEM model of the windmill-structured energy harvester, as well as these 7 types of blades, were built by software COMSOL Multiphysics 4.2. Under same initial conditions, the wind velocity distribution and pressure distribution for each blade working in the energy harvester were simulated respectively. Additionally, the condition of the windmill structure during a rotating cycle was studied by simulating the windmill structure at various angles (0°, 30°, 60°) in a wind field. The insets of Fig. 2(a) and (b) show the simulation results of type 4 for illustration. The inlet wind flowed from the right to the left at 1 m/s.

As shown in Fig. 2(a) and (b), due to the different blade curve shapes – planar shape (type 1), standard circular arc shape (types 2 and 4) and end-concentrated circular arc shape (types 3, 5, 6 and 7), the distributions of wind velocities and pressures of the 7 type of blades presented various characteristics even at same rotating angle. Among the 7 types, type 4 produced the highest wind velocity and maximum pressure at different rotating angles, which meant that it can produce the largest pushing force and highest acceleration during rotation. In this case, with the same input wind velocity and actuation time, type 4 can generate a higher rotating frequency, making it the most efficient blade design. To further confirm the aerodynamic efficiencies of the 7 designs, the performances of the 7 types of blades were characterized by experimental method.