Energy harvesting from wind by a piezoelectric harvester

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1. Introduction

The increasingly consumption of traditional energies has caused serious energy crisis and environmental pollution on a global scale. Wind energy has been regarded as one of the most important renewable and green energy sources to solve the above problems [1]. Wind turbines have been used on one of the traditional ways of transferring kinetic energy from wind based on the principle of electromagnetic induction [2,3]. The power coefficient of the wind turbines with output of megawatt has been reported up to 40–45% at the optimal tip speed ratio of 5–7 [4]. However, these large-size turbine generators are always complex, costly, and nor-

mally induce a cogging torque which restricts the cut-in speed. For

early works about a piezoelectric windmill were carried in liter-atures [9,10]. The proposed devices had ten piezoelectric bimorphs arranged along the circumference of a horizontal-axis wind turbine rotor shaft in the cantilever beam form. The oscillating torque to vibrate the bimorphs was generated using the camshaft gear mechanism. A power of 7.5 mW at the wind speed of 10 mph was measured across a matching load of 6.7 kΩ. Authors also addressed some drawbacks of this device and gave an optimized structure made of only plastic parts in the later work [11]. Sirohi et al. [12] developed a piezoelectric energy harvesting device based on a galloping cantilever beam. The harvested wind energy is transferred to a galloping beam which has a rigid tip body with a D-shaped cross section. Piezoelectric sheets were bonded on the top and bottom surface of the beam. During galloping, vibrational motions are induced due to aerodynamic forces on the D-section, which is converted into electrical energy by the piezoelectric (PZT) sheets. Their experimental and analytical investigations of dynamic response and power output have shown that a maximum output power of 1.14 mW was measured at a wind velocity of 10.5 mph on a prototype device of length 235 mm and width 25 mm. Rezaei-Hosseinabadi et al. [13] presented a topology for piezoelectric energy harvesting made of a lift-based wind turbine and a piezoelectric beam with contactless vibration mechanism. The research results showed that a power density of 2 mW/cm³ at 3.8 V at the wind speeds above 0.9 m/s can be achieved. Kishore et al. [14] designed an ultra-low start-up speed windmill made of a 72 mm diameter horizontal axis wind turbine rotor with 12 alter-

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Abstract

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nating polarity magnets around its periphery and a 60 mm × 20 mm × 0.7 mm piezoelectric bimorph element having a magnet at its tip. This wind turbine was found to produce a peak electric power of 450 µW at the rated wind speed of 4.2 mph. Wu et al. [15] developed an effective and compact wind energy cantilever harvester subjected to a cross wind. Sufficient electrical energy output as high as 2 W was realized by tuning the resonant frequency of the harvester with a proof mass on the tip of the cantilever.

The aforementioned piezoelectric harvester devices have been mainly developed for energy supplies of wireless sensors. Therefore, most of them are small in sizes and the energy outputs are always in the scale of mW. Recent researches have shown that piezoelectric harvesters can harvest power range from several watts to hundreds of megawatts [19–23]. Xie et al. [19,22] developed a novel piezoelectric technology of energy harvesting from high-rise buildings and found that a power up to 432.2 MW can be realized. Viet et al. [23] proposed a floating energy harvester (FEH) using piezoelectric effect to harvest energy from water waves. Based on their simulated results, the root mean square (RMS) of 103 W can be achieved when the wave amplitude is 2 m. Hence, it is imperative to develop harvesters with high power using piezoelectric effect from wind.

In this research, a wind energy harvester using piezoelectric technique is developed. This proposed piezoelectric wind turbine incorporates the advantages of the conventional wind turbines and the piezoelectric harvesters. Wind turbine rotor blades with the shape optimized by aerodynamics and connected to a horizontal shaft are employed as the driving device. The wind-induced rotational motion of the shaft is converted into translation motion of a slotted rod through a Scotch yoke mechanism. Both sides of the slotted rod are linked with a spring used for transferring the linear motion into vibrations of two piezoelectricity-levers. The extracted wind power is directly converted into an applied force on the piezoelectric bars with levers for amplification to achieve a more efficient energy harvesting process. In addition, since only few structural components with small sizes are required, the current engineering structure device is much smaller and lighter than the conventional wind turbines.

2. Design and modeling methods

Design of a horizontal piezoelectric wind turbine is depicted in Fig. 1(a and b). Three blades with a radius of R are attached to a shaft that is used to link the internal piezoelectric device. As seen in Fig. 1(b), the main piezoelectric harvester consists of a Scotch yoke mechanism, two springs with stiffness coefficient of \( k_1 \) and two piezoelectric levers. The Scotch yoke, shown in Fig. 2, is a reciprocating motion mechanism, converting a rotational motion into a linear motion [24]. A slotted rod is used to make sure the motion is only in the direction perpendicular to the axis of the shaft by a cylindrical slider attached to a wheel. When the wheel rotates at an angular velocity, \( \omega \), the end points of the slotted rod are displaced from their initial position by an amount \( z_t \) (in time t) given by \( z_t = Y \sin(\omega t) \), where \( Y \) is the amplitude, i.e. the distance between axes of the cylindrical slider and the shaft.

The piezoelectricity-lever device, shown in Fig. 3(a), consists of a lever with a long moment arm \( L_2 \) and a short moment arm \( L_1 \), a fixed-hinge for restricting linear displacements of the lever, and a piezoelectric bar with a Young’s modulus, width, length, and height of \( \varepsilon_P \), \( a \), \( b \), and \( h \), respectively. Since the piezoelectricity-lever devices are connected to the slotted rod by two springs, the harmonic motion is then converted into a spring force \( F(t) \). The force location is at the point C and magnified \( n \) times at the point A on the piezoelectric bar by the lever mechanism, where \( n \) is the ratio of the length of the long moment arm to that of the short moment arm, \( n = L_2/L_1 \). Consequently, the electric power is generated by the piezoelectric-lever design.

In order to estimate the spring force \( F(t) \), one of the piezoelectric lever is used as an example and is simplified as a damped single-degree-of-freedom (spring-mass) system, shown in Fig. 3(b) [23,25]. The equivalent mass \( m_e \), spring stiffness \( k_e \), and damping coefficient \( c \) can be derived from the material properties and dimensions of the lever and piezoelectric bar.

In the proposed design, the piezoelectric bar is firmly bonded on the lever at the region of point A. Due to the high tensile/compression stiffness of the piezoelectric bar in the force direction, the lever is supposed to be fixed throughout points A and B and equivalently transformed into a cantilever beam with a length of \( L_2 \). Hence, the equivalent mass \( m_e \) can be calculated as \( m_e = \rho A \ell n^2 \), where \( \rho \) and \( A \) are material density and cross-section area, respectively. In this work, the lever is made of steel, and its cross-section is rectangular in shape with a width and height of \( S_1 \) and \( S_2 \), respectively. The dimensions of the lever face are selected as \( S_1 = 0.015 \) m and \( S_2 = 0.004 \) m, unless otherwise noted.

Since the applied force at point C induces an elastic deflection of the cantilever and axial deformation of the piezoelectric bar, the equivalent spring stiffness, \( k_e \), in Fig. 3(b) can be yielded as [26]:

![Fig. 1. Schematic diagram of a horizontal piezoelectric wind turbine: (a) an overview of the device, and (b) an internal structure of the device.](image-url)
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